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Analysis and Estimation of Microplastics from Landfill Leachate in Urban India from 1960 to 2022

A Master's Thesis submitted for the degree of
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supervised by
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Affidavit

I, **BINNU JACOB EAPEN, B TECH**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ANALYSIS AND ESTIMATION OF MICROPLASTICS FROM LANDFILL LEACHATE IN URBAN INDIA FROM 1960 TO 2022", 87 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

A rapidly developing country like India has an ever-increasing rate of consumption. With consumption comes the problem of waste generation especially the generation of municipal solid waste. Plastic, a versatile material used by various industries is commonly found as a component of MSW in unsanitary landfills. As unsanitary landfills become the cheapest and the easiest method of disposing of waste, the problem of plastic pollution is increasing day by day in the urban areas of India. With the accumulation of large amounts of plastic waste in these landfills combined with the varying environmental conditions, the larger plastic pieces disintegrate into smaller particles called microplastics. Thus, landfills are a repository of microplastics that gets transported into the soil through landfill leachate. Microplastics have garnered attention as a toxic contaminant affecting soil and water in the terrestrial ecosystem. The objective of the thesis aims to estimate the quantity of microplastics that leach out from unsanitary landfills from a period ranging from 1960 to 2022. The work also provides an estimation of the total quantity of MSW generated during the above period and the amount of landfill leachate. This is followed by an assessment of the negative impacts related to the emission of microplastics. The thesis employs a comprehensive literature review to achieve the objective and a calculation that gives an estimate of the amount of microplastics discharged along with the other objectives. After the extensive literature review and calculations, it was found that the amount of microplastics discharged into the ground through landfill leachate over the past 62 years is in the range from 6570 tonnes to 12810 tonnes cumulatively. The amount of MSW dumped in such unsanitary landfills is estimated to be about 1986 MT while the amount of leachate that percolates into the ground from landfills is about 28461 ML. The above results point out that the unsanitary landfills in urban areas are potential sources of microplastics that cannot be neglected. Therefore it is necessary that landfills must be engineered scientifically to minimize the infiltration of water into the landfill and also to reduce the leachate release into the ground.

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List of Abbreviations

ABS	Acrylonitrile Butadiene Styrene
ALK	Aliphatic Polyketones
ATR	Attenuated total reflection
BD	Bulk density
BOD	Biochemical Oxygen Demand
BoPET	Biaxially-oriented polyethylene terephthalate
CA	Cellulose acetate
CI	Carbonyl index
COD	Chemical Oxygen Demand
DEHP	Di(2-ethylhexyl) phthalate
DBP	Dibutyl phthalate
DMP	Dimethyl phthalate
EDX	Energy dispersive X ray
EP	Epoxies
EVA	Ethylene Vinyl Acetate
FMCG	Fast-moving consumer sector
FT-IR	Fourier-Transform Infrared Spectroscopy
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GDP	Gross Domestic Product
HDPE	High-Density Polyethylene
HI	Hydroxyl index
IBEF	India Brand Equity Foundation
LDPE	Low-density polyethylene
MSW	Municipal solid wastes
MSWM	Municipal Solid Waste Management
NCR	National Capital Region
NFHS	National Family Health Survey
PA	Polyamide
PAH	Polycyclic aromatic hydrocarbons

PCB	Polychlorinated biphenyls
PCCP	Personal care and cosmetic products
PE	Polyethylene
PES	Polyethersulfone
PET	Polyethylene terephthalate
PMDS	Polydimethylsiloxane
PMMA	Polymethyl methacrylate
POPs	Persistent organic pollutants
PP	Polypropylene
PPE	Personal Protective Equipments
PPC	Polypropylene carbonate
PS	Polystyrene
PVB	Polyvinyl butyral
PVC	Polyvinyl chloride
PUR	Polyurethane
SEM	Scanning Electron Microscope
SOC	Soil organic carbon
SUP	Single-use plastic
SWD	Submarine water discharges
WHA	Water holding capacity
WSA	Water stability aggregates

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1. Introduction and Background

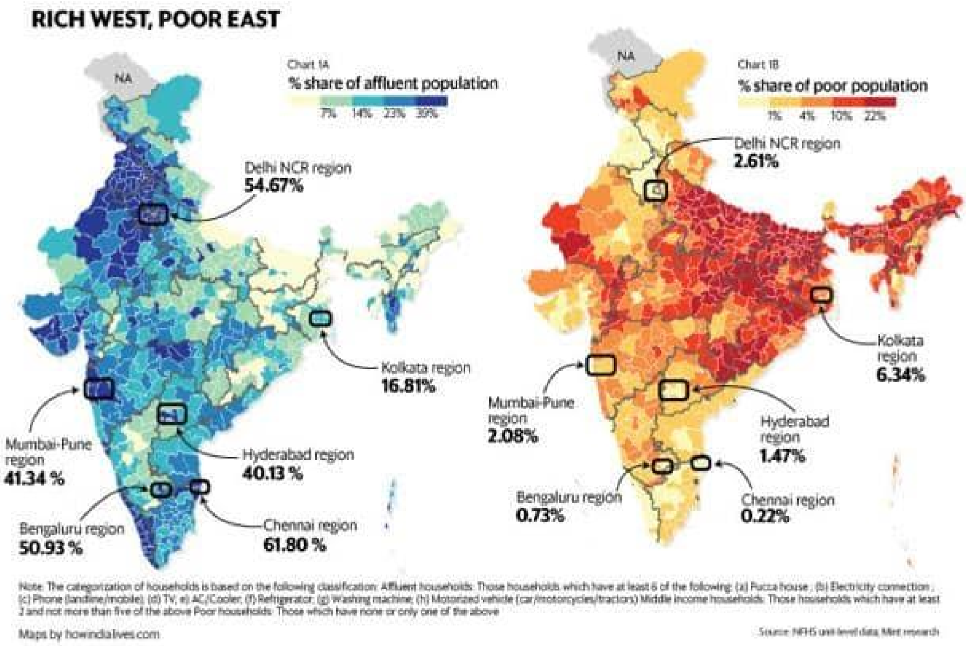
1.1. Introduction

As India aims to be one of the major superpowers in the world, the needs of the most populous country in the world cannot be overlooked. Consumption is one of the main drivers of growth in the country be it in different sectors of the economy. Given that the nation's financial resources are dispersed throughout the country, urban areas serve as catalysts for development. Urban areas, home to the wealthy and the rising middle-class income earners spur the growth with consumption. As businesses need their products to be sold, plastic usage and packaging have become an important part that assists every sector of the economy. With the increasing population, the waste generated is also mounting especially the plastic waste in the Municipal Solid Waste (MSW). The thesis focuses only on the Municipal Solid Waste generated in the urban areas of the country from the period from 1960 to 2022. Due to the inefficiency of the waste management policies in India, the MSW is dumped in poorly managed and non-engineered landfills in and around the cities. Being said, landfills are the cheapest method of disposal in developing countries. As the plastic waste in landfills is subjected to varying environmental conditions of sunlight, temperature, precipitation, evaporation, etc, the bigger plastic particles disintegrate into smaller particles called microplastics. The liquid that flows out from the landfill i.e. leachate, is laden with microplastics in addition to other contaminants in the mixture. Over the passage of time, the leachate seeps into the soil, and some of the microplastics get retained in the pores of the soil. Finally, the leachate reaches the groundwater which further exacerbates the pollution of groundwater. The groundwater contamination of microplastics may reach the oceans by means of submarine water discharges and contribute to marine pollution as well. Therefore, the thesis aims to determine the quantity of microplastics in the landfill leachate in the urban context from 1960 to 2022.

1.2. Background

According to the World Bank, India is one of the most rapidly expanding economies in the world and is expected to sustain its growth trajectory. By 2047, it aims to achieve the upper middle-income status which marks the 100th anniversary of the independence of India from British colonial rule. Furthermore, the country is fully committed to ensuring that its growth policies and expansion strategy are equipped to address any obstacles posed by climate change harmonizing with its objective of attaining net zero emissions by the end of the year 2070. The prosperity that the country has experienced over the past twenty years has led to tremendous breakthroughs in the alleviation of high levels of poverty. It is projected that between the years 2011 and 2019, the country has anticipated to reduce the proportion of people living in severe poverty by 50%. During the fiscal year of 2022/23, the country had a growth of 6.9% in its real gross domestic product (GDP). The expansion was bolstered by robust domestic demand, heightened investment activity propelled by the government's focus on infrastructure development, and vigorous private spending, particularly among persons with higher incomes or wealthy people ("India Overview: Development News, Research, Data | World Bank," n.d.).

According to the National Family Health Survey (NFHS), the urban areas in India have a high concentration of wealthy people (NFHS-4,2015-16). A study conducted by Mint on the NFHS data revealed that the affluent population in India is concentrated in the top six metropolitan areas namely Delhi National Capital Region (NCR), Chennai, Hyderabad, Kolkata, Mumbai, and Bengaluru. The combined population of the six urban cities is slightly less than one-sixth of the overall population of the country. The NCR region accounts for almost 11% of the wealthy citizens of the country and holds the apex position in terms of wealthy citizens. The majority of the affluent people in India are located in the southern, western, and northwestern regions. If an imaginary line is drawn from the top of the country to the bottom, the wealthy districts are located to the left of the line while the impoverished districts are to the right of the line (Bhattacharya and Kundu 2018).



Note: The categorization of households is based on the following classification: Affluent households: Those households which have at least 6 of the following: (a) Pucca house ; (b) Electricity connection ; (c) Phone (landline/mobile); (d) TV; e) AC/Cooler; (f) Refrigerator; (g) Washing machine; (h) Motorized vehicle (car/motorcycles/tractors) Middle income households: Those households which have at least 2 and not more than five of the above Poor households: Those which have none or only one of the above

Maps by howindialives.com

Source: NFHS unit-level data, Mint research

Figure 1 Wealth concentration in India (Source: NHFS unit level data, Mint Research)

Affluent individuals tend to select urban areas owing to the wide variety of amenities and services the cities provide within the city ecosystem. Urban areas offer a broad extensive range of employment opportunities, being the epicentres of economic activity. Furthermore, the existence of functional infrastructure, accessibility to services including financial institutions, entertainment, shopping, and educational institutions, and the presence of a lively atmosphere all contribute to the perception that city life offers a higher quality of life. Cities not only function as economic centers but also as areas for social differentiation. The ability to reside in a major metropolitan area could act as an emblem of affluence facilitating the formation of bonds among people of similar socio-economic standing and fostering a sense of affiliation with an exclusive cohort. Dreaming of the above status and facilities in cities, there is a growing trend of migration from the villages to the cities. The population explosion in the cities owing to the inherent expansion of the cities and migration leads to the generation of waste especially municipal solid wastes (MSW).

Municipal Solid Waste Management (MSWM) encompasses a variety of operations ranging from the generation, storage, collection, transfer and transport, processing, and disposal of solid waste. However, the MSWM system in the majority of the cities comprises of the four main activities namely, waste generation, collection, transportation, and disposal. The MSWM requires necessary infrastructure, maintenance, and enhancements for operations. This leads to increasing complexity and increasing finances owing to the continuous and unregulated growth of the cities. The primary cause of the difficulties associated with delivering the desired level of public services is the insufficient financial resources of the municipal corporations coupled with the bureaucracy and administration. The amount of MSW generated depends on a myriad of factors such as dietary patterns, living standards, commercial activity, and the season (Sharholy et al. 2008).

Sharholy et al. (2008) further suggest that the majority of metropolitan cities follow the open uncontrolled, and poorly managed method of dumping MSW which gives rise to deleterious environmental conditions(Rathi 2006,Mufeed 2005, Ray et al. 2005). In cities and suburban areas, a large amount of the MSW is disposed of improperly on land. In cities such as the Delhi-NCR land is limited for waste disposal. A large portion of the urban areas dispose of the MSW in low-lying areas that are outside the vicinity of the city even without abiding by the principles of sanitary landfilling. At the majority of the disposal sites, compaction and leveling of wastes in addition to the final covering of the wastes with earth is infrequently observed. Moreover, the aforementioned low-lying areas are devoid of the necessary equipment to monitor and collect landfill leachate or gas (Bhide and A.V 1998, Gupta et al. 1998). In the absence of source segregation of MSW, nearly all kinds of wastes including hospital waste finally end up at the disposal site. Sometimes, industrial refuse is deposited in landfills designated for household waste as landfilling is the cheapest and the easiest method of disposing of waste. The study concludes that in the coming years, landfilling will be the most prevailing method of disposal (Sharholy et al. 2008). For developing countries such as India, landfilling is a viable method of disposal of waste. Owing to the fact that the deposition of waste in open dumpsites does not require expertise or experience, the majority of the waste management practices in developing countries lie in between open dumps and control dumps (Daskalopoulos, Badr, and Probert 1998). The primary objective of landfills is to mitigate the risk of human and environmental exposure to hazardous substances (Narayana 2009). However, the un-engineered and unscientific methods of using landfills pose a threat to the environment. In the Indian scenario, landfills that are devoid of leachate treatment systems, baseliners, and gas ventilation systems. Additionally, the percolation of excessive precipitation through the various layers of the landfill produces a liquid called leachate which is abundant with harmful contaminants. It is the principal agent responsible for the waste mobilization from the landfill sites to the neighboring environment (Christensen and Kjeldsen 1968). The predominant cause of the environmental losses of plastics from the environment can be attributed to the improper management of the MSW facilities which includes landfills and open dumping. Approximately one-third of the environmental plastic losses are accounted for in the Asian region (Ryberg et al. 2019). In developed countries, the quantity of landfills has projected a declining trend over the past few decades. An example of this is evident from the decrease in the number of landfills from 6000 in 1990 to 1200 in 2018 in the USA(“Facts and Figures about Materials, Waste and Recycling | US EPA,” n.d.). The terrestrial environments serve as a more substantial receptacle for plastic pollution compared to oceans discharging 20 times more plastics into the land. However, the trend is reversed in developing countries due to the economic viability and less technical experience (Horton et al. 2017). Plastic losses from landfills occur primarily through inundation, wind, leaching, animal migration, and human activities (Yadav et al. 2020). Compared to the detrimental impacts caused by wind, precipitation, and floods, the losses of plastic induced by anthropogenic and biota are indeed deemed inconsequential. India is anticipated to be the third-largest consumer market for plastics in comparison to plastic production worldwide (Hung, Wang, and Shammas 2014). Plastic waste generated in India accounts for 8% of the total waste generation (Hossain et al. 2022a, Hossain et al. 2022b). The plastic waste in landfills undergoes multiple abrasive activities and generates secondary microplastics. Secondary microplastics are the plastic products that are formed through the degradation, partition, and migration activities in the landfill (Kabir et al. 2023). A study reported that the microplastics formed in the above manner act as carriers of toxic elements by adsorbing heavy metals, germs, antibiotics, and persistent organic pollutants (Jagadeesh and Sundaram 2021). When the particle size is small, the specific adsorbent area of the particle increases. The adsorbed toxic microplastics when released into the environment will pollute and can cause deleterious impacts on living organisms through breathing or skin contact or ingestion (Yee et al. 2021). There is also an occurrence of microplastics in the various tissues of the human body including human blood (Leslie et al. 2022) and even in the human placenta (Ragusa et al. 2021). The occurrence of microplastics in human tissues may be attributed to the contamination of potable water. Groundwater is a significant source of drinking water in various nations and has the capacity to store microplastics originating from unscientific practices, landfills, etc (Samandra et al. 2022). Additionally, microplastics has the ability to move downwards through the pores in the soil and reach the groundwater system (J. Liu et al. 2023). This leads to the contamination of the groundwater which is the most reliable source of drinking water in cities.

Microplastics were detected in all groundwater samples investigated in an unconfined groundwater aquifer in Australia (Samandra et al. 2022). A similar study also revealed that the groundwater in the Jiaodong Peninsula also carried microplastics (Su, Zhou, and Lin 2021). The lowest concentration of microplastics was discovered in Holdorf, Germany with a concentration of 0.0007 particles/L(Mintenig et al. 2019). In India, a comparable study conducted reported a concentration of microplastics in the landfill leachate from a landfill in Hyderabad to be between 9 and 21 items/L(Sekar and Sundaram 2023). The above background necessitates the importance of calculating the amount of microplastics in the landfill leachate in urban areas from 1960 to 2022 as one of the sources of groundwater contamination in the terrestrial ecosystem which is a new area of research compared to that of marine microplastic contamination.

2. Objective and Research Question

2.1. Objective

- To estimate the quantity of municipal solid waste that has been landfilled in urban India over the last 62 years
- To assess the amount of landfill leachate that infiltrates into the ground
- To estimate the quantity of microplastics discharged into the ground
- To assess the negative impacts associated with the emission of microplastics

2.2 Research Question

Based on the above background, the thesis attempts to answer the following question

- How much municipal solid waste (MSW) has been landfilled in India from 1960-2022, during the period when plastic usage has increased significantly?
- What amount of landfill leachate, which seeps into the ground, can be expected from these landfills?
- What is the quantity of microplastics seeping into the ground from landfill leachate in urban areas of India between 1960 and 2022?
- What negative impacts are associated with the emissions of microplastics in general and specifically from landfill leachate?

3. Methodology

The fundamental foundation for the thesis is the range of sources of literature used in this paper. The literature consists of scientific academic journals, websites, newspaper articles, reports from various international organizations, municipal and government reports on municipal solid waste management in India, historical records, and databases pertaining to waste management in India. The methodology of the research can be divided into two categories. A comprehensive review of the literature is conducted in the first section to establish the groundwork for the present state of the art and offer the necessary context for assembling the latest information for the analytical portion. The systematic search strategy involves using important and relevant keywords such as “landfills in India”, “landfill leachate”, “microplastics”, and “per capita waste generation in India”. The academic databases utilized were Science Direct, Pubmed, Google Scholar, etc. The search results were examined to ascertain the reports and studies that are more relevant to the study. The sources were selected on the basis of credibility, relevance, and geographical focus.

The second part of the thesis is the empirical analysis which aims to answer the research questions. To that end, the population data was taken from the World Bank from 1960 to 2022. The per capita MSW generation from 1960 was taken from a scientific paper and therefore was able to calculate the total waste generated. An increase of 5% was assumed for each decade till 2030. An increase of 10% was also added to incorporate plastic waste generation during the COVID-19 pandemic. The amount of MSW landfilled in urban areas was calculated based on the above data. In order to ascertain the volume, the data was taken from a government report on waste management from India. Similarly, data for the height of landfills were sourced from multiple scientific articles and the average was taken from a range of heights. The area of the occupied landfill was obtained by dividing the total volume over the years in consideration by the height. The annual rainfall received in India and the average surface runoff annually were taken from a scientific paper. Using the above data, the amount of leachate was calculated. Given the amount of concentration of microplastics in a scientific paper from Hyderabad, the total amount of microplastics was assessed.

4. Literature Review and Empirical Analysis

4.1. Microplastic Taxonomy

4.1.1. History of Microplastics

The first synthetic plastic was discovered in 1907, namely Bakelite. The discovery of Bakelite which revolutionized modern life and polymer science has introduced plastic formulations and various polymers that people use even today (Shashoua 2012). This discovery set the stage for the Polymer Age analogous to the Stone Age and Iron Age of the past. The polymer age is also relatable to the Age of Plastics. Plastic is derived from the Greek word “plastikos” which translates to mouldable. Plastic is a widely and commonly used term for a plethora of manmade or synthetic polymers (poly means many). Polymers are huge molecules consisting of smaller independent units called monomers (mono means one). In nature, there exist thousands of polymers. The most abundant and common naturally occurring polymer in the world is cellulose. Cellulose is the major structural component of trees. Even polymers are found in human beings. The proteins that carry the genetic codes namely Deoxyribonucleic acid (DNA) are polymers (“Bakelite® First Synthetic Plastic - National Historic Chemical Landmark - American Chemical Society,” n.d.).

The invention of celluloid changed the course of history. Celluloid was similar chemically to ivory. At room temperature, it became a permanent hard solid. At elevated temperatures, it could be moulded into any shape and rolled into sheets. Baekeland, the person behind Bakelite had been offered a patent in 1906 for his invention of the polymer. Approximately 400 patents were bagged by Baekeland related to the manufacture of Bakelite. Bakelite had numerous advantages compared to its expensive predecessor. The polymer can be moulded into any shape and is cheap to manufacture. The process of moulding is quick and can be leveraged for mass production where similar products could be manufactured in varying shapes and sizes. Bakelite is considered a thermosetting resin which means that it retains its shape even if it is mixed with solvents or heated. Due to the high resistance not only to electricity but also to chemical solvents and heat, bakelite was perfect for the emerging automobile and electrical industries. Soon it became commonplace for its wide applications in non-conducting parts of radios and other electrical appliances such as sockets and bases for electric light bulbs, insulators, and automobile caps. Apart from its wide applications in electrical uses, bakelite was a natural choice for modern life. The polymer was pervasive and developed a resilient presence within the technological infrastructure. Its use ranged from telephones and washing machines to novelty jewellery ("Bakelite® First Synthetic Plastic - National Historic Chemical Landmark - American Chemical Society," n.d.).

Plastic consumption has reached record highs due to the numerous advantages it offers. The versatility of the plastic is due to its low electrical and thermal conductivity, low density, and corrosion resistance which grants it the ability to act as an oxygen and water barrier. Moreover, the low price and the ease with which it is manufactured find itself useful in a variety of applications ranging from technological and medical applications to the packaging industry. On the contrary, what was considered a revolutionary and versatile material has gradually become an environmental threat with its presence almost everywhere- atmosphere, hydrosphere, and lithosphere (Bergmann, Gutow, and Klages 2015, Wagner and Lambert 2018). Due to the inherent and naturally occurring conditions prevailing in these ecosystems, especially the interaction with solar radiation, dynamics in the ocean, and interactions with the organisms and ships, the plastic items gradually degrade and disintegrate into smaller fractions called microplastics.

The term microplastics to explain the aggregation of pieces of plastic particles in marine sediments and in the waters of Europe (Thompson et al. 2004). Later in 2009 it was suggested that an upper limit to the size and the microplastics were known as "plastics smaller than 5mm". Further modification to the definition was made in 2011 in which microplastics were categorized microplastics according to their origin as primary or secondary plastics. Primary microplastics are those that are of microscopic dimensions while secondary microplastics are formed from the disintegration of larger plastics (Cole et al. 2011). The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, GESAMP has defined microplastics as plastic particles less than 5mm in diameter which includes the particles in the nano-size range (1nm). GEASMP was founded in 1969 as an independent advisory body that provides scientific advice to the United Nations system regarding the protection of the marine environment (GESAMP 2015).

There is still no consensus on the upper and lower limits to microplastics even though the most used definition is from Arthur et.al. Some authors consider the lower limits ranging from 1-20 µm (Van Cauwenberghe et al. 2015, Ryan 2015, De Witte et al. 2014). On the other hand, the upper size ranges from 500µm to 5mm as the upper limit (Desforges et al. 2014). However, the commonly accepted definition is that microplastics are small particles that are formed from the degradation of plastics with a diameter of less than 5mm. The subsequent definition of microplastics is proposed (Frias and Nash 2019) *"Microplastics are any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 µm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water*"

The 20th century is famous for the revolution caused by the plastic industry starting from the manufacture of a myriad of plastic products ranging from buckets to cars. On the other hand, 21st century is famous for facing the pressure of plastic pollution and its related consequences. The lack of awareness about the negative effects of plastic pollution, reckless way of dumping waste coupled with the unprofessional management of waste practices has converted the "blue planet" to a "plastic planet"

4.1.2. Statistical distribution of Microplastics

Microplastics are present everywhere due to their nondegradable nature and insolubility in nature. They are found in the air, soil, and especially in water. Microplastics have been found even in the ice caps at the poles, the deepest trenches, and in the lakes in the remote mountains. Due to their ubiquitous nature, microplastics have detrimental effects on plants, animals, and human beings. As a result of the ubiquitous nature of these harmful particles, microplastics are found in drinking water and in various food products such as honey, salt, and in the organisms in the oceans. As a consequence of their presence even in the atmosphere, they are also inhaled as well. Once inhaled, the microplastics find their way to the lungs, heart, spleen, reproductive organs, and even to the brain. Moreover, microplastics are capable of transporting persistent organic pollutants (POPs) or heavy metals such as cadmium, mercury, etc from invertebrate organisms to those in superior trophic levels.

Microplastics are found everywhere, from the most populous areas like China and India to even places humans have the least possibility to adapt such as Artic and Antarctica. These areas are researched due to the increased concentrations of microplastics that have been occupied for years. The regions with the increased concentration of microplastic pollution are Africa, Europe, and the North Pacific Gyre which is in Asia. Research in the field of microplastics is being carried out. China and India have been the pioneers in microplastic research from 2010 till now (John et al. 2023). It has been discovered that China contributes to 42.3% of the total studies in Asia. It has also been found that there is a pertinent risk of microplastic concentrations on the coast of the Indian Ocean. Countries from the global south have the ever-present problem of microplastics as a potential environmental concern. As per research conducted by Tun et al. (2022) soil samples collected from six countries such as India, Cambodia, Indonesia, Laos, Vietnam, and the Philippines tested confirmed the presence of microplastics. The sample size consisted of 54 open dumpsites. The dominant polymers found in the soil samples comprise polyethylene terephthalate, polyethylene, and polypropylene. The sample collection from these countries shows the prevalence of microplastics in dumping sites. The Indian soils traditionally contain phthalate plasticizers like di(2-ethylhexyl) phthalate (DEHP), dimethyl phthalate (DMP), and dibutyl phthalate (DBP). In Chennai, the dumping site contains predominantly PET and PVC (John et al. 2023).

4.1.3. Primary Sources of microplastics

a) Plastic Pellets

Plastic pellets are a kind of materials which are granular in structure with a diameter ranging from 2 to 5mm and have regular shape (Karlsson et al. 2018). The plastic pellets are used to make a variety of plastic products. Plastics are manufactured from coal and petroleum which are then used to produce styrene, vinyl chloride, propylene, and other related materials. There are two categories to which plastics can be divided to thermoplastics and thermosetting plastics. Generally, thermoplastics are manufactured from virgin plastic pellets which are also named preproduction pellets or beads or nurdles. These plastic pellets are considerably slow to degrade once they are released into the environment. Due to their small size, they are easily consumed by birds, or fish and can easily be passed on to the higher levels in the food chain, which will have a detrimental effect on humans. In order to meet the growing demands of the population, plastic pellet production has been increased substantially. As a result of this massive production, there are possible transmission losses during the manufacture, transportation, storage, and recycling of these particles. As per a study conducted in the UK, the country emits about 5.3 billion tonnes of plastic particles annually into the environment. China, a similarly populous country, has witnessed a demand for plastic particles ranging from 5.11 million tons to 13.79 million tons from 2009 to 2017 (An et al. 2020).

b) Paint

Paints consist of fillers, pigments, solvents, and small amounts of additives depending upon the function. Paints find uses as automotive coatings, marine coatings, architectural coatings, aircraft coatings, etc. Based on their film forming material paints can be classified into nitro paint, amino paint, epoxy paint, acrylic paint, phenolic paint, etc. Studies have shown that the application of paint on to the surfaces can release tiny particles of plastic depending on varying degrees of erosion, aging, and abrasion. As a result, paints are considered as one of the sources of microplastics (An et al. 2020). According to the India Brand Equity Foundation (IBEF), the paints and coatings industry is expected to reach USD 12.22 billion in the next four years. Currently, the paints and coatings industry is valued at USD 7.57 billion. The architectural sector dominates the industry with a 69% volume share and the industrial sector dominates with the remaining share. During the financial year of 2022-23, the paint industry saw an increase in the production of paints and coatings due to a decrease in the prices of raw materials ("Paints and Coatings Industry Is Expected to Touch US$ 12.22 Billion (Rs. 1 Lakh Crore) in Five Years: Akzo Nobel India | IBEF," n.d.). Due to an increase in the production of paints and coatings, plastic polymer particles fall off from the painted surfaces and are washed away by the rain.

c) Vehicle Tyre Wear

One of the main sources of microplastics is the wear and tear of rubber tires. Normally the three stages in the life of an automobile or motorcycles are manufacturing, use, and disposal. Most of the carbon emissions are found in the use stage. The tires can be divided into natural rubber tires and synthetic rubber tires. Synthetic rubber tires are manufactured from SBR or butadiene rubber. Natural rubber is commonly used in advanced automotive tires because its durability is better than that of synthetic rubber. However, the cost of making rubber tires from natural rubber is expensive. On the other hand, synthetic rubber manufactured from petroleum is commonly used. To enhance the performance requirements of the tires manufacturers mix various types an mix of chemical additives into the rubber. The four major classes of plastics that are dominated by thermoplastics are polyvinyl chloride (PVC), polyethylene (PE), polyethylene terephthalate (PET), and polypropylene (PP). During the process of running on the road, shear and heat are developed on the tires. The emission of large particles of tires occurs due to the shear forces. As heat increases, hot spots are created on the surface of the tires. The increased temperature causes the volatile content in the rubber to evaporate. This results in the emission of small particles which are sub-micrometers in size. It is found that the density of rubber tires varies from 1.2 -1.3 g/cm3. Due to the wear and tear from the tires, the rubber particles are found in various environments such as sewers, soils, and water. In order to increase the safety of the driver, the tire manufacturers increase the friction of the tire to reduce the braking distance. However, this results in the increased emission of rubber tires from the rubber tires (An et al. 2020).

c) Toy Industry

The toy industry is worth above 90 billion USD worldwide and is experiencing a strong upward trajectory. The toy industry extensively uses various types of plastics in its products. Certain reports claim that around 90% of toys are made up of plastics. The toy industry is booming due to numerous advantages such as their multi-attractive colors, enhanced durability, and lightweight in nature. The sad part of the story is that most of the toy products end up finally in landfills and cannot be potentially recycled (Yunlong Luo, Naidu, and Fang 2024). The ubiquitous components used to make toys are Bisphenol A (BPA) and polyvinyl chloride (PVC). Vinyl chloride, the monomer used to make polyvinyl chloride is known to be a carcinogenic agent for humans and animals. These cancer-causing agents leaching out can cause serious harm. On the other hand, BPA is used to give the toy's durability and strength. However, BPA is known to be an endocrine disruptor, which has the ability to interfere with the hormone system of the body (Charron, n.d.). Under certain conditions, the plastic toys degrade to release microplastics into the landfills. The degradation of microplastics may occur in ways such as abrasion. Microplastics can also be released to various types of mechanical stress such as cutting, tearing, squeezing, etc. After subjecting to mechanical stress, the microplastics stick to the parent blocks in different sizes and shapes (Yunlong Luo, Naidu, and Fang 2024). Polyester is another form of plastic that is used for making soft toys for babies and toddlers. It is classified as a predominant kind of microplastic due to its high propensity to release microplastics when subjected to washing or physical contact. Due to the rate at which it sheds microplastics, these are found in the air and even in the Arctic. Around 75% of the microplastics are found in the Arctic and 66.7% are found in the air ("Why Polyester Is Dangerous for Babies and Children - The Microplastic Catastrophe No One Is Talking about PlasticFreeJuly - Pure Earth Collection," n.d.).

d) Cosmetics

Presently, the scientific community is actively engaged in discussing the issue of environmental degradation caused by plastics, particularly microplastics. Microplastics are used extensively in personal care and cosmetic products (PCCP). In the cosmetic industry, these are called microbeads. Microbeads are utilized for the purpose of physically abrading surfaces, such as teeth and skin. Before the use of microbeads, natural materials like fruit stones, crushed shells, and inorganic powders were used. Microbeads are now used extensively because of their cost-effectiveness and durability over the passage of time (Guerranti et al. 2019, Huang et al. 2020). The common personal care products that contain microbeads are body wash, cosmetics, sunscreens, facial cleansers, deodorants, hairsprays, face powders, toothpaste, mascaras, shaving creams, nail polish, eye shadows, bubble baths etc. The common microbead ingredients in use are nylon (PA), polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), and polymethyl methacrylate (PMMA) (An et al. 2020). Microbeads have substituted natural exfoliating agents such as walnut husks, pumice, and oats. Due to the sphericity and uniform particle size, these microbeads cause a ball-bearing effect (Shaik Khaja Moinuddin et al. 2024). This gives the lotions and creams a soothing and smooth and soothing texture. Microbeads are widely utilized for their efficient and non-hazardous exfoliating characteristics. These microbeads aid in the elimination of dead and dry cells from the skin while also unclogging the surface. Their ability to produce blemish-free and flawless skin is highly valuable to customers, especially female customers (Yuwen Zhou et al. 2023).

e) Glitters

Another important source of microplastics is glitter. Glitters are a collection of small, reflective particles. Glitters are widely used in cosmetics and textiles and are produced from a polymer called Mylar. It is a particular type of polyester film called BoPET (Biaxially-oriented polyethylene terephthalate). The film is a kind of polyester produced from stretched polyethylene terephthalate (PET). In order to obtain high reflectivity, the particles are coated with metal i.e aluminum-coated polyethylene terephthalate glitter. These glitters are found in a wide variety of colors, especially gold and silver. The glitters are found in different shapes such as hexagonal, square, and triangle, Glitters are classified as microplastics as they are commercially marketed with a size below 5mm. They are messy and easy to spill away. The normal glitters are produced from PET polymer. Apart from the normal glitters, glitters are also made from poly methyl methacrylate (PMMA), acrylic, and plastic epoxy resin mixture. The lifecycle of glitters begins with their production from polyesters, a petroleum derivative which is followed by their transfer to suppliers and finally to the end consumers in a breadth of products such as shoes, bags, jewellery, stickers, etc (Yurtsever 2019). When these products are used, these glitters begin to detach themselves from the main product. If they are not attached, these find their way to landfills where they contaminate the soil and water. Not only are the glitters used in cosmetic products but also in the preschool and kindergarten settings for multiple art classes. They use a coating material for ornaments, puzzles, EVA (Ethylene Vinyl Acetate) paper stickers, dolls, and toys. A different version of glitters is sequins made from melamine and polyester, PVC, PET, and recycled PET. Such kinds of sequins and glitters are employed extensively in textiles and after their productive usage cycle end up as waste unless reused. At the end of the life cycle these textiles are dumped in landfills if not burned.

f) E-waste

Globally there is an exponential increase in the generation of electronic waste(e-waste) due to the rapid development in the field of science and technology. The general e-waste comprises electronic appliances that are discarded such as mobile phones, televisions, laptops, desktop computers, headsets, headphones, etc. Even though the recycling of electronic waste is connected with material recovery and utilization, its contribution as a potential source of microplastics is generally underestimated. Most of the electronic devices are encased in plastic. The plastic casings are engineered for durability and to be flame-retardant. Hence, finds numerous uses in the business of technological products. The casings having no use after, find themselves in the waste. Improper waste management such as burning in the open results in the fragmentation of the macro plastics to the microplastics. Landfills, the cheapest way to waste disposal act as the main reservoirs for these wastes. Under varying conditions of pressure, temperature, and climate, the macro plastics disintegrate into smaller fractions. In developing countries, generally, landfills are the last resort for the dumping of these wastes ranging from modern facilities to unscientific dumpsites. These dumpsites are also a potential source of microplastics that are circulated by environmental dispersion. The less scientific method of open dump burning without proper measures to contain the fire releases toxic pollutants such as dioxins and furans into the soil and atmosphere (Shaaban et al. 2024)

g) Textile Industry

The emission of microfibres from the textile industry is a contributing factor to the growing problem of pollution caused by extremely small microplastics. In terms of length, these fibers have dimensions that range from 1 µm to 5 mm, and their ratio of length to diameter is greater than 100. These microfibers have a greater surface to volume ratio, which contributes to the enhancement of their impacts on the environment. Microfibres account for 91% of the microplastics which are prevalent in 90% of all surface waters. Synthetic fibers vary widely and can include polyethylene terephthalate (PET), plastics polyamide, modacrylic, polyvinyl chloride, polyacrylonitrile, polyurethane/elastane, and other polyesters. Currently, polyester is considered to dominate the market. The clothes undergo a variety of changes that cause “pilling” or “furring” or “felting”. This results in the appearance of fiber ends in the exterior of the fabric. The type of textile determines the length, strength, and amount of the extruded fibers. As the number of exposed fibers on the surface increases, more is left into the environment. The released fibers are either unbroken or broken during washing. It is not necessary that fibres will be released during washing bur also be liberated during normal day to day activities. The quantities released in this manner is similar to that obtained during washing (Mishra et al. 2020).

4.1.4. Secondary source of microplastics

a) Plastic bottles

The bottles are normally containers that are manufactured using plastics such as polypropylene(PP), polyethylene(PE), and polyethylene terephthalate (PET). The bottles are made using a combination of the required constituent plastic by heating at an elevated temperature or with a corresponding organic solvent. Then the process leads to the formation of plastic mold through blow molding, injection molding or extrusion molding. Normally plastic bottles are used for traditional uses as disposable containers for solid and liquids such as pickles, beverages, dried fruits, edible oils, medicines, solutions, etc. In developing countries potable drinking water is packaged in plastic bags especillay plastic bottles. Moreover, due to the added advantages such as low cost, convenience, hygiene and the transparency people purchase mineral water in such plastic bottles. At present it is believed that one million plastic bottles are sold every minute. During the period from 2006 to 2016 the global sales of plastic bottles has peaked up to 480 billion per year (An et al. 2020).

b) Disposable plastic tableware

The disposable utensils such as spoons, plates, forks, bowls, and other related materials intended for use during meals or similar purposes are called disposable plastic tableware. These products are manufactured from the thermoplastic molding of resins or other thermoplastic materials. The tableware does not include food packaging materials for long-term purposes. These materials are used commonly for advantages such as for its durability, waterproofness, cost, and lightness. The normal plastic polymers used for making disposable plastic tableware are polystyrene, polyethylene, and polypropylene. Polystyrene also named as polystyrene foam is majorly used for the production of packaging materials and food servicing items such as fast food boxes, instant noodle boxes, foam cups, etc. When the above-mentioned items are not properly disposed of in the required manner, they end up in landfills or sewers, etc. which results in the formation of microplastics harmful to the environment (An et al. 2020).

b) Plastic packaging

The process in which the plastic material is used to envelop an item or group of items so as to preserve the original quality so that it does not lose its value during processes such as transportation, distribution, and storage is called packaging. The packaging materials include films, boxes, bags, etc. Because of advantages such as superior moisture-blocking properties, inertness to biological materials, and lightness, plastic has replaced traditional materials such as glass, paper, metal, etc (Boustead 1998) . Not only is the plastic packaging used in the food industry but also in the textile, automobile industries, etc. The tremendous increase in packaging objects after the advent of the e-commerce industry has made the issue of plastic pollution a matter of grave concern. Similar is the increase of plastic packaging in the fast food and express delivery of some industries. In 2016, it is estimated that in China, about 14.7 billion plastic bags were consumed in the express delivery industry (Hidalgo-Ruz et al. 2012).

c) Fishing wastes

The commonly found fish wastes are fishing lines, cables, buoys, fishing rods, fish tanks, fishing nets, etc. Globally the amount of commercial fishing equipment that is discarded per year has been estimated to be from 0.13 to 13500 tonnes (Merrell 1980). The main ingredient of fishing ropes and nets are polypropylene monofilament, polyethylene or low density polyethylene and polyamide. The ropes and nets can be differentiated based on the difference in the transparency and diameter. When these are released into the environment the ropes and fishing nets disintegrate into fibers (Andrady 2011).

4.1.5. Types of microplastics in groundwater

Microplastic pollution in groundwater has become a matter of concern in recent decades across the world. K et al. (2021) states that in comparison with the discoveries of microplastics from regions across the world, contamination with microplastics could be more serious in the inland waters of Asia. Certain research states that the microplastics are unevenly distributed in the groundwater samples and the majority of the items were found near the dumping sites.

A study was conducted to evaluate the characteristics of microplastics in groundwater in municipal solid waste disposal locations at Perungudi and Kodungaiyur sites in Chennai, India. The location of the groundwater was within two and one-kilometer distances respectively. The topography of the study area was flat and the sea level area was 6.7m lower than the ground level area. Nylon was the most common type of microplastic found in both the waste dumping sites with pellets, foam, polythene, fibers (PVC), and fragments found in decreasing order. This may be attributed to the waste disposed from industries such as clothing, cosmetic products, etc (Qiu et al. 2020). A similar study was conducted by Sekar and Sundaram (2023) in Hyderabad. Hyderabad holds the position of the fourth largest city in India. Around 4 million people live in the city. The waste that is generated is collected and dumped in the integrated municipal solid waste management at the Jawahar Nagar landfill. The samples from the leachate pond were analyzed using FTIR spectroscopy and micro-Raman spectroscopy. The results from the FTIR spectroscopy showed the presence of polyethylene terephthalate (PET), nitrile, and cellulose acetate (CA) while the results from the Raman spectroscopy revealed the occurrence of polypropylene, cellulose acetate, and low-density polyethylene (LDPE). A study on the landfill sites around the Gulf of Thailand was conducted. The samples of landfill leachate were sourced from 12 landfill sites. Within each site, ten leachate and soil samples were collected. The leachate samples were sourced from a leachate pond. The type of microplastics were identified using the Fourier Transform Infrared Spectroscopy model Alpha -E. The images of microplastics were evaluated using a stereoscopic microscope. The results conveyed that the landfill soil and leachate samples contained PET, PE, and PP (Puthcharoen and Leungprasert 2019). Leachate samples were collected from six MSW landfill sites in four cities in China namely Changzhou, Suzhou, Wuxi, and Shanghai. The samples were extracted from collecting wells or equalization basins. After the laboratory procedures were finished, microplastic particles were found in all the leachate samples from the active and closed landfills. The various types of the microplastics found were PF (0.16%), PMMA (0.32%), ABS (0.32%), PA (0.64%), EP (0.32%), PUR (1.45%), PPC (0.16%), PVC (0.32%), EVA (0.64%), PES (2.74%), ALK (4.35%), PTFE (5.48%), PMDS (2.25%), PS (4.99%), PET (5.96%), PE (34.94%) (He et al. 2019). Sun et al. (2021) conducted research on the leachate samples from an MSW landfill in Suzhou, China. The landfill is a receptor of 480 tonnes of MSW in a day. The material properties of the polymer were identified using microRaman spectroscopy. The results from the spectroscopy showed that PP and PE were the two most prominent polymers. PP accounted for 32.4% of the sample while PE accounted for 33% of the sample. The other polymers that were detected from the sample were polymethyl pentene (PMP), polyacrylic acid (PAA), polyvinyl alcohol (PVA), polyamide (PA), polyvinyl butyral (PVB). According to Praagh, Hartman, and Brandmyr (2019), landfill leachate samples were collected from the landfill sites hosting MSW in the Nordic countries-Finland, Norway and Iceland. The selection of landfills was based on the criteria that all of the landfills selected belonged to the non-hazardous class except one in the southwest of Finland. The samples were analyzed by the Environmental Agency in Austria. The technique used for the analysis was the Fourier Transform Infrared Spectroscopy method and the material of polymers that constituted microplastics were PE, PET, PS, PU, PMB, PMMA, PP, PVC, and PA. Wan et al. (2022) conducted a study in an informal landfill in South China. Within and around the landfill, samples were collected from the leachate, groundwater, landfill refuse, and the underlying soil. The samples were tested using a scanning electron microscope and Fourier Transform Infrared (FTIR) spectra. The predominant polymer materials were found to be PP, PE, and PET. Another notable discovery was that the microplastic samples found in the groundwater and landfill leachate were even smaller than those in the underlying soil and refuse. These studies confirm the fact that microplastics from an informal landfill can leak into the surrounding environment without sufficient protection.

4.1.6. Shapes of microplastics

A wide variety of shapes and sizes may be found in microplastics. Microbeads, pellets, films, fiber, and fragments are all examples of the various forms that they might take.

Microbeads- Small, spherical particles that are formed of microplastics are referred to as microbeads. Exfoliants, face scrubs, body wash, and toothpaste are examples of personal care products that release a significant number of microbeads into the environment. In addition to the spherical shape, the majority of the microbeads were shaped irregularly. Scrubs were majorly characterized by plastic particles that are irregularly shaped. The potential for a considerably more efficient scrubbing is because of the coarse texture and sharp edges. A smooth spherical shape with a well-defined structure derived from face washes may not be as efficient compared to irregularly shaped microbeads. The priority of making the microbeads in an irregular shape is due to the aesthetics of the product. The irregular shapes have detrimental effects on the environment. It provides a higher surface area for the adsorption of potential contaminants once released into the environment. Owing to the sharp edges in the irregularly shaped microbeads it causes potential physical damage to the organisms who ingest them in the form of injuries and cuts (Alex, Maes, and Devipriya 2024).

Pellets- Microplastic pellets are also called nurdles. Generally speaking, pellets have a spherical form. The majority of the time, pellets are tough and have a stiff structure. The majority of the time, pellets are discharged from recycling facilities and producers of polymeric materials. According to the website ecos, the pellets are mistaken as fish eggs which marine animals like fish and birds feed on (Prapanchan et al. 2023).

Film- Films are released into the environment due to the fragmentation of plastic bags, low-density plastic, and plastic packaging. Films are thin, soft, and transparent (Prapanchan et al. 2023).

Fiber- The presence of microplastics in fiber form is attributed to their elongated and fibrous shape. Industrial fibers and textiles are the primary sources of fiber microplastics (Prapanchan et al. 2023).

Fragments- Fragmentation occurs when bigger pieces of plastic debris break down into smaller fragments. They possess considerable strength and have a rough and uneven appearance (Prapanchan et al. 2023).

4.1.7. Detection of microplastics

a) Visual examination

To quantify microplastics in various environmental matrices, the first method is the visual inspection with the naked eye or with a microscope or stereoscope. On the one hand, larger microplastics can be easily separated while the smaller microplastics require further examination with a microscope. Microplastics can be visually identified depending on the uniformity in brightness, color, and the deficiency in the cellular features (Seth and Shriwastav 2018). To validate the existence of plastics various studies have prompted visual inspection using hot needle testing. The technique of visual inspection employs certain criteria for identifying microplastics that lack distinct biological structures. The microplastics may be recognized by their evenly colored particles, which are clearly different from segmented fibers and have a flat, ribbon-like appearance. In addition, it was noticed that items designated as plastics melted when they came into touch with a heated needle (Sathish, Jeyasanta, and Patterson 2020). Normally microplastics are classified based on their attributes such as shape, size, and color which enables us to know their source. Depending on the size of the microplastics, counting visually can save time. However, it has its disadvantages as well. It is prone to error as it might lead to an under or over-estimation of the exact number of microplastics (Prapanchan et al. 2023).

b) Fourier-Transform Infrared Spectroscopy (FT-IR)

Fourier-Transform Infrared Spectroscopy is the most common and frequent method for detecting and measuring microplastics (Veerasingam et al. 2021). The study and analysis of microplastics have been conducted extensively using the FTIR spectroscopy method. Depending upon the unique chemical fingerprint spectra, the spectroscopy method allows for the precise identification of the various polymer types. In various environmental matrices, approximately 80% of the research studies utilized the FTIR spectroscopy technique to identify the polymer types of microplastics. In the research and further analysis of microplastic contamination, the most commonly used FTIR spectral region is the mid-infrared band which is in the range of 400-4000 cm^{-1}. The two most common spectroscopic modes employed are the transmission and attenuated total reflection (ATR). The ATR-FTIR technique is used to characterize big microplastics of size greater than 500 µm in water and sediment samples (Seth and Shriwastav 2018) . For microplastic particles of size less than 500 µm, m-FTIR imaging or chemical imaging is used. M-FTIR method is a technique that combines FTIR with a confocal microscope to identify microplastics in water, salt, and sediments (Sathish, Jeyasanta, and Patterson 2020, Seth and Shriwastav 2018). In addition to the categorization and identification of microplastics, the FTIR method was utilized for analyzing the weathering pattern (Veerasingam et al. 2016, Veerasingam et al. 2021). However, there are some limitations to the FTIR spectroscopy method in spite of the potential to identify various types of microplastic polymers. The FTIR spectra which is obtained through different methods do not align with each other. Therefore, it is imperative to find out how chemical degradation affects the FTIR spectral bands of plastic materials before analyzing the microplastic samples collected from various sources. Identification is critical for retaining the particles during spectrum collection. But, the issue of spectroscopic interference generated from the application of a substrate filter has not been resolved adequately. Owing to the defects in the refractive properties, minute microscopic particles with irregular shapes could generate incoherent FTIR spectra. Additionally, the FTIR method is highly effective in identifying the presence of water, generating broad peaks that extends beyond the 3000 cm-1 range. Therefore, it was imperative to prepare the sample before conducting the measurements (J.-L. Xu et al. 2019). The process of using FTIR spectroscopy methods involves the quantification of the absorbed infrared light through the chemical bonds available in the sample microplastic material. The measurement obtained is then compared with a pre-existing spectrum in the database which stores information on various types of plastics. Especially with regard to the detection of modified plastics, there are limitations on the accuracy of this method. The innate constraint of this spectroscopic method is that the database containing the relevant information by the manufacturers may not be matching with the data of the modified polymers. Modifications may arise due to the result of several events which include the subjection of the microplastic sample to light, heat, and chemicals. These events could lead to an alteration in the chemical structure and properties of the microplastic. Before the measurements could be taken, it was required to make aware that the reference spectrum for an altered microplastic could not correspond to any spectrum in the database. This poses as a challenge in terms of identification (Veerasingam et al. 2021). When the plastic remains as such without any alteration, the FTIR approach can deliver statistical information on the degree of alignment between the observed spectrum and the expected spectrum. Futhermore, the operator has the capability to establish a limit of approval by evaluating the degree of resemblance between the spectrum and the reference. For instance, if there is any ambiguity regarding the identification the operator might set a limit of accepatance where the statistical measure exceeds 75% of the matching score. In conclusion, the FTIR spectroscopy method is a highly efficient method for identifying microplastics in the sample. However, it has its own limitations as it is difficult to recognise the plastics that have been modified. Operators should be mindful of these limitations while analyzing the data (S. et al. 2023).

c) Scanning Electron Microscope SEM/EDX Spectrometer

The valuable techniques in microplastic studies are Scanning electron microscopy and energy dispersive X ray spectroscopy. The morphology and the elemental composition of microplastics in various environmental samples containing microplastics are provided by the results from these techniques. Yet there are advantages as well as limitations to using these techniques. The high-resolution imaging capability which can show the morphology and surface features of the microplastics can be regarded as one of the prime advantages of the technique. SEM generates a three-dimensional image of microplastics which gives a more precise assessment of the size and shape of the microplastics. The combination of SEM and EDX can deliver extra information on the composition of microplastics on an elemental scale. This assists the researchers to detect and estimate the various types of microplastics present in the sample. The next advantage of the combination of SEM and EDX is the ease with which it is able to be used relative to other techniques and the requirement of minimum sample preparation. This makes it easily accessible to researchers and technicians. A comprehensive assessment of microplastic pollution is possible due to the wide range of sample type it can analyze such as sediments, water (Patterson et al. 2019, Singhal et al. 2019), salt (Sathish, Jeyasanta, and Patterson 2020), and biota (Patterson et al. 2019, Reddy et al. 2006, Van Cauwenberghe et al. 2013, Blair et al. 2019) . In spite of the advantages the technique offers, it has its downsides. The technique requires a large amount of the sample to be collected which is quite a challenge considering the sample that may have small quantities of microplastics. Due to the similar elemental profiles of the microplastics present in the sample, the combination of SEM and EDX cannot differentiate between the different types of microplastics present. When analyzing complex samples with a high level of interference or background noise, the EDX and SEM cannot be able to produce the actual result. Instead, it may offer a false positive result. The combination technique is not simple to master. However, it requires expertise and special training to make sure there is an accurate interpretation of results. To conclude, the combination of SEM and EDX is a valuable technique in microplastic study analysis. The method should be used in association with other technical methods to get a comprehensive analysis of the nature of microplastics in the samples from the environment. The researchers should be aware of the disadvantages of the techniques when analyzing the results and rely on multiple samples to ensure their discoveries are accurate enough (Imhof et al. 2013).

d) Raman Spectroscopy

A number of environmental samples containing microplastics can be identified through another spectroscopic method called Raman spectroscopy (Hidalgo-Ruz et al. 2012, Van Cauwenberghe et al. 2013, Imhof et al. 2013, Murray and Cowie 2011). This technique is used for the investigation of large, optically sorted microscopic particles. It is associated with microscopy. A wide variety of size categories can be identified using Raman spectroscopy. The size ranges from extremely minute microplastics to sizes less than 1µm (Hidalgo-Ruz et al. 2012). Raman spectroscopy can be utilized to identify microplastic in sediments and in the polymer categories where the absorption spectrum ranges from n 200 cm−1 and 3500 cm−1 (Dodson et al. 2020,Edo et al. 2019, Fok et al. 2017, Lots et al. 2017, Young and Elliott 2016, S. Zhao, Zhu, and Li 2015). The Raman spectroscopy has a better lateral resolution compared to the FTIR spectroscopy. The spectral range is better with Raman spectroscopy with less liquid interference and with a characteristic signature spectrum. The major disadvantage is the weakness of Raman scattering which demands a longer acquisition time to reach a better signal-to-noise ratio. For spectroscopy less than 20 µm the spectroscopy is limited by poor signals for the purpose of characterising the microplastic samples. However, the issue can be resolved by extending the fluorescent interference and measurement times depending on the properties such as biofouling, colour, and deterioration (Primpke et al. 2020) . Another version of Raman spectroscopy is the nano-Raman spectroscopy. It is a tool with a powerful range for studying microplastics due to the capability to generate information in the nanoscale. The technique makes the provision for characterising and identifying the various types of microplastics which is paramount for determining the impact and distribution in the environment. The high spatial resolution is the major advantage of nano Raman spectroscopy. The possibility of identifying the smallest of the microplastics even at the sub-micron level with a detailed information on the chemical composition. This method can be used for the determination of the sources of microplastics, the pathways in which the degradation occurs and the complex interactions with the environment (Prapanchan et al. 2023).

4.1.8. Impact of COVID-19 on plastic waste generation

The COVID-19 pandemic is a significant turning point in the history of mankind and has changed the way the world works in a variety of ways. It has affected every sector in the world namely the Fast- Moving Consumer Goods (FMCG) sector, the construction industry, the packaging industry, the medical and healthcare industry, etc. Plastic waste management even before the pandemic was considered a major environmental concern due to the deleterious pollution on the marine and terrestrial ecosystems. The pandemic has had significant indirect effects on numerous aspects of the environment such as microplastic pollution in addition to the direct health implications. Due to the interruptions in the global supply chains and various sectors of manufacturing, the consumption and production of plastics have shifted in the early stages of the pandemic. Plastics are manufactured from unrefined crude oil. During the pandemic, the worldwide demand for oil had plummeted. As a consequence, the production of virgin plastics increased compared to recycled plastics because of the decline in oil prices (Klemeš et al. 2020). Furthermore, concerns and cautiousness regarding viral transmission, lockdowns, and restrictions on mobility led to adjustments and modifications to the existing waste management systems across the globe. The increase in the usage of single-use plastic items in conjunction with a rise in the demand for personal protective equipment including face shields, masks, and gloves has also led to a spike in the production of plastic (Pandey et al. 2022, Emenike et al. 2022, Khan et al. 2023).

The manufacturing procedure for the production of Personal Protective Equipments (PPE) involves the use of polyvinyl chloride (PVC), polycarbonate (PC), low-density polyethylene (LDPE), polyurethane (PU), and polypropylene (PP). PVC is commonly found in face shields and medical gloves as it is used widely in medical applications owing to its durability and resistance to chemicals. PC known for its ability to resist high temperatures, optical clarity, and large impact resistance is commonly used in protective eyewear and face shields. LDPE is used mainly for the manufacture of protective aprons and gloves because of its moisture resistant properties and flexibility. Also, PU is often used in gloves, masks, and face shields due to its ability to provide a protective barrier, flexibility, and durability. PP is conveniently used in the manufacture of items like coveralls and masks owing to its barrier properties and breathability (Chen et al. 2020). The lockdowns have laid immense pressure on people to shop online and depend on home delivery for essential goods and food. The advent of this novel consumerism paradigm prompted an upsurge in the need for single-use plastic (SUP) and alternative plastic packaging methods. This is the normal trend when a pandemic strikes. Consumers frequently modify their behavior and demand in response to a pandemic, stockpiling food items, making chaotic purchases, and accumulating food supplies. This leads to an increase in the production and utilization of plastic-based packaging (Grashuis, Skevas, and Segovia 2020, Laato et al. 2020, Wang et al. 2020).

The plastic waste management initiative in India is operating inefficiently consisting of an inappropriate method of dumping medical waste in landfills (Corburn et al. 2020). A landfill site in New Delhi has been a repository for COVID-19 wastes such as discarded N-95 face masks, testing kits used for COVID-19, protective gear, etc.("In Pictures: India Landfill Site a COVID-19 Risk for Scavengers | Coronavirus Pandemic | Al Jazeera," n.d.). The plastic refuse was disposed of improperly due to the delay in collection, closures of facilities, and diminished recycling facilities (Mohamed et al. 2022). As a result, an increased amount of plastic waste infiltrated into the environment which finally assisted in the decomposition of larger plastic objects into microplastics. The huge amount of PPE in landfills leads to the formation of microplastics (Khan et al. 2023b). The insufficient management of plastic waste during the pandemic has also worsened the pre-existing problem of microplastic contamination.

4.2. Landfill Dynamics

4.2.1. Classification of Landfills

Landfills are the most widely used method for disposing the solid waste and occupy the most preferred choice in solid waste management. It is the final disposal technology that comes into the picture even when sophisticated waste management options are employed for recycling and volume reduction. Most of the developing nations employ this method because of the lowest cost for disposal. Even most of the industrialized nations like the USA still depend on this method of waste disposal as an important part of solid waste management (Agamuthu 2013). The quantity and constituents of municipal solid waste generated in a locality rely on the patterns and levels of consumption by the people. However, the quality and the quantity of the waste that enters the landfill depend on a number of factors such as the national waste management strategy, volume reduction measures such as incineration and efficacy, and the national waste recycling policies and programs. In most developing countries there exists a lack of transparency and unavailability of data and informal recycling is the prevalent norm (Agamuthu 2013). In developing countries, the landfills and dumpsites are used interchangeably. The difference between a dumpsite and a landfill is given by the Joint United Nations Environment Programme / United Nations Office for the Coordination of Humanitarian Affairs Environment Unit (Joint UNEP/OCHA Environment Unit, 2011)

“Landfill: A scientifically designed and constructed site where waste is disposed of systematically and where all emissions of gases, liquids, and solid materials are controlled and not allowed to contaminate the surrounding environment.”(“Landfilling | UNDRR,” n.d.)

“Dumpsite: A non-scientifically designed and constructed site where waste is disposed of unsystematically, and where gas emissions, liquid leakage, and solids contamination of the surrounding environment are not controlled or managed and where scavenging by waste pickers often takes place.” (“Landfilling | UNDRR,” n.d.)

The landfills are classified into the following types

i) Uncontrolled dumping

Uncontrolled dumping is the method of disposing of waste without giving any consideration for any degree of control. The detrimental effects of uncontrolled dumping are possibilities of uncontrolled burning, infiltration of leachate into the ground and surface water, emissions of greenhouse gases, and other potential negative environmental effects (Idowu et al. 2019). This method is also known as non-engineered landfills. These types of landfills are most common in low-income countries. The wastes remain for a longer time leading to their degradation. It is followed by the infestation of mosquitos, rodents, and flies. This is followed by air and water pollution. In many of the Indian cities, open, poorly managed, and uncontrolled dumping is followed (Rajput, Prasad, and

Chopra 2009).

ii) Semi-controlled facility

Semi-controlled facilities are those facilities where basic control functions such as the position of waste in designated areas, availability of site staff, site equipment, operation, and management of the site. Traffic management, vehicular access to the site, and site security with a fence. Another consideration is the unloading of waste and being directed to a designated area controlled by a site supervisor(Idowu et al. 2019).

iii) Medium controlled facility

A facility with satisfactory control is called a medium-controlled facility. It includes site equipment with a waste compactor, rough and hard surfaces of access roads with breadth and load carrying capacity, certain leachate containment and treatment methods, and trained staff. The facility also includes emission control equipment to seize particulates and a few leachate and treatment methods. An essential component is the proper management of ash(Idowu et al. 2019).

iv) High State of the art facility

High state-of-the-art facilities are landfill sites with fully functioning sanitary landfill sites that are scientifically designed and engineered. These facilities possess equipment for gas and leachate collection, leachate contamination, gas flaring, and finally a post-closure plan. The fly ash is controlled as a hazardous waste with the best appropriate technology (Idowu et al. 2019).

The waste management practices in India are more inclined towards landfilling instead of other methods such as incineration and recycling. The financial resources or capital required to set up a landfill is negligible compared to that of incineration. For example, incineration demands a lot of financial resources, procurement of the necessary technology, operational expenses, and wages for the workers. Recycling on the other hand needs proper sorting facilities, proper education and awareness programs, and trained people. Based on the above factors, landfilling is a better option for disposing of MSW. Some of the factors leading to poor MSW practices are insufficient finance, lack of technical expertise in managing waste, limited government waste management policies and containment structure, cultural awareness, and belief. Agricultural residues, municipal refuse, recycled discards, hospital waste, residential waste, and various other materials are ultimately deposited in landfills within the Indian context. Throughout history, landfills have consistently served as the primary method for disposing of municipal solid waste. Hazardous wastes accumulate in landfills due to unprofessional segregation practices or the absence of segregation facilities at waste generation locations. The disposal of substances such as insecticides, pesticides, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) in landfills results in an escalation of their toxicity(Agamuthu 2013). Approximately 2% of the population in urban areas in Latin America and Asia rely on picking waste as a means of survival. In China, six million people rely on picking waste while in India, around one million people do the same. The composition and the quantity of the waste ending up in the landfill depend on the informal waste-picking activity. In addition to causing harm to the ragpickers who gather the detritus, their actions also result in soil and groundwater contamination. Unfortunately, substantial ecological harm to groundwater is inflicted by non-engineered landfills in the majority of developing countries through the release of volatile vapors or through biological, chemical, or physiochemical processes (Swati et al. 2018)

Landfill sites in India lack adequate gas ventilation systems, leachate treatment containers, and baseliners. The inadequate dispersal of refuse originating from residential, industrial, and hospital sources constitutes a substantial contributor to ecological imbalances and environmental risks (Narayana 2009). Additionally, the haphazard landfill is vulnerable to precipitation. As excess water percolates through the various strata of the landfill, it produces leachate, a liquid that is highly contaminated with impurities. The components present in the leachate are considerably impacted by the composition of the landfill. In shallow areas, the landfill effluent ultimately percolates into the groundwater via leachate and soil (*Sanitary Landfilling: Process, Technology and Environmental Impact* 1968).

Leachate from landfills consists of high-strength liquid with toxic effluents with a combination of inorganic and organic pollutants. It is formed as a result of the interaction of rainwater, and the existing moisture of the MSW through multiple layers of waste. It is produced due to the chemical, physical, microbiological, and biochemical interaction of the organics within the waste mass with the intrinsic moisture content in the bulk(W. Li et al. 2010,Schiopu and Gavrilescu 2010). In developing countries such as India, one of the major environmental impacts is the leaching of toxic chemicals from an open dumpsite/unlined landfill(Mor et al. 2006). The generated leachate from the landfill picks up the inorganic, organic, COD, BOD, heavy metals, and xenobiotics compounds as its constituents by virtue of its chemical, physical, and fermentative processes(Al-Yaqout and Hamoda 2003). Additionally, the leachate from subsoil migrates downward and reaches the groundwater in case of shallow groundwater making it unfit for human consumption. Many studies were conducted to find the interaction of the unconfined aquifer and open dump and its impact on the hydrogeological chemistry of the groundwater(Mor, Negi, and Khaiwal 2018, Bogas and Gomes 2015). When the leachate reaches the groundwater it becomes polluted and the contamination will remain for a long time. It will become difficult to treat the polluted groundwater due to the large storage, inaccessibility and long residence times (Junjie Wang, He, and Chen 2012)

4.2.2. Phases of waste decomposition in landfill

Landfills accept waste over an extended duration of time and hence are sometimes referred to as “legacy waste”. During the long duration, the disposed municipal solid waste undergoes several transformations and processes that are physical, chemical, and biological in nature. These processes include the suspension and dissolution of materials, evaporation of water and chemicals, the formation of leachate, and the absorption of semi-volatile and volatile organic compounds by the contents in the landfill. These processes take place in different phases within the landfill. The different phases are primary adjustment, transition, acid generation, methane formation, and final maturation (Al Raisi 2022,Lebron et al. 2021,Sankoh, Yan, and Tran 2013)

Phase I: The first phase is termed as the adjustment phase. It is linked to the placement of solid waste and the accumulation of landfill moisture. In this phase, oxygen gets trapped in the voids when the waste gets buried from the top by the above layer. The trapped oxygen along with the dissolved oxygen acts as the primary electron acceptor. The carbon source for the microbial activity is provided by the soluble sugars. Carbon dioxide and water are formed when the degradable solid waste reacts with the oxygen. This phase proceeds until the available oxygen gets consumed (Mor and Ravindra 2023, Farquhar and Rovers 1973)

Phase II: In this phase, the environment shifts to an anaerobic environment from an aerobic condition. There is a switch from oxygen to sulfates and nitrates as electron acceptors. In addition, the CO_2 replaces the available oxygen laying the foundation for an environment with anaerobic conditions. The conclusion of this phase is marked by the presence of the volatile organic acids and chemical oxygen demand in the leachate (Mor and Ravindra 2023)

Phase III: In phase III, the microbial activity is intensified. Phase III is known as the acid generation phase with considerable volumes of organic acids and the formation of less hydrogen gas. This is followed by the hydrolysis and the continuous fermentation process. A continuous hydrolytic process is formed through the production of intermediate volatile organic acids at high concentrations. This is followed by the microbial decomposition of organic substances that are biodegradable. During this stage, carbon dioxide and hydrogen are the most common gases formed. This process is facilitated by the facultative, non-methanogenic, and obligative anaerobic bacteria. The leachate conductivity, carbon oxygen demand (COD) and biological oxygen demand (COD) is enhanced by the breakdown of the organic acids. The decreased pH facilitates the mobility of heavy metals and essential nutrients are eliminated from this phase (Mor and Ravindra 2023)

Phase IV: The phase is termed as the fermentation phase. The methene forming consortium or the methanogenic bacteria produce the intermediate acids. The intermediate acids are converted to CH_4 and CO_2 (*Waste Bioremediation* 2017) Acid production and CH_4 are formed at the same time. But, the pH inside the landfill increases to a near neutral level which is in the range between 6.8 and 8 and the acid production rate slows down significantly. This condition influences the formation of methane-producing bacteria. During this phase the COD, BOD, and the conductivity of the leachate increases.

Phase V: The phase is called the maturation phase. The decomposable organic material that is readily available is processed into CH_4 and CO_2. The phase is also called as the stabilization phase. A dramatic reduction in the production of landfill gas occurs during this phase as the leachate from the previous phases and the slow decomposition of substrates eliminate the majority of the nutrients that are available. The active disintegration is succeeded by a state of relative dormancy. The biological processing is further complicated due to the ubiquity of the humic and fulvic acids in the leachate. A possible resurfacing of oxygen and oxidized species is contingent upon the capping process (Mor and Ravindra 2023)

4.2.3. Formation of microplastics in landfills

Under aerobic and anaerobic conditions, the organic waste in landfill sites undergoes degradation and decomposition in the presence of micro-organisms producing leachate (He et al. 2019). But on the other hand, plastics that are non-biodegradable persist in landfills. The main sources of plastics in landfills are plastic carry bags, plastic films such as packing sheets, polyvinyl chloride (PVC) pipes, container bottles, disposable diapers, disposable cups, kitchen utensils made of plastics, etc. The following conditions such as fluctuations in temperature i.e. 30°C to 60°C, high salinity, and the liberation of toxic gases such as CO, CO_2, CH_4, and H_2S within the landfill create biochemical reactions to create an environment for the degradation and disintegration of plastics(Sun et al. 2021,Tupsakhare et al. 2020). The pH of the landfill influences the maturity of the landfill. Fresh landfills that are generally new produce acidic leachate i.e. acetogenic while the older landfills generate leachate that is highly alkaline i.e. methanogenic (Kjeldsen et al. 2002). Due to the extreme environmental conditions, disintegration of the plastic debris in the landfills occurs resulting in the formation of secondary plastics which are also accompanied by microbial degradation (Sun et al. 2021). The primary microplastics that directly contribute to the leachate come from microbeads used in personal care products, and glitters while the secondary microplastics from the disintegration of rubber tires also contribute to the leachate. Additionally, the generated leachate acts as a medium to transport the microplastics originating from the landfills (He et al. 2019). Within the landfills, the formation of microplastics occurs through weathering of larger plastics through mechanical fragmentation, photodegradation, thermal degradation, and biodegradation (Tu et al. 2020, Resmeriță et al. 2018). Chemical degradation alters the molecular structure of the plastics while physical degradation changes the bulk structure of the plastics (Chamas et al. 2020). When the plastics are initially dumped into landfills, they are prone to aerobic biodegradation (Hou et al. 2020). This takes place in Phase I of the waste decomposition mentioned above. However, it shifts to anaerobic conditions due to the gases and acids produced due to the degradation of the solid waste which occurs in Phase II. An anaerobic environment sustains the survival of microorganisms which have the capability to degrade the plastic waste accumulated in the landfills which is evident in Phase III. This leads to the formation of tiny particles of plastic (Upadhyay and Bajpai 2021). Due to the extreme variations in temperature inside the landfills microplastics are subjected to thermal degradation. The presence of metals such as copper, iron, and chromium accelerates the thermal oxidation process (Hou et al. 2020). Furthermore, due to continuous exposure to sunlight and due to anthropogenic activities, the larger microplastics undergo mechanical abrasion to break into smaller microplastics. The time duration taken for the degradation of the plastic varies depending on the physical properties, chemical properties, and environmental conditions. The physical and chemical properties of the plastics include their shape, size, and crystallinity while the environmental conditions are influenced by the moisture content, oxygen content, temperature, and biofilms. The polymer chain in the plastics is weakened by the biological enzymes and the moisture content present in the landfill leachate. This weakening of the polymer chains accelerates the fragmentation of the plastic waste resulting in the formation of fractures and cracks. This results in the formation of microplastic particles of different sizes and shapes. Additionally, the porosity of the microplastics and the formation of the rough edges on the surface is enhanced by the weathering of microplastics. Subsequently, the weathering and the degradation process in the landfills plays a pivotal role in the production of microplastics of varying sizes and shapes (Premarathna et al. 2023). Thus, polluting the leachate in addition to the contamination by heavy metals and other harmful substances.

4.2.4. Impact of landfill age on microplastics

Landfills are a repository of plastic waste which is a component of MSW. Over the passage of time, the plastic waste degrades under the influence of internal and external conditions and finally results in the formation of microplastics. A study was done to determine the impact of landfill age on microplastics. For this the plastic waste samples were taken from an MSW landfill in Shanghai, China. The landfill is the largest domestic landfill in China. In order to analyze the oxidation level of polymers, the carbonyl index (CI) and hydroxyl index (HI) are used. Also, in order to establish the relationship between the landfill age and the degree of degradation CI and HI are used as indicators of degradation.

“The carbonyl index is defined as the peak areas of carbonyl moieties relative to the areas of the reference peak methylene moieties”.

“The hydroxyl index is a ratio between the hydroxyl group band area under the methylene scissoring peak” (F. Yu et al. 2022)

$$\mathrm{CI} = \frac{C = O\ (Peak\ area)}{-CH_2\ (Peak\ area)}$$

$$\mathrm{HI} = \frac{-OH\ (Peak\ area)}{-CH_2\ (Peak\ area)}$$

To determine the type of plastic used and to calculate the carbonyl index, Fourier-transform infrared spectroscopy was used. After the experiment, it was found that the CI was 0.24 for a 27-year-old polypropylene plastic while the CI for a 7-year-old polypropylene was 0.16 which shows that the CI is increasing over time. This proves that microbial degradation or auto-oxidation is happening continuously (Parte 2018, Matjašič et al. 2021). Scanning electron microscopy combined with energy spectroscopy (SEM-EDS) is used to determine the elemental composition and the surface morphology. The observation proves that there is a loss of plastic gloss in the old plastic. The old plastic has turned yellow and the surface appears to have a rough surface which might lead to fracture. This assists in the formation of smaller plastic debris under complex conditions. For instance, the SEM images of the original polyethylene show a smooth visible surface. On the other hand, the surface topography of the same PE from the landfill in Shanghai seems to be rougher and has even the appearance of holes or layers with the passage of time in a landfill. The CI of old plastic samples is two times higher than that of fresh samples which shows that the CI increases as the age of the landfill increases (Canopoli et al. 2018). Also, the observation points to the detection of metal elements such as Ti, Co, Al, etc. The comparison of samples from different landfill ages indicates that the content and species of elements on the surface of the plastic increase with the landfill time (F. Yu et al. 2022). Crystallinity is a major physical property of synthetic polymers showing the order of molecules. The DSC results convey that there is a decrease in crystallinity to 20.8% from 55.6% for polyethylene. For polypropylene, there is an increase to 56.8% from 25% (Kawai, Kawabata, and Oda 2019). “Differential Scanning Calorimetry is a thermo-analytical technique in which the difference in the amount of heat required to increase the temperature of a sample and reference is measured as a function of temperature” (Freire 1995). In a landfill, the chains of carbon molecules of PE get rearranged. In the process, the long-chain molecules are converted to short-chain under the action of biological enzymes. This is due to the presence of a large quantity of humus that is decomposed on the plastic surface. Therefore, the crystallinity of the PE shows a decrease. In the case of the crystallinity of polypropylene, the amorphous part of the polymer is destroyed than the region of crystallinity (Yang et al. 2014). In order to determine the degree of weathering of plastic it is necessary to analyze the loss of mechanical properties. Under the same stress, it is observed that PE plastics are essentially flexible and can be easily deformed. The degradation of mechanical properties implies that the extended burial in the landfill has changed the molecular structure of the plastics which could be potentially controlled by environmental weathering. Contrastingly, the PP plastic has a higher hardness making it more resistant to elastic deformation (F. Yu et al. 2022).

4.3. Transport of microplastics

4.3.1. Non- Biological transport of Microplastics

A vital role in the transportation and distribution of microplastics is the non biological modes of transportation. A study concluded that once the microplastics reach the soil surface, these particles have the potential to be transported across very long distances from the initial location of deposition. This could be done through the action of surface runoff or airstreams (Allen et al. 2021, Lange et al. 2021). Also under the influence of external factors such as soil erosion, leaching, and stormwater infiltration, the microplastics can move through pore channels in the soil and reach the groundwater. Certain microplastics may be even retained in soil pores because of the size exclusion or by clinging onto the soil particles in the subsurface region (Dong et al. 2022, Zhao et al. 2020). During intermittent infiltration rainstorm events, there is a downward migration of subsurface microplastics. These movements are observed in soils with higher permeability (Mohanty et al. 2015) . The microplastic properties such as shape, size, density, and surface chemistry along with the characteristics of the soil such as mineral content, porosity, and natural organic matter content have a profound impact on the movement and distribution of microplastics (O’Connor et al. 2019, M. Li et al. 2023) .

Leaching is stated as the loss of organic and mineral solutes due to the percolation in soil which is a porous medium with micrometer-sized pores. The pores in the soil facilitated the movement of granules and soluble materials (Grayling et al. 2018). As a result, the soil texture decides the size of the pores in the soil which has a direct effect on the migration of the microplastics (Lamy et al. 2013). By enhancing the ionic strength of the soil, the retention capacity of the microplastics in sand media containing quartz (Hou et al. 2020). This can be attributed to the considerable force exerted by ions against the double thickness, which leads to a depreciation in the energy barriers and an increase in the depths in the subprime polar and elementary regions (B. Li et al. 2018). Kurlanda-Witek, Ngwenya, and Butler 2015, Hou et al. 2020 stated that even though the impact on the ion strength of pore water in the soil is hypothetical, the absence of experimental evidence invalidates this notion. Additionally, the movement and fixation of microplastics in quartz sand are influenced by multiple factors such as saturation, hydrodynamics conditions of the medium, biofiltration, organics, and surface roughness. Li et al. 2018,Lamy et al. 2013,X. Wang et al. 2019 claims that the physicochemical sedimentation and strain regulate the critical interactions between colloidal fixation and migration in accordance with the research on colloidal migration in sand. Yujie Zhou et al. (2020) state that the solid-liquid interface adhesion, air-water interface capture, membrane strain, and pore repulsion have been determined as the primary mechanisms by the results. Keller, Jimenez-Martinez, and Mitrano (2020) prepared a mixture of a microplastic fiber and a passive inorganic tracer. The mixture was rapidly and quantitatively analyzed in simulated soil columns using inductively coupled plasma mass spectroscopy (ICP-MS). The mobility and transport of microplastics into the soil may be influenced by their bulk and aggregation state. The movement or transport may also be influenced by the morphology or polymers. The additional factors to be considered are the existence of highly variable soil conditions such as temperature, soil type, and water status which affect the behavior and fate of microplastics. The above data can be used for the investigation of microplastic movement in the soil. In contrast, soil is a significantly more complex heterogenous medium than quartz sand. A simulation study by Wu et al. (2020), Luo et al. (2020) revealed that pH, $Fe2O3$, clay, and soil organic carbon(SOC) play vital roles in the migration and adsorption of polystyrene microplastics. According to Cai et al. (2020), Huang et al. (2020), Rezaei et al. (2019), soil microplastics could migrate under the influence of dynamic driving forces such as wind, water, or soil erosion. Especially in cultivated soils with irrigation canals, overland runoff, and ditches, these migration risks could be relatively high. Additionally, important factors that affect the migration of microplastics are the properties of microplastics. The hydrophobicity, size, and surface properties of the polymers influence the migration of the microplastics (Nizzetto et al. 2016, Johnson 2020, O’Connor et al. 2019). The migration of the microplastics is influenced by the changes in the adsorption capacity caused by the process of aging (Lang et al. 2020). Spherical and granular-shaped microplastics are more easily prone to migrating downwards into the deeper soils whereas microplastics having the shapes like fibers and films interact in a different manner with the soil agglomeration. O'Connor et al. 2019 stated that microplastics with low density have difficulty penetrating downwards into the soil. Furthermore, the transport of microplastics can be affected by the differences in the ecological communities. The changes may be due to the degradation processes and the surface properties of the plastics. Generally, the microplastics having a size less than the pore size will be leached into the soil while those that are greater than the pore size will be clogged in the topsoil. After leaching, the microplastics end up in the groundwater that is shallow while larger microplastics will be retained in the soil which acts as a sink (Yujie Zhou et al. 2020,Leslie et al. 2022).

4.3.2. Biological transport of microplastics

A long term sink of microplastics is now considered to be soil. It is also considered as a source of microplastics entering the groundwater. It therefore behaves as a porous medium and contains cracks and pores ranging from the milli-meter to micro-meter scale (J. Xu et al. 2023). These linking channels serve as important conduits for transportation. In 2022, it was additionally suggested that the presence of preferred flow routes enhances the movement of minuscule particles (Viaroli, Lancia, and Re 2022). It has been under consideration that when the size of the microplastics is lesser than the pore-throat size of the medium through which they are moving then, it is comparatively easier for the downward movement of the particles. The detection of microplastics in the deep soil layers is considered compelling evidence of their downward migration. It was discovered that with the increase in dry-wet cycles, the penetration depth of microplastics in the sandy soils increased (O'Connor et al. 2019) . It was also under the inference that over extended periods of penetration into the ground, the microplastics can pollute shallow groundwater (Koutnik et al. 2022). The infiltration of microplastics into the groundwater can be attributed to biogenic processes. The above assertion has been disregarded since there is a thicker layer of soil that is commonly found. The methods by which the downward migration and distribution of microplastics occur can be through activities such as crawling, pushing, ingestion, burrow construction, and maintenance (Heinze et al. 2021). Heinze et.al (2021) performed an investigation to examine the influence of earthworms on the downward movement of microplastics into the soil. Their research revealed that there was a significant downward movement of microplastics that was facilitated by the earthworms through their ingestion and excretion activities (Heinze et al. 2021). In addition, the earthworms can assist in the movement of microplastics from the surface soil to the deeper parts of the soil. The additional study demonstrated that the microplastics can also be detected in the filtered drained water that has been filtered following a leaching exposure experiment. Furthermore, the presence of earthworms facilitated the downward migration of the microplastics from the soil matrix (M. Yu et al. 2019). Based on the above results, the researchers hypothesized that the microplastics could be carried by the earthworms from the surface to the soil layers in depth and may even lead to leaching into the groundwater that is shallow in certain regions (J. Xu et al. 2023) Not only do earthworms play a role in the movement of microplastics through the soil but also mites, collembolan, and even digging animals (S. W. Kim and An 2019, Rillig 2012) . A research discovered that soil microarthropods had the ability to raise the range of the microplastics by 9 cm (Zhu et al. 2018). Moreover, the prevalence of a predator-prey connection resulted in an increase of 40% in the mobility of microplastics when compared to an environment where one species is present. Here the collembolan is the prey while the predators are the mites. Maaß et al. (2017) discovered that two collembolans facilitated the movement of microplastics through their pushing and carrying behaviors.

4.3.3. Submarine Groundwater Discharges

Submarine groundwater discharges (SGD) have been considered as an unrecognized source of water. The prevalence of freshwater amidst the sea was a source of surprise for the communities across the coast in ancient times (Lino et al. 2023). SGD is defined as the flow of groundwater through the continental margins into the oceans or seas regardless of the components it is carrying (Burnett and Dulaiova 2003, Moore 1996). Moore defined a subterranean estuary as "a coastal aquifer where groundwater derived from land drainage measurably dilutes seawater that has invaded the aquifer through a free connection to the sea" (Valsan et al. 2023). Because of the pathway in which it provides pollutants or dissolved nutrients to the oceans (Paytan et al. 2006 Rodellas et al. 2015,Oehler et al. 2018), SGD has come to place itself as a major factor for planning and understanding the management practices of freshwater in the coastal regions (Kontar et al. 2002). SGD holds a significant position in the hydrological cycle linking the marine and terrestrial ecosystems (Moore 2010, Bugna et al. 1996). The contribution of chemical loading discharges by surface water is similar to the chemical loading by SGD (Moore 1996, Kim et al. 2003, Bugna et al. 1996). The main drivers of SGD are the hydraulic connection and the hydraulic gradient between the sea and land (Mejías et al. 2012). The occurrence of SGD can be through confined and unconfined aquifers through tidally controlled groundwater discharge, submarine springs, or seepage. It is necessary to maintain the health of the coastal ecosystem by characterizing SGD and nutrient fluxes associated with it (Narasimhan 2008). In today's world of climate change with its unprecedented occurrences of unnatural events, a complete comprehension of SGD is needed of the hour as it may lead to disruptions in the coastal hydrology. SGD is a pathway for pollutants that might harm the marine ecosystem. This is a particular concern for the Indian coast where factors such as industrial expansion, agriculture, overpopulation, and urbanization exert a huge amount of pressure on the coastal aquifers. The above-mentioned factors have led to the contamination of groundwater, intrusion of seawater, and the discharge, and recharge along the coasts of India (Jacob, Babu DS, and K 2009, George et al. 2021). The SGD was identified and researched through various approaches such as using a resistivity survey to determine subsurface examination, pore water temperature, chemical profiling, ground penetrating radar, using geochemical tracers such as strontium, radon, and radium (Jacob, Babu DS, and K 2009, Rahman et al. 2012, Yadav et al. 2020). Studies have also shown proof of SGD along the east and west coast of India. The heterogeneity of the hydrological characteristics of the study area determines the SGD. The variance in the freshwater SGD rates is mainly accrued to the change in the aquifer layers and their associated properties, the influence of streams, hydraulic gradient, and the rate at which coastal groundwater is withdrawn is a matter of concern. The southwest coast of India is characterized by undulated topography with a higher slope in elevation. The coast also borders the Western Ghats which influences the topography with a steeper hydraulic gradient. As a result of the steep slope, it influences the recharge-discharge pattern and reflects it in the water table (Varma 2017).

4.4. Impact of microplastics

4.4.1. On Physical Properties of Soil

The microplastics undergo a variety of physical interactions with the soil characteristics. To decipher the risks imposed by the microplastics, the changes in the soil properties are the primary index (Liu et al. 2017,Zhang and Zhang 2020,Rillig 2012). The microplastics can integrate with the soil to form various types of aggregates. Loose aggregates are formed with plastic debris while more compact aggregates are formed in combination with microplastic fibers (Rillig, Ingraffia, and De Souza Machado 2017,Wong et al. 2020). According to De Souza Machado et al. (2018), the impact of four of the common types of microplastics such as PE fragments, PET fibers, PA microbeads, and PP fibers on water holding capacity (WHC), bulk density (BD), and water stability aggregates (WSA) were carried out and were found to be different among the four. For instance, in soils contaminated with PET fibers, it was deduced that with increasing concentrations of PET, the WSAs and BD decreased notably. On the other hand, the other microplastics did not exhibit similar effects. The physical properties of the soil linked with microplastics can notably influence various physiological indicators like root growth and photosynthetic efficiency (Gao, Liu, and Song 2019,De Souza Machado et al. 2019). Also, microplastics can affect evaporation by changing the water percolating capacity (WPC) of soils (Boots, Russell, and Green 2019, De Souza Machado et al. 2018). The above-mentioned studies show that microplastics can change the soil-water cycle, affect the migration of pollutants, and increase the soil water shortages in the deep soil.

4.4.2. On Chemical Properties of Soil

Yujie Zhou et al. (2020) reported that microplastics have an impact on soil nutrient cycling and transfer. According to Fei et al.(2020), microplastics exert substantial impacts on the operations of highly catalytic enzymes in the soil. As significant regulators of soil nutrient cycling, these enzymes are closely linked with several soil biochemical processes(Tian et al. 2020,Hu et al. 2020). When the microplastics from the landfill leachate percolate into the soil, they remain in the soil for a long time and exert multiple effects on the soil properties by reducing soil fertility (Scheurer and Bigalke 2018, Qi et al. 2020, Tang 2020). This is done by affecting the pH of the soil, electrical conductivity and nutrient cycling. Depending upon the type of the soil the microplastics can either increase (Qi et al. 2020, Joos and De Tender 2022) or decrease the pH. It is found that PE can decrease the pH in acidic soils while increasing the pH in alkaline soils (Dissanayake et al. 2022). HDPE is found to decrease the pH of the soil as well (Boots, Russell, and Green 2019). Nutrients are originally formed from the disintegration of organic and mineral materials. Enzymes which are pivotal indicators of soil fertility govern the nutrient cycle. However, microplastics can alter the nutrient cycle and nutrient profiling (Tang 2020,Z. Li et al. 2023, Sharma et al. 2023). In a nitrogen cycle, there are various processes such as immobilization, mineralization, ammonia volatilization, nitrification, and denitrification (HaniF 2023). Several enzymes such as nitrate reductase, glutamine synthase, and nitrite reductase(Kishorekumar et al. 2020) are targeted by the microplastics and cause a reduction in the activities. This affects the nitrogen cycle(Z. Li et al. 2023) in the soil. Similar is the case with the carbon cycle. The carbon in the microplastics is primarily inert making it difficult to degrade. Microplastics also alter the carbon cycle and the movement of nutrients such as nitrogen and phosphorus with the help of dissolved organic matter. Furthermore, the microplastics can increase the ratio of carbon to nitrogen which enhances the immobilization of microbes (Rillig et al. 2019). It is also reported that microplastics can transport and absorb chemical substances such as heavy metals, and antibiotics. Moreover, microplastics act as carriers of pathogens (Hanif et al. 2024).

4.4.3. On fish

The primary pathway of microplastics entering the marine population is through ingestion. Ingestion happens when the tiny particles are swallowed through water or food. Seafood especially shellfish contain microplastics because of their filter-feeding behaviour. Filter-feeding behaviour enables marine animals to consume the abundant but smaller schools of fish and crustaceans by gulping the individual items of prey in a single feeding event. This form of adaptation was developed in response to the availability of prey and unique patterns of productivity in the marine ecosystem (Croll, Tershy, and Newton 2009). Microplastics can pile up in various tissues of the organisms because of their presence in the water column and finally reach the humans at the top of the food chain. The consumption of microplastics is observed across a range of organisms at different levels of the food chain including fish, invertebrates, marine mammals, and birds that prey on fish. Due to the small size of the microplastics, they can be easily ingested by marine organisms with different feeding behaviours. The feeding behaviour depends on the substrate that they feed on like being dependent on sediment or organic matter or filter feed (Masura, Baker, and Foster 2015) . Evidence and documentation of ingestion of microplastics have been found in natural and controlled laboratory environments. The marine organisms include fish (Bellas et al. 2016, Foekema et al. 2013), seabirds (Provencher et al. 2018), zooplankton(Boerger et al. 2010, Desforges, Galbraith, and Ross 2015) and bivalves (Browne et al. 2008) all of which are used for human consumption. For example, microplastics were discovered in the samples of harvested bivalves from a fishery market in China (J. Li et al. 2015). Different forms of microplastics such as pellets, fragments, and fibres. A significant proportion of microplastics consists of a size range below 250 µm. Research conducted in California, USA and Makassar, Indonesia stated the presence of microplastics in the shellfish and fish ready for human consumption. The study revealed the presence of microplastics in 55% of species and 28% of fish in Indonesia. Similar was the results of the study in California which showed that around 67% of the species and 25% of the individual fish. Additionally, 33% of mussels in the study showed the presence of microplastics. A similar study was conducted in the Bay of Bengal, Bangladesh. The research showed the presence of microplastics in almost all species on an average of 2.2 per fish. The most prevalent form of microplastics is in the form of green fibres and films under 500 µm. The microplastics were originally composed of polypropylene and polyethene (Ghosh et al. 2021). As the most consumed seafood in India is fish, the following are the main effects of microplastics in fish related to the body parts. The gills in fish assist in navigation and movement in the sea/ocean. An accumulation of microplastics causes a spike in lipid peroxidation levels, an increase in neutrophil infiltration and oxidative stress. Microplastics also cause structural damage to the gills. Another major impact is on the brain. Microplastics have been found to cause a depreciation in the activity of glutathione reductase and acetylcholinesterase. Microplastics also cause an increase in the level of lipid peroxidation in the brain, an alteration in the motor and feeding activity as well as alteration of behaviour in shallow waters. Additionally, microplastics suppress the activity of glutathione reductase with a spike in lipid peroxidation and oxidative stress. Similarly in the liver, the microplastics alter the activity of liver enzymes, amino acids, carbohydrates, fatty degeneration of hepatocytes and also the inflammatory changes in the liver. Microplastics also cause disturbances in the reproductive system and lead to a decrease in the generation of caviar. It can also penetrate the eggs in the fish (Zolotova et al. 2022).

4.4.4. On humans

The microplastics from the groundwater reach the marine environment through submarine water discharges. Hence it is a potential pathway for the contamination of the oceans with microplastics from the terrestrial environment. As India relies on seafood, especially South India, one way the microplastics reach the plates is through fish as stated above. The following are some of the effects of microplastic contamination through seafood.

a) Gastrointestinal problems

A significant health concern related to exposure to microplastics is gastrointestinal problems. The ingestion of microplastics through contaminated food leads to different gastrointestinal issues (Y. Zhao, Liu, and Xu 2023). Some of the problems are constipation, alterations in permeability, irritable bowel syndrome and inflammation of the digestive tract (Qiao et al. 2019, Zhao, Liu, and Xu 2023) . Also, the accumulation of microplastics in the digestive system causes blockages and physical irritation (Wright and Kelly 2017). Additionally, the microplastics can increase the immune response to biomolecules which are adsorbed (Powell et al. 2010). The exposure of microplastics to the gut has several implications for the symbiotic relationship between natural gut microbiota communities. This disturbance is known as dysbiosis. This may lead to a deleterious impact on the immune system of the host which may lead to chronic diseases and vulnerability to increased pathogenic infections (Fackelmann and Sommer 2019, Deng et al. 2020). Research has shown the impact of the digestion of microplastic on humans. The study shows that microplastics cause cytotoxicity in a moderate manner. The smaller microplastics had a more noticeable impact on the cell membranes while the larger particles showed an increase in the reactive oxygen species production. The study on the first polymer breakdown during human digestion was carried out to determine the impact of microplastics on the human gut microbiota and their changes within the gastrointestinal tract. The research group made a simulation to understand the passage of polyethylene terephthalate (PET) through the digestive system. The study also revealed that the PET microplastics underwent structural alterations in the digestive system, especially the colon (Tamargo et al. 2022).

b) Endocrine disruption

A related health concern caused by microplastics is the disruption of the endocrine system. Microplastics has the ability to absorb different chemicals from the surroundings which includes endocrine-disrupting compounds (EDC). EDCs are exogenous substances or combinations of substances that possess the capability to disrupt the normal processes of the endocrine system (Surana et al. 2022). The frequently used EDCs in plastics are nonylphenol, phthalate esters, bisphenol A and octylphenol. These are normally found in microplastics as reaction agents or additives (Wee et al. 2022, Domenech and Marcos 2021). The microplastics release the EDCs when ingested which further causes the disruption of the endocrine system. This disruption leads to detrimental impacts on reproductive health, hormonal balance, development and overall health (Kontrick 2018)

4.5. Assessment of Microplastics generation and pollution from Landfill Leachate in Urban India

4.5.1. Overview

For the calculation, the population projections spanning the years 1960 to 2022 were sourced from the World Bank. By employing the per capita MSW generation data from 1960, sourced from a scientific article, it was possible to compute the total quantity of MSW generated. A 5% increase in per capita waste generation was assumed from 1960 to 2022. Furthermore, a 10% increase was integrated to account for the plastic waste generated during the COVID-19 pandemic. The calculation of the amount of municipal solid waste (MSW) that is deposited in landfills was performed utilizing the data mentioned i.e. by multiplying the population, per capita waste generation, and number of days in a year. The information employed to ascertain the volume was extracted from a report published by the Indian government concerning waste management. A mean value for the landfill height was computed by averaging a range of heights obtained from an extensive collection of scientific articles that detailed the vertical extent of landfills. With the height in consideration, the area of the occupied landfill was determined by dividing the cumulative volume over a period of years by the height. From a scientific article, the annual average surface discharge and annual precipitation in India were extracted. By employing the data provided earlier, the volume of leachate was determined using the water balance method. The quantification of microplastics in its entirety was ascertained by consulting the concentration of microplastics detailed in a scientific article originating from Hyderabad.

a) Urban Population

Urban population is defined as the "percentage of the total population of a country, territory, or geographic area living in places defined as urban, at a specific point of time, usually mid-year". The word urban in this context refers primarily to towns, cities, and other densely populated areas. The countries normally define urban areas as part of the census procedures. The demarcation of areas is generally centered on the classification as administrative, population density, or the type of economic activity undertaken by the residents among other special criteria. ("Proportion of Urban Population," n.d.). The population of the urban areas must be ascertained prior to calculating the quantity of MSW produced. Data pertaining to the urban population of India, sourced from the World Bank, is utilized for the purpose of this analysis. The time period for the analysis includes the period from 1960 to 2022. Villages and rural regions are undergoing a transformation due to the exponential expansion of cities throughout the globe. Transitioning from an economy rooted in agriculture to one that is service-oriented, technologically advanced, and of mass-production is the essence of the change for a country like India. Employment opportunities and the revenue they generate, in addition to health care and education initiatives, are the primary attractions of urban areas. Primarily, urban areas provide a more conducive environment than rural areas for addressing economic and social issues. Moreover, urban areas offer prospects for the advancement of female empowerment and the consolidation of social movements. These factors have a profound impact on the consumption patterns of the urban dwellers. The data about the urban population is as follows. ("Urban Population - India | Data," n.d.)

b) Per-capita MSW generation

As the population data is from 1960, the per capita MSW generated in 1960 is assumed to be at a rate closer to the rate in 1947 assuming a similar rate of development, income, and consumption. Hence, the per capita MSW generation is taken as 0.31kg/cap/day for the year 1960. Assuming a 5% increase every decade, the MSW per capita generation is taken as 0.326 kg/cap/day,0.358 kg/cap/day, and 0.393 kg/cap/day for the period 1970-80,1980-90,1990-2000. For the next three decades, 2000-10,2010-2020,2020-30, the values are 0.439 kg/cap/day,0.498 kg/cap/day, and 0.569 kg/cap/day (K. D. Sharma and Jain 2019). A 10% increase is assumed during 2020 and 2021 due to the increased MSW generation due to the COVID-19 pandemic in India.

c) Yearly MSW generation

Given the data for the urban population from 1960-2022, per capita generation of MSW during this period, and the number of days in a year, the amount of MSW generated in a year can be calculated taking into account the leap years as well. As it is an estimation, the values generated are in accordance with three significant digits.

d) MSW dumping in landfills

Sanitary landfills are utilized for the appropriate management and disposal of a mere 21% of the MSW in India (Mor and Ravindra 2023). The above statements shows that the amount of MSW disposed in open dumpsites is 79%. A comparable investigation found that approximately 80% of MSW is disposed of without regard to sanitary principles (Patel, Mujumdar, and Srivastava 2023). Hence, approximately 80% of the overall MSW generated is disposed of in landfills devoid of scientific disposal methods and non-engineered landfills.

e) Density of the MSW in landfills

The determination of the landfill's refuse volume may be predicated on the municipal solid waste management plan (MSWM) and the subsequent supposition. One metric tonne of municipal solid waste is equal to one cubic meter of landfill volume. This is due to the fact that the initial specific weight of refuse in the landfill is 0.8t/m^3, which increases to 1.2t/m^3 over time as a result of settlement within the landfill (Central Public Health and Environmental Engineering Organisation (CPHEEO), 2016)

f) Volume of the landfill

From the above information, it is possible to calculate the volume occupied by the MSW in the landfill in the urban areas. The volume of the MSW in each year starting from 1960 to 2022 is added and calculated to get the total volume of the MSW in the urban areas of India.

Table 1 Data regarding population, MSW generated, landfilled quantity, and volume of MSW

Year	Population	per capita (kg/per capita/day)	Days	MSW (kg)	MSW (tonnes)	Landfilled quantity (tonnes)	Volume m^3
1960	79932899	0.31	366	9070000000	9070000	7256000	7256000
1961	82289370	0.31	365	9310000000	9310000	7448000	7448000
1962	85082467	0.31	365	9630000000	9630000	7704000	7704000
1963	87963683	0.31	365	9950000000	9950000	7960000	7960000
1964	90940579	0.31	366	10300000000	10300000	8240000	8240000
1965	93946480	0.31	365	10600000000	10600000	8480000	8480000
1966	96971069	0.31	365	11000000000	11000000	8800000	8800000
1967	100070141	0.31	365	11300000000	11300000	9040000	9040000
1968	103304423	0.31	366	11700000000	11700000	9360000	9360000
1969	106674456	0.31	365	12100000000	12100000	9680000	9680000
1970	110162257	0.326	365	13100000000	13100000	10480000	10480000
1971	113948536	0.326	365	13600000000	13600000	10880000	10880000
1972	118438504	0.326	366	14100000000	14100000	11280000	11280000
1973	123114078	0.326	365	14600000000	14600000	11680000	11680000
1974	127986735	0.326	365	15200000000	15200000	12160000	12160000
1975	133010186	0.326	365	15800000000	15800000	12640000	12640000
1976	138180350	0.326	366	16500000000	16500000	13200000	13200000
1977	143540276	0.326	365	17100000000	17100000	13680000	13680000
1978	149104062	0.326	365	17700000000	17700000	14160000	14160000
1979	154888632	0.326	365	18400000000	18400000	14720000	14720000
1980	160953420	0.358	366	21100000000	21100000	16880000	16880000
1981	166932604	0.358	365	21800000000	21800000	17440000	17440000
1982	172426704	0.358	365	22500000000	22500000	18000000	18000000
1983	178095921	0.358	365	23300000000	23300000	18640000	18640000
1984	183956909	0.358	366	24100000000	24100000	19280000	19280000
1985	189973343	0.358	365	24800000000	24800000	19840000	19840000
1986	196158550	0.358	365	25600000000	25600000	20480000	20480000
1987	202485214	0.358	365	26500000000	26500000	21200000	21200000
1988	208957670	0.358	366	27400000000	27400000	21920000	21920000

1989	215601807	0.358	365	28200000000	28200000	22560000	22560000
1990	222374415	0.358	365	29100000000	29100000	23280000	23280000
1991	229151406	0.393	365	32900000000	32900000	26320000	26320000
1992	235824041	0.393	366	33900000000	33900000	27120000	27120000
1993	242620668	0.393	365	34800000000	34800000	27840000	27840000
1994	249539704	0.393	365	35800000000	35800000	28640000	28640000
1995	256565748	0.393	365	36800000000	36800000	29440000	29440000
1996	263686524	0.393	366	37900000000	37900000	30320000	30320000
1997	270911166	0.393	365	38900000000	38900000	31120000	31120000
1998	278238779	0.393	365	39900000000	39900000	31920000	31920000
1999	285648480	0.393	365	41000000000	41000000	32800000	32800000
2000	293168849	0.393	366	42200000000	42200000	33760000	33760000
2001	301227098	0.439	365	48300000000	48300000	38640000	38640000
2002	310207535	0.439	365	49700000000	49700000	39760000	39760000
2003	319267849	0.439	365	51200000000	51200000	40960000	40960000
2004	328414552	0.439	366	52800000000	52800000	42240000	42240000
2005	337558628	0.439	365	54100000000	54100000	43280000	43280000
2006	346659205	0.439	365	55500000000	55500000	44400000	44400000
2007	355789232	0.439	365	57000000000	57000000	45600000	45600000
2008	364989009	0.439	366	58600000000	58600000	46880000	46880000
2009	374274816	0.439	365	60000000000	60000000	48000000	48000000
2010	383721793	0.439	365	61500000000	61500000	49200000	49200000
2011	393333604	0.498	365	71500000000	71500000	57200000	57200000
2012	403171286	0.498	366	73500000000	73500000	58800000	58800000
2013	413200994	0.498	365	75100000000	75100000	60080000	60080000
2014	423338709	0.498	365	77000000000	77000000	61600000	61600000
2015	433595954	0.498	365	78800000000	78800000	63040000	63040000
2016	444186310	0.498	366	81000000000	81000000	64800000	64800000
2017	455009748	0.498	365	82700000000	82700000	66160000	66160000
2018	465871825	0.498	365	84700000000	84700000	67760000	67760000
2019	476786386	0.498	365	86700000000	86700000	69360000	69360000
2020	487702168	0.548	366	97800000000	97800000	78240000	78240000
2021	498179071	0.602	365	$1.09\text{x}10^{11}$	109000000	87200000	87200000
2022	508368361	0.569	365	$1.06\text{x}10^{11}$	106000000	84800000	84800000

g) Height of landfill

As the landfills are the cheapest and the easiest method for the disposal of MSW, the height of unscientific and un-engineered landfills have varying heights around cities. A study was conducted on two significant dumpsites in Chennai namely Kodungaiyur and Perungudi. The height of the landfill sites varies from 10-15m (Peter, Shiva Nagendra, and Nambi 2019). A non-engineered landfill at Vendpalayam in Erode is located near living communities. The height of the dumping sites varies from 12 to 15m. Another study estimates the height of the landfills to be in the range of 50-70m (Somani et al. 2022). Assuming the above data as the representative range of landfill heights across the country with regard to the non-engineered landfill sites in urban locations, the average height of the landfill sites is taken by the average of the ranges. Therefore, the approximate height of the landfill used for the estimation is 30m.

h) Area of the occupied landfill

By dividing the total volume of the MSW in the landfill by the height of the landfill, the area of the non-engineered landfill occupied by the MSW in the urban area is obtained.

i) Amount of leachate

The amount of runoff into the soil was calculated.
Average annual rainfall of the country=1170mm/a……………………….............(a)
Volume of average annual rainwater=4000 km^3/a……………………………………(b)
Sum of run off and excess water infiltration into soil = 1869 km^3/a………..............(c)
(Rakhecha 2016)
Using a, b and c, the sum of run off and excess water infiltration into soil is calculated 547 mm/a. ……………………………………………………………………….(d)
Average water lost by evaporation and transpiration= (a)-(d)=1170-547=623mm/a
Assuming that the landfill has a low slopped surface and hence only a small quantity of runoff i.e 10% of the precipitation/annual rainwater. Therefore Runoff is 117mm/a and amount of leachate is calculated

Table 2 Amount of leachate

Volume of average annual rainwater	1170	mm/a	i
Average water lost by evaporation and transpiration	623	mm/a	ii
Sum of run off and excess water infiltration into soil	547	mm/a	i-ii
Runoff	117	mm/a	iv
Amount of leachate	430	mm/a	i-ii-iv

j) Quantity of microplastics

A study conducted to determine the concentration of microplastics in from landfill leachate was done in Hyderabad, India. It is the fourth largest city as per the census conducted in India in 2011. The study revealed that the concentration of microplastics from the landfill leachate was from 9 to 21 items/L (Sekar and Sundaram 2023). The amount of microplastics from the landfill refuse and leachate was found to be from 20,000-91,000 items/kg (Golwala et al. 2021).

Table 3 Range of microplastics

Total mass of the MSW	1986	MT	
Area of occupied landfill	66200000	sq.m	
Total leachate volume	28461	ML	
Lower limit concentration	9	items/L	i
Upper limit concentration	21	items/L	ii
Lower limit range in kg	20000	items/kg	iii
Upper limit range in kg	91000	items/kg	iv

Using i, ii, iii, iv the quantity of the microplastics seeping down is in the range of

6570 tonnes to 12810 tonnes.

k) Results

The quantity of MSW landfilled in the urban areas of the country in the following range from 1960 to 2022 is 1986 Mega tonnes (MT)

The amount of landfill leachate that infiltrates into the ground in the urban areas of the country in the following range from 1960 to 2022 is 28461 Mega litres (ML)

The quantity of microplastic emanating from landfills in the period ranging from 1960 to 2022 is in the following range i.e. 6570 tonnes to 12810 tonnes cumulatively.

4.5.2. Relevance

Microplastics emitted through landfill leachate from urban areas in India show the poor waste management strategies as unsanitary landfills are the cheapest and easiest method for disposing of MSW. Unsanitary landfills are an important source to be considered and managed properly for waste disposal which if unchecked would lead to health issues for those above and below the land. The microplastics that are retained in the soil are capable of affecting the physical and chemical properties of soil thereby impacting soil flora and fauna. Moreover, during the passage of time, the microplastics find their way to the groundwater and finally to the marine environment through submarine water discharges. This causes microplastic contamination in the oceans as well. The microplastics that remain in the oceans are mistaken as food by marine organisms, especially fish. As fish are captured for human consumption, they finally reach the dining table and are in turn consumed by human beings. Thus, microplastics find their way to humans affecting their health.

5. Conclusion

The increasing population and rapid urbanization have led to the ever-increasing problem of waste generation especially plastic waste in the urban areas. As India is a developing country, unsanitary landfills are a common and the cheapest choice for dumping waste. Depending on the literature review conducted landfill leachate is a source of pollution that cannot be neglected. This leads to the contamination of soil, and groundwater, ultimately impacting human beings themselves. The challenges faced during the research lie in the accuracy of data over the years especially the population data, precipitation data, per capita waste generation data, etc. There is no method available to determine the exact quantity of microplastic entering the soil and percolating into the groundwater. Assumptions were taken especially to get the per-capita waste generated starting from 1960 as a 5% increment has been taken during each decade. Furthermore, a 10% increase in per capita waste generation is taken during the years 2020 and 2021 to incorporate the increase in plastic waste generated during the COVID-19 pandemic. As the study points out a huge quantity of microplastics are being leached out from unsanitary landfills, the waste sector in India should aim to construct landfills scientifically to mitigate the release of microplastics into the environment. By adhering to scientific methods such as selecting a location away from public and surrounding water bodies, using a liner, cover etc.

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