

**INVESTIGATION ON RECYCLING POTENTIAL OF  
PLASTIC WASTE AS AGGREGATE IN GREEN  
SUSTAINABLE CONCRETE: AN ECONOMIC  
APPROACH**

*THESIS SUBMITTED BY*

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## **DECLARATION**

I declare that,

- a. The work contained in the thesis is original and has been done by myself under supervision and guidance of my supervisor.
- b. The work has not been submitted to any other institute for any degree or diploma.
- c. Whenever I have used materials (data, theoretical analysis and text) from other sources, I have given due credit to them by citing them in the text of the thesis and giving their details in the references.

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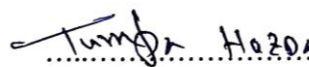
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## **ABSTRACT**

Plastic waste management is one of the major global challenges at present. Recycling single used plastic waste as partial replacement of natural aggregates in concrete may encounter the issues regarding mismanagement of plastic waste and unsustainable utilisation of natural resources as aggregates. This concept has been explored in many studies and positive results are obtained in terms of viability regarding mechanical properties of the concrete, but still it has not been materialized at a large scale due to the uncertainty regarding its economic viability. The present study therefore focuses on the economic aspects of using Polyethylene (PE) based fine aggregates and Polyethylene Terephthalate (PET) based coarse aggregates as partial replacement (10%, 20%, 30% and 40%) of natural fine and coarse aggregates separately and simultaneously, with special emphasis given on environmental and social cost. A material flow diagram using STAN (subSTance flow ANalysis) is first developed to calculate plastic waste generation. An industrial survey has been conducted to estimate production cost of plastic aggregates, while social cost as Willingness to Pay (WTP) is determined through Contingent Valuation Method (CVM). The result shows that the total cost of concrete decreases with the increase of replacement percentage and cost reduction varies between 0.65% and 5.42% compare to conventional concrete depending on the percentage and type of replacement without compromising mechanical strength. So, alongside being hugely beneficial to environment and society in terms of reduction of leachate and greenhouse gas generation, micro-plastic pollution, requirement of landfill area, mosquito borne diseases, erosion, sedimentation, land loss etc.; the concept of recycling plastic waste as partial replacement of natural aggregates in concrete has been proved to be economically viable and beneficial too. Based on the result, policy makers can make suitable methodology and specifications for successful implementation of this proposed strategy, which may help the society to achieve a sustainable future.

**Key Words:** Economic analysis, Plastic waste management, Recycling, Plastic based aggregate, Green sustainable concrete, Environmental cost, Social cost

## **LIST OF ABBREVIATIONS**

ANOVA	: Analysis of Variance
AUD	: Australian Dollar
BAC	: Brick Aggregate Concrete
BIS	: Bureau of Indian Standard
CA	: Coarse Aggregate
CAGR	: Compound Annual Growth Rate
CBA	: Cost-Benefit Analysis
CER	: Carbon Emissions Reduction
CO <sub>2</sub> e	: Carbon-di-Oxide Equivalent
CPCB	: Central Pollution Control Board
CVM	: Contingent Valuation Method
C&D	: Construction and Demolition
ETB	: Ethiopian Birr
FA	: Fine Aggregate
GHG	: Greenhouse Gas
GVW	: Gross Vehicle Weight
GWP	: Global Warming Potential
HDPE	: High-Density Polyethylene
HKD	: Hong Kong Dollar
INR	: Indian Rupee
KMC	: Kolkata Municipal Corporation
LCCA	: Life Cycle Cost Analysis
LDPE	: Low-Density Polyethylene
LLDPE	: Linear Low-Density Polyethylene
MoEFCC	: Ministry of Environment, Forest and Climate Change
MCX	: Multi Commodity Exchange
MSW	: Municipal Solid Waste
MSWM	: Municipal Solid Waste Management
MTPA	: Million Ton per Annum
NZD	: New Zealand Dollar
O&M	: Operation and Maintenance
PCA	: PET based Coarse Aggregate

PCB	: Polychlorinated Biphenyl
PE	: Polyethylene
PET	: Polyethylene Terephthalate
PFA	: PE based Fine Aggregate
PLA	: Polylactic Acid
PP	: Polypropylene
PPA	: Polypropylene aggregate
PS	: Polystyrene
PVC	: Polyvinyl Chloride
PWM	: Plastic Waste Management
RCA	: Recycled Concrete Aggregate
SAC	: Stone Aggregate Concrete
STAN	: subSTance flow ANalysis
TPA	: Ton per Annum
TPD	: Ton per Day
UNEP	: United Nations Environment Programme
USD	: United States Dollar
USEPA	: United States Environment Protection Agency
UTs	: United Territories
WTA	: Willingness to Accept
WTP	: Willingness to Pay

## **LIST OF SYMBOLS**

A = Quantity of total generation of plastic waste in Kolkata, TPA

B = Quantity of collected plastic waste in Kolkata, TPA

C = Quantity of uncollected plastic waste in Kolkata, TPA

$C_1$  = Landfill disposal cost per ton of waste, INR

$C_2$  = Municipal solid waste management expenditure for per ton of waste, INR

$C_3$  = Value of reduction of per ton of CO<sub>2</sub>e, INR

$C_4$  = Leachate cost per ton of waste, INR

D = Quantity of plastic waste going into the landfill in Kolkata, TPA

e = Margin of error

E = Quantity of plastic waste going into the marine environment from Kolkata, TPA

F = Quantity of plastic waste stays littered in Kolkata, TPA

$G_1$  = GHG emission from landfill and dump sites for per unit of PE and PET waste, Kg CO<sub>2</sub>e/ton

$G_2$  = Gas emission from transportation of per unit of aggregates, Kg CO<sub>2</sub>e/ton

$G_3$  = Generation of CO<sub>2</sub> from fuel consumption, Kg/L

$G_4$  = CO<sub>2</sub> generation for consumption of per MWh electricity, ton

H = Distance between the source of aggregate and destination, Km

I = Average of the mileages of the vehicle when fully loaded and when fully empty, Km/L

J = Payload of the vehicle, ton

K = Quantity of aggregates to be transported, ton

L = Yearly production of a processing plant, ton

M = Yearly consumption of electricity due to processing, MWh

n = Sample size

N = Landfill area requirement for per TPA waste, ha.

p = Population size

$P_1$  = Collection efficiency of MSW in Kolkata in percentage

$P_2$  = Recycling rate of plastic waste in Kolkata in percentage

$P_3$  = Consumption of PE and PET out of total plastic usage in percentage

$P_4$  = Budget allocated for collection and transportation of MSW out of total budget in percentage

$Q_1$  = Quantity of PET available to replace natural aggregates, TPA

$Q_2$  = Quantity of PE available to replace natural aggregates, TPA

$R_1$  = Amounts of CA that can be replaced by plastic aggregates, TPA

$R_2$  = Amounts of FA that can be replaced by plastic aggregates, TPA

$S_1$  = Yearly landfill disposal cost saved by recycling and reusing PE and PET in Kolkata, INR

$S_2$  = Extra yearly expenditure on collection and transportation of the uncollected PE and PET waste at Kolkata, INR

$S_3$  = Yearly gas emission cost saved by recycling and reusing PE and PET in Kolkata, INR

$S_4$  = Yearly landfill leachate emission cost saved by recycling and reusing PE and PET in Kolkata, INR

$S_5$  = Gas emission cost due to transportation of aggregates, INR

$S_6$  = Additional cost of gas emission from processing plants, INR

$S_7$  = Landfill area saved due to not disposing PE and PET waste at landfills in Kolkata, ha.

$SG_1$  = Specific gravity of natural coarse aggregates

$SG_2$  = Specific gravity of natural fine aggregates

$SG_3$  = Specific gravity of PET based aggregates

$SG_4$  = Specific gravity of PE based aggregates

$X$  = Quantity of PE and PET going into landfill in Kolkata, TPA

$Y$  = Quantity of PE and PET going into marine environment in Kolkata, TPA

$Z$  = Quantity of PE and PET dumped openly in Kolkata, TPA

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# Chapter 1: Introduction

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## 1.1. Motivation

From cable wires to water bottles, from cell phones to bicycle helmets, plastic has moulded the society in many ways to make life easier and safer. It is everywhere. Various types of plastic products have become an indispensable part of lifestyle because of their low cost, durability, light weight and flexibility. Commercial production of plastics has started around 1950's [Lebreton and Andrady, 2019] and since then, the usage of plastic has increased tremendously, especially in last few decades. However, the success and dominance of plastic has created many environmental issues and left harmful imprints on the environment and human health due to their slow decomposition in natural ecosystem. A direct replacement of it is yet to be found. With this increase in production and consumption of plastic, generation of plastic waste has also increased significantly, and plastic waste management has become a more severe problem globally. An example of mismanaged plastic waste is shown in Figure 1.1.



*Figure 1.1: Mismanaged plastic waste* [Temming, 2021]

Despite having better management approaches of plastic waste such as recycling and incineration, still globally a significant portion (56%) of plastic waste either disposed at landfill or escapes into the environment without treatment [Tsakona et al., 2020]. Though the recycling rate is higher in case of India, but still it is not high enough to be a sustainable

approach. This not only creates problem regarding land availability, but also harms the environment in terms of generation of leachate and greenhouse gasses. Furthermore, landfill leachate consisting micro-plastic, heavy metals and toxic chemicals, contributes significantly in groundwater pollution. Presence of uncollected plastic waste in agricultural fields also reduces the productivity of the land. On the other hand, a vast amount of uncollected plastic waste goes into the water bodies, causes micro-plastic pollution and disrupts the aquatic environment. Nearly 45000 marine animals have ingested plastics, of which 80% were died or injured [MoHUA, 2019]. Figure 1.2 shows the effects of plastic waste on the biodiversity. Apart from these, many social inconveniences such as blockage of drainage system, excessive breeding of mosquitoes, generation of fouling smells etc. occur due to mismanagement of plastic waste. Hence, there is a huge need for change in strategy of management of plastic waste to reduce the amount and make it sustainable.



**Figure 1.2: Effect of plastic waste on the biodiversity** [WWF, 2023; Wilcox et al., 2015]

On the other side, the exponential increase of world population has created the need for more residences and infrastructures; subsequently the demand of concrete has skyrocketed in recent years. Concrete is the second most used substance in the world after water [Gagg, 2014], and is the most widely used building material. Fine and coarse aggregates occupy within 55% to 80% of the total volume of a concrete mixture [Alqahtani et al., 2021]. Sand, gravel and crushed stone are used mainly for this purpose, and these natural sources are neither unlimited, nor renewable. Hence, this excessive extraction of natural aggregates is unsustainable and causing damage to the environment in various ways, such as conversion of land use, changes to the landscape, loss of habitat, erosion, sedimentation, alteration of river bed, land loss etc. Between 2012 and 2017, the land loss at flood plains amounted up-to 285.78 ha due to aggregate extraction [Udom, 2018]. Not only that, mining process of natural

aggregates also causes blasting effect, noise and dust pollution. Figure 1.3 shows the sand mining process for the collection of fine aggregate of concrete. As natural aggregates for production of concrete are already struggling to meet its constantly increasing demand, it is a high time to find a replacement of natural aggregates to use in concrete.



*Figure 1.3: Sand mining for collection of fine aggregates* [Bhoopathy and Subramanian, 2022]

Using recycled solid waste as a partial replacement of natural aggregates in concrete is a growing trend now. Use of construction and demolition (C&D) waste for this purpose has already started in few places. Recently studies have been conducted regarding using waste plastic based aggregate in concrete as partial replacement of conventional natural aggregates, which tackles both the global challenges of unsustainable extraction of natural aggregates and mismanagement plastic wastes simultaneously. Even though the studies show that the introduction of plastic aggregates alters some mechanical properties and causes reduction in compressive strength of the concrete, still replacement up-to a certain percentages have been concluded as acceptable [Tamang et al., 2017; Hossain et al., 2016; Subramani and Pugal, 2015; Ismail and AL-Hashmi, 2008]. On the other hand, it increases tensile strength [Harini and Ramana, 2015; Raghatate, 2012], bending strength [Wei and Sakai, 2021], workability [Shiuly et al., 2022] and durability [Elango and Kumar, 2018] of the concrete while reducing the density [Osei, 2014], so that it can be used as light weight concrete and places where the requirement of compressive strength is less but the need for durability is more. Positive results have been obtained in case of using Polyethylene (PE) and Polyethylene Terephthalate

(PET) waste based aggregates as partial replacement of natural aggregates and it allows to replace up-to 30% without compromising the mechanical properties much and manufactured concrete can be used for structural purposes [Sau et al., 2023a; Sau et al., 2023b; Shiuly et al., 2022]. This provides a unique opportunity to utilise mismanaged waste plastics in a sustainable way by producing green concrete.

Despite many environmental and social advantages of using plastic aggregates in concrete, their commercial production for use in structural application is severely limited, presumably due to the lack of research work regarding its economic feasibility. For successful implementation of this, study on detailed economic analysis is much required to know its viability from the economic point of view. It will present the necessary information for further researchers as well as individuals or companies that might want to use these materials in concrete production and it gives the government and policy makers a platform to develop suitable policies regarding implementation of this which may lead us to a sustainable future.

## **1.2. Objectives and Scope of Work**

The primary objective of this work is to present a study of economic feasibility by performing an economic viability analysis while giving special emphasis on environmental and social costs and benefits regarding recycling of plastic waste as partial replacement of natural aggregates in green sustainable concrete.

In order to achieve this objective, it is necessary to evaluate the present plastic waste management system of the area under Kolkata Municipal Corporation (KMC), estimate the quantity of mismanaged PE and PET waste and check its availability to meet the demand, estimate the processing cost of plastic aggregates; and direct, environmental and social cost associated with the proposed strategy after identifying the potential benefits, compare the production cost of plastic aggregate based concrete and conventional concrete and check the economic viability and recommend an optimum replacement percentage based on the result of the comparison without compromising the mechanical properties of concrete.

Accordingly, the scope of the work is outlined as follows:

- Literature survey regarding acceptance and changes in mechanical properties of concrete after using waste plastic based aggregates as partial replacement of natural coarse and fine aggregates in concrete.

- Evaluation of the present plastic waste management system and identification of its deficiencies.
- Quantity estimation of mismanaged PE and PET waste by creating a plastic waste flow chart of Kolkata using STAN 2.7.101.
- Checking of the availability and feasibility of PE and PET waste to meet the demand considering the requirement of concrete at Kolkata.
- Estimation of the processing cost of waste plastic based aggregates considering all the components by doing an industrial survey and direct interviews with processing plant owners.
- Assessment of the environmental and social benefits associated to recycling of mismanaged plastic waste in green sustainable concrete.
- Monetization of the direct and environmental benefits and additional expenditures on the basis of secondary data collected from scientific literatures and relevant websites.
- Estimation of the social cost by calculating household's Willingness to Pay (WTP) for improved plastic waste management system. Estimation of WTP requires:
  - Design of survey experiment
  - Collection of data from households in KMC area
  - Analysis of data using one-way ANOVA (Analysis of Variance)
- Data collection of mix design to estimate the requirement of raw materials including plastic aggregates for production of conventional concrete as well as plastic aggregate based concrete.
- Collection of data regarding market prices of the raw materials of concrete.
- Comparison of the production costs of 12 different replacement scenarios with conventional concrete by developing an economic index.
- Checking of the economic viability of utilising waste plastic based aggregates as partial replacement of natural aggregates in concrete.

- Recommendation of the optimum value on proportional replacement while considering not only economic index but also the concrete properties.

### **1.3. Organisation of Thesis**

The thesis comprises of nine chapters organized as follows:

#### ***Chapter 1: Introduction***

This chapter presents a brief overview of two severe global challenges, plastic waste management and scarcity of natural aggregates along with the consequences. Also a potential sustainable solution to both of the issues has been discussed here. Furthermore, the specific objective and scope of the present work are presented in this chapter.

#### ***Chapter 2: Literature Review***

In this chapter, background, present scenario and other aspects of different topics related to the proposed study have been discussed. Also, various national and international literatures relevant to this research work have been summarized in chapter 2. Different cost components and their methods of estimation are also mentioned here briefly.

#### ***Chapter 3: Study Area***

Chapter 3 contains some basic statistics of the area on which the study has been conducted and few important locations relevant to the study within the study area. A brief overview of the present solid waste management system of the study area is also represented here along with the fate of generated plastic waste and the deficiencies of the present system.

#### ***Chapter 4: Methodology***

To cover the deficiencies of the present system of plastic waste management, a new management strategy has been proposed in chapter 4. To achieve the objective, an overview of the approaches taken at different stages of the work has been summarized here. A schematic representation of the whole methodology is also included in this chapter.

#### ***Chapter 5: Quantity Estimation***

In this chapter, the flow of plastic waste of the study area has been estimated and presented in a schematic diagram using STAN. The amount of mismanaged PE and PET waste, which are relevant to this study, are determined here. Also, the feasibility of the proposed strategy in

terms of potential utilisation of the total quantity of mismanaged PE and PET waste of the study area considering the demand of concrete has been checked in chapter 5.

### ***Chapter 6: Economic Evaluation***

Chapter 6 contains estimation of all the associated costs to the proposed strategy including processing cost of plastic aggregates. Also, a feasibility check of the proposed strategy has been conducted by comparing the production cost of conventional concrete and plastic aggregate based concrete.

### ***Chapter 7: Conclusion and Recommendation***

A conclusion based on economic evaluation has been drawn in this chapter. Also, some recommendations which are necessary for successful implementation of the proposed strategy are mentioned here. Furthermore, the major challenges of this proposal of change in plastic waste management system are discussed here along with future scope of this study.

# Chapter 2: Literature Review

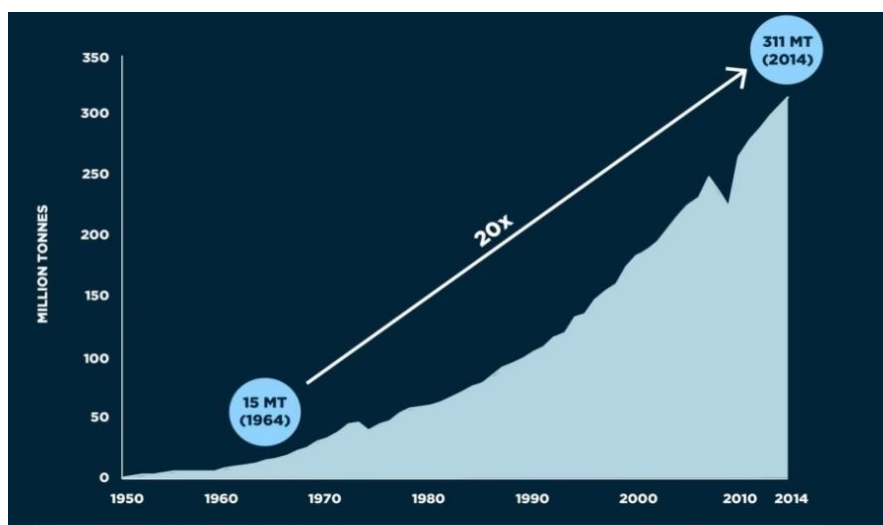
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## 2.1. General

This chapter involves brief discussions related to present scenario of generation, management and legislation related to plastic waste and its detrimental effects. Chapter 2 also gives insight about the demand of natural aggregates and effects of unsustainable extraction of it on the environment as well as society. Alongside those, available literatures directly and indirectly related to this research work have been summarized here. This chapter also deals with the different costs and a review of different methods to estimate the different types of costs.

## 2.2. Present Scenario of Generation of Plastic Waste

Plastic products have become a big part of our daily life due to their wide range of applications. Commercial production of plastics has started around 1950's [Lebreton and Andrady, 2019] and since then an exceptional growth all over the world has been seen. Plastic production has increased tremendously in past 50 years. Globally, plastic consumption was 279 million ton in 2011, which has been increased up-to 367 million ton in 2020 [Plastics Europe, 2021]. The consumption of plastic is increasing worldwide at an alarming rate of 4% per year [Miandad et al., 2016] and with the present rate of growth, it is estimated to be doubled within the next 20 years. The exponential growth of global plastic production is shown in Figure 2.1.



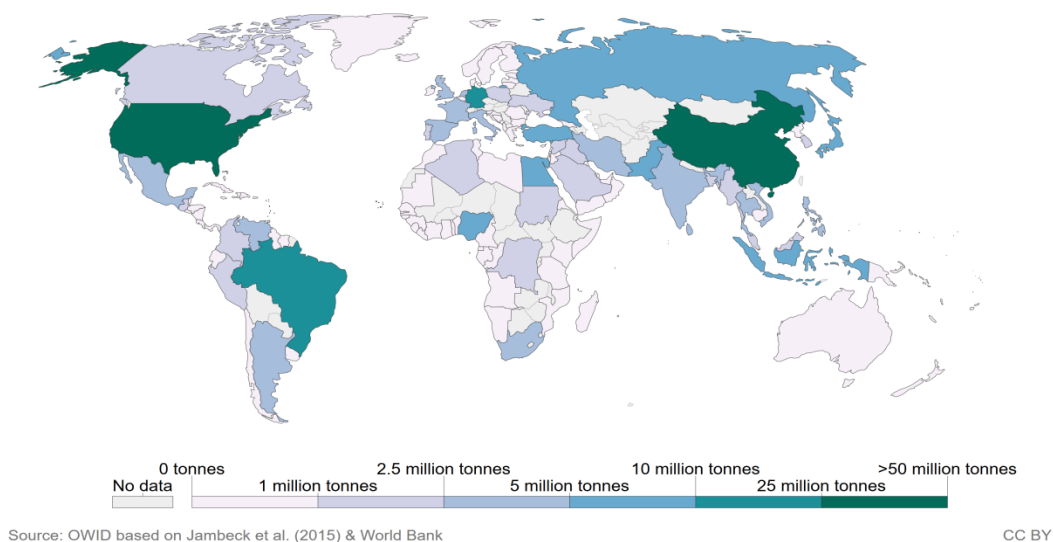
*Figure 2.1: Global plastic production* [World Economic Forum, 2016]

Plastics are generally broadly divided into 7 categories [Plastics for change, 2021]:

1. PET (Polyethylene Terephthalate)
2. HDPE (High-Density Polyethylene)
3. PVC (Polyvinyl Chloride)
4. LDPE (Low-Density Polyethylene)
5. PP (Polypropylene)
6. PS (Polystyrene)
7. Other

Out of the above mentioned types, PET and PE (HDPE and LDPE) are mostly used mainly for packaging purposes. Even though recycling rates are relatively higher in case of PET and HDPE, scenario of mismanagement of single used plastics (mostly LDPE) is very severe as recycling of this type of plastic is extremely challenging.

China is among the largest plastic products consumers accounting for 20% of the global plastic consumption and followed by Western Europe with 18% and then United States of America [Tsakona et al., 2020]. The approximate production of plastic by country is given in Figure 2.2.



**Figure 2.2: Plastic production by country [Lai, 2022]**

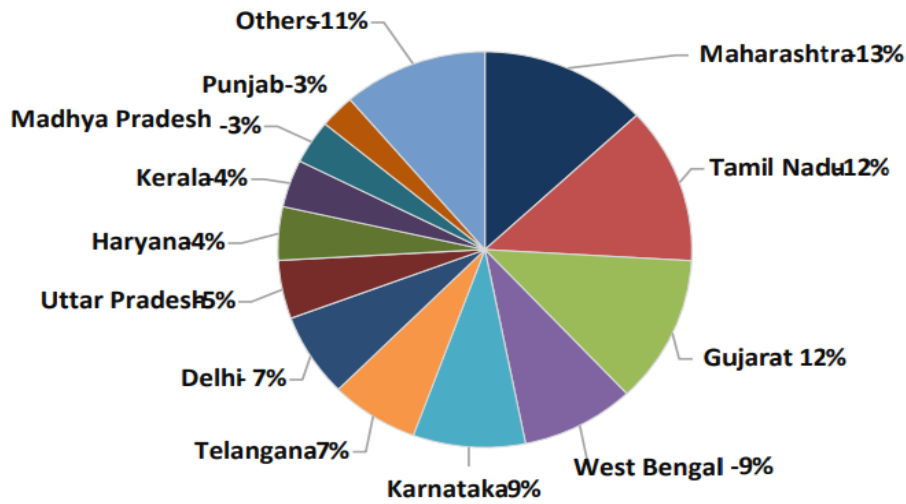
According to an annual report by CPCB (2020), China leads the table of annual generation of plastic waste, while India is the fifth highest generator among the world. Quantity of plastic waste generation by different countries is given in Table 2.1 [CPCB, 2020].

**Table 2.1: Plastic waste generation in different countries [CPCB, 2020]**

<b>Countries</b>	<b>Plastic Waste (MT)</b>	<b>Reference Year</b>
China	61	2016
US	34.5	2015
Indonesia	9.6	2018
Japan	8.9	2018
India	3.5	2020
Canada	3.2	2016
Australia	2.5	2016
Sweden	1.6	2016
UK	1.5	2016
Israel	0.9	2018
Switzerland	0.78	2019
Denmark	0.35	2017
Zimbabwe	0.3	2019

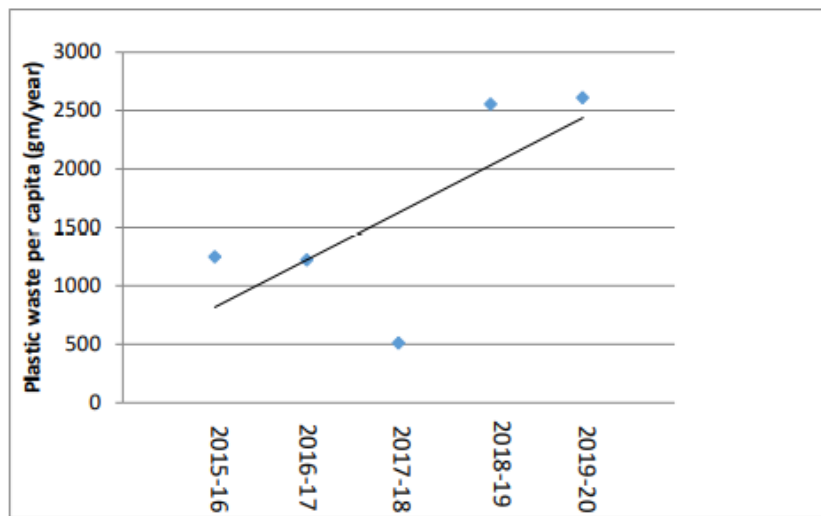
The Indian plastic industry has expanded at a Compound Annual Growth Rate (CAGR) of 10% in volume, from 8.3 million ton per annum (MTPA) in the year 2010 to 13.4 MTPA in 2015. The major application of plastic can be seen in packaging sector followed by construction, electronics and transportation sectors [FICCI, 2014].

With generation, consumption of plastics in India has shown a significant increase too and subsequently the quantity of plastic waste has increased. The estimated plastic waste generation during the year 2019-20 was approximately 34,69,780 ton per annum (TPA). From Figure 2.3, where state wise plastic waste generation is presented, it can be seen that the maximum quantity of plastic waste was generated in Maharashtra followed by Tamil Nadu and Punjab. West Bengal was also one of the high plastic waste generated states with contribution of around 9% of total [CPCB, 2020].



**Figure 2.3: State/UT wise plastic waste generation [CPCB, 2020]**

It has been observed that the per capita plastic waste generation for India had doubled over the period of 5 years between 2015 and 2019 (Figure 2.4) [CPCB, 2020]. While at the year of 2015-16 it was around 1.25 Kg/year, later in 2019-20 it became more than 2.5 Kg/year.



**Figure 2.4: Per capita plastic waste generation in India [CPCB, 2020]**

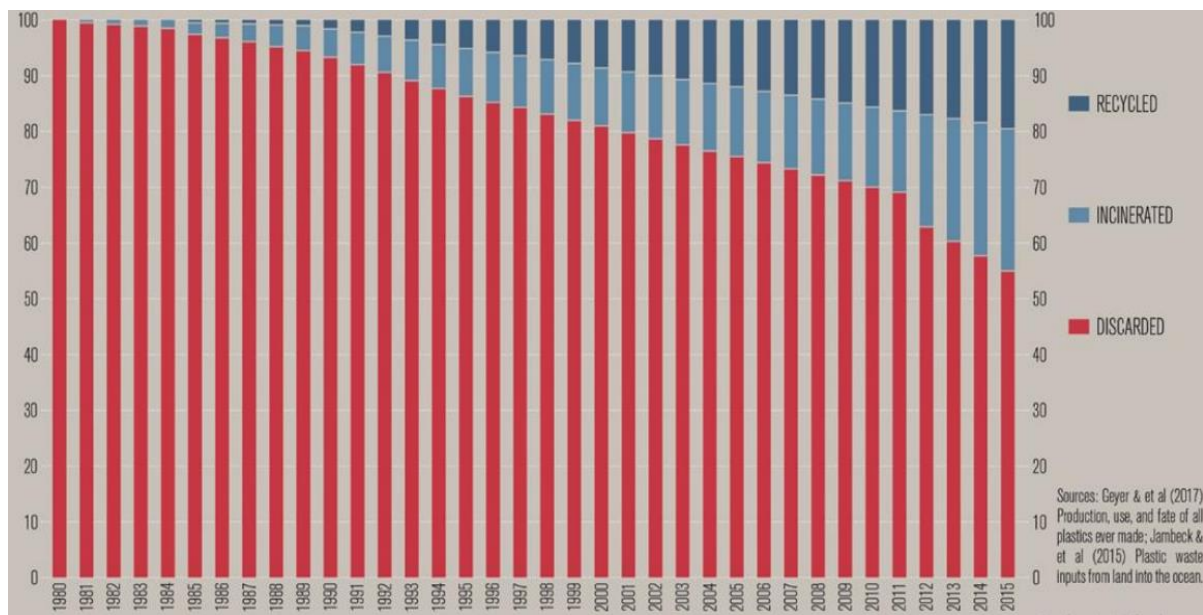
Goa, Delhi and Kerala have reported the highest per capita plastic waste generation while Nagaland, Sikkim and Tripura have reported the lowest. Between all the metropolitan cities of India, Delhi holds the first place in terms of daily generation of plastic waste with 689.8 ton followed by Kolkata and Chennai with 429.5 ton per day (TPD) and 429.4 TPD respectively [Agarwal, 2022].

With this high amount of generation of plastic waste and further increase of the rate of generation every year, plastic waste management is becoming a more and more severe issue globally.

### 2.3. Present Management System of Plastic Waste

Between 1950 and 2015, 8.3 billion ton of plastic that have been introduced in the market globally, a total of 5.8 billion ton turned into waste. Of that, 12% has been incinerated, 9% recycled, and around 60% discharged in landfills or in the environment [Tsakona et al., 2020].

Earlier, between 1950 and 1980, disposal in landfills or in the environment and open burning were the go to practices to treat plastic waste. Later in the 80's, recycling and incineration were introduced as alternative treatment methods. Since then, these two methods of treatment have become more popular and at present, recycling and incineration of plastic waste has reached respectively 19%, and 25%. Still, the rest 56% of plastic is disposed in landfills or escapes into the environment as shown in Figure 2.5 [Tsakona et al., 2020].

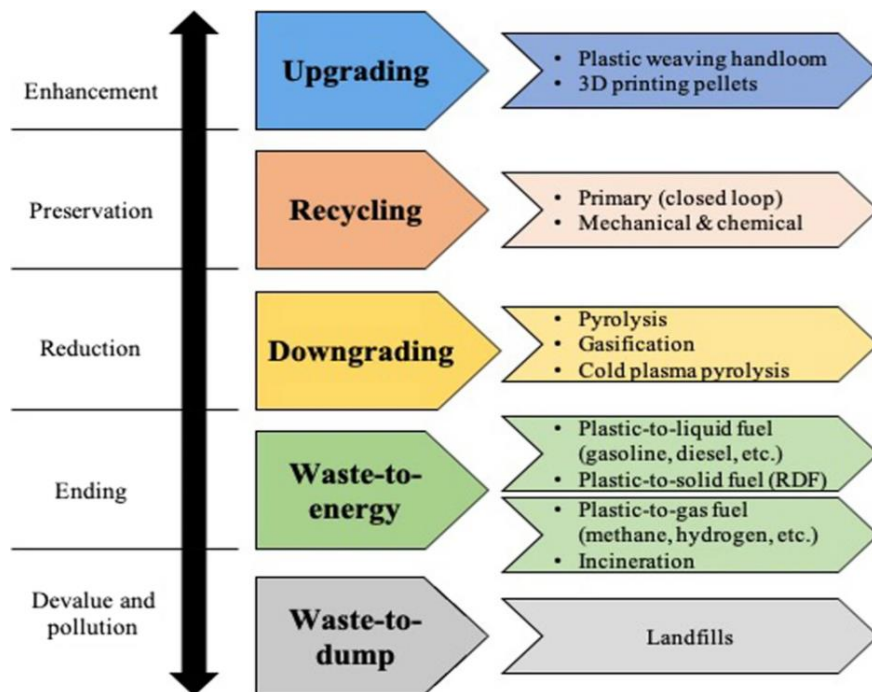


**Figure 2.5: Estimated percentage of managed global plastic waste: recycled, incinerated and discarded (1980-2015) [Tsakona et al., 2020]**

In India, around 9.4 MTPA of plastic waste was generated in the year 2016-17, out of which nearly 5.6 MTPA plastic waste was recycled while the rest 3.8 MTPA of plastic wastes remained uncollected or littered [Mohanty, 2018]. Out of 60% plastics recycled, 70% was

recycled at the registered facilities, 20% was recycled by the informal sector whereas the remaining 10% of the plastic waste was domestically recycled. The recycling statistics for India shows almost 40% higher as compared to the global average of 20%, yet there is a lack of proper guidelines for efficient plastic waste management [Rafey and Siddiqui, 2021]. Also, recycled products are more harmful to the environment as this contains additives and colours. The recycling of a plastic material can be done 2-3 times only, because after every recycling, the plastic material deteriorates due to thermal pressure and its life span is reduced [MoHUA, 2019]. Hence, recycling cannot be the most sustainable solution for plastic waste disposal.

Other than recycling, there are some other processing options too like pyrolysis, gasification, refused derived fuel etc. which are shown in Figure 2.6 according to their preference.



*Figure 2.6: Different processing pathways for plastic waste* [Shanker et al., 2023]

The management of such a large quantity of plastic waste in India was achieved through 4,773 registered plastic manufacturing/recycling units including 7 compostable plants and 1,084 unregistered plastic manufacturing/recycling industries [CPCB, 2019].

#### **2.4. Adverse Environmental Effects of Plastic Pollution**

Excessive usage and mismanagement of plastic has shown various negative effects on the environment. Some of the major adverse effects of plastic pollution are-

### **2.4.1. Ground Water and Soil Pollution**

Plastic is a type of material which does not bio-degrade due its chemical composition and remain in the soil for many years. When buried in a landfill, toxic chemicals and plastic additives such as stabilizers, harmful colorant moieties, plasticizers and heavy metals can leach and seep into groundwater, flowing downstream into lakes and rivers, thereby causing soil and water contamination.

Also in agricultural fields, presence of plastic causes reduction in water percolation and normal agricultural soils aeration and thus resulted in reduced productivity of the land.

### **2.4.2. Pollution in Oceans**

The last sink of plastic garbage is the oceans. In 2012, around 165 million ton of plastic waste was estimated to be present in the oceans with about 5 trillion plastic pieces floating on the ocean, while on an average 8 million ton of new plastics are still released into the oceans annually [Alabi et al., 2019]. These plastics in ocean get partially degraded within a year and during this process toxic chemicals get released into the water causing pollution.

Among all over the continents, Asia is the world leader in terms of plastic pollution in oceans. Philippines alone dumped over 1 billion pounds of plastic in the oceans. With this rate, in 30 years, there is likely to be more plastic in the oceans than fish [MoHUA, 2019].

As plastics travel with ocean currents, an island of trash called the “Great Pacific Garbage Patch” has been created. There are now many islands of trash within the seas. Figure 2.7 presents one of such islands.



*Figure 2.7: Great pacific garbage patch* [Bellini and Urso, 2022]

In mid-oceans, these plastic bags look like fish prey. When fishes, turtles, mammals and other sea animals try to eat these plastics, they end up getting choked. Also the plastics get accumulated in their gut, causing blockage of stomach, digestive tracks and damage the organs, sometimes lead to death. Over 600 marine species are affected by plastics. Nearly 45000 marine animals have ingested plastics, of which 80% were injured or killed [MoHUA, 2019]. The effects of plastic waste on the marine animals are given below in Table 2.2 [Worm, et al., 2017].

**Table 2.2: Effects of plastic wastes on sea animals** [Worm, et al., 2017]

Species	Species variant	Plastic type	Effects
Sea Bird	Greater Shearwater	Plastic bottle cap	Starvation due to gastrointestinal obstruction
	Magellanic penguin	Fragments, line and straws	Stomach perforation
Sea Turtles	Green sea turtles	Plastic bags and other debris	Impediment of hatchling movement towards the sea, exposure to predators
	Leatherback turtle	Plastic bags and debris	Blocked and injures cloaca, impedes laying of eggs
Fish	Bigeye tuna	Fragment line	Ingestion of plastic fragments
	Japanese medaka	Particulate plastic	Hepatic stress from exposure to plastic pollutant
	Orchid dottyback	Plastic bags	Leached nonophenol additives caused mortality
	Larva Perch	Micro-plastic particles	Inhibited hatching, decreased growth rate and altered behaviour
Mammals	Fur seal	Plastic particles	Bioaccumulation of particulate plastic from prey fish
	Sperm Whale	Plastic bags and debris	Stomach rupture and starvation
	Australian Sea lion	Plastic fishing gear	Entanglement caused mortality
Invertebrates	Urchin larva	Polyethylene pellets	Plastic leachates caused abdominal development

Species	Species variant	Plastic type	Effects
	Mussels	Micro-plastic particles	Accumulation of micro-plastic in circulatory system
	Oyster	Micro-plastic particles	Interference with energy uptake and reproduction
	Norway lobster	Plastic strands and particles	Ingestion and accumulation of plastics in the gut

India was estimated to release 0.09–0.24 MTPA litter into the marine environment and was ranked as the 12th largest contributor of plastic wastes to the ocean. In the year 2015, 0.12 million ton plastics lead into the ocean from river Ganges, caused damages to the marine ecosystem [Rafey and Siddiqui, 2021].

### 2.4.3. Air Pollution

During the degradation of plastic, carbon dioxide and methane gas are generated and released into the air from landfill, causing air pollution. During the decomposition of solid waste in landfills in 2008, an estimated equivalent volume of 20 million ton of carbon dioxide was released into the atmosphere [Alabi et al., 2019].

Also, open burning of plastic products releases pollutants such as heavy metals, dioxins, furrans, Polychlorinated Biphenyls (PCBs) etc. which cause severe health problems like cancer, endometriosis, neurological damage, endocrine disruption, birth defects and child developmental disorders, reproductive damage, immune damage, asthma, and multiple organ damage when inhaled.

Not only open burning, during incineration of plastic waste, toxic compounds are generated too which eventually go into the atmosphere and create health hazards in many different ways as shown in Table 2.3 [Nagy and Kuti, 2016].

**Table 2.3: Compounds generated during incineration of plastic waste and their harmful effects** [Nagy and Kutu, 2016]

Compound	Health effect(s)
Acetaldehyde	It damages the nervous system, causing lesions.
Acetone	Irritates the eyes, the respiratory tract.

<b>Compound</b>	<b>Health effect(s)</b>
Benzaldehyde	Irritates the eyes, skin, respiratory system, limits brain function.
Benzole	Carcinogenic, adversely effects the bone marrow, the liver, the immune system.
Formaldehyde	Serious eye damage, carcinogenic, may cause pulmonary oedema.
Phosgene	Gas used in the World War I. Corrosive to the eyes, skin and respiratory organs.
Polychlorinated dibenzo-dioxin	Carcinogenic, irritates the skin, eyes and respiratory system. It damages the circulatory, digestive and nervous system, liver, bone marrow.
Polychlorinated dibenzofuran	Irritates the eyes and the respiratory system, causes asthma.
Hydrochloric acid	Corrosive to the eyes, the skin and the respiratory tract.
Salicyl-aldehyde	Irritates the eyes, the skin and the respiratory tract. It can also affect the central nervous system.
Toluene	Irritates the eyes and the respiratory tract, can cause depression.
Xylene	Irritates the eyes. It can also affect the central nervous system, reduces the level of consciousness and impairs learning ability.
Propylene	Damages the central nervous system by lowering of consciousness.
Vinyl chloride	Carcinogenic, irritating to eyes, skin and respiratory system. Effect on the central nervous system, liver, spleen, blood-forming organs.

Other than these major issues, plastic waste can create nuisance in several other ways like sewage system blockage in towns and cities especially in developing countries, reducing productivity of agricultural lands, creating conducive environment for breeding mosquitoes and other disease causing vectors, environmental natural beauty deterioration, production of foul smells etc. So the primary goal should be to reduction of plastic waste as well as finding different plastic waste management options with less adverse effects to the environment.

## **2.5. Rules and Regulations Related to Plastic Waste Management (PWM)**

Every country has their own rules and regulations regarding management of plastic waste, so does India. Amidst the increase of generation and consumption of plastics, management of plastic got attention when the Bureau of Indian Standards (BIS) published Indian Standard

codes in the year 1992 for testing of plastics. After that, several IS codes listing guidelines about plastics identification, labelling, design, etc., were notified and are amended from time to time. Legislations for PWM in India were framed in 1999 for packaging of food products in recycled plastics which got amended in the year 2003. Later, Plastic Waste (Management and Handling) Rules were notified in 2011 by Ministry of Environment, Forest and Climate Change (MoEFCC), which were superseded by PWM Rules in 2016.

The major aims of Plastic Waste Management Rules, 2016 were [Vikaspedia, 2021]-

- Increase the minimum thickness of plastic carry bags from 40 to 50 microns.
- Expand the jurisdiction of applicability from the municipal area to rural areas.
- To introduce a collection of plastic waste management fees through pre-registration of the producers, importers of plastic carry bags/multi-layered packaging, and vendors.
- To promote the use of plastic waste for road construction as per Indian Road Congress guidelines or energy recovery, or waste to oil, etc.

PWM Rules, 2016 were also amended in 2018 with special emphasis on single-use plastics, and then again twice in 2021 and once in 2022. A chronological outline of important PWM legislations of India is presented in Table 2.4 [Rafey and Siddiqui, 2021].

**Table 2.4: Chronological outline of important PWM legislations in India**

<b>Year</b>	<b>Legislation/Guidelines</b>	<b>Contents</b>	<b>Issuing Authority</b>
1992	IS 13360–1992 Part 1–15	Different methods for testing plastics.	BIS
1998	IS 14534:1998	Guidelines to the manufacturers giving information about pattern to be made on final product in order to simplify identification of the basic raw material to ensure proper recognition of the material used in the end product	BIS
1998	IS 14535:1998	Guidelines for classification of recycled plastics material based on their properties and applications	BIS

<b>Year</b>	<b>Legislation/Guidelines</b>	<b>Contents</b>	<b>Issuing Authority</b>
1999	Recycled Plastics (Manufacture & Usage) Rules	Regulation for controlling the packaging of food products in recycled plastics	MoEFCC
1999	IS 10171:1999	Regulation for the food packer to select the specific thermoplastic material for designing adequate food packaging system	BIS
2001	IS 2828:2001	Code for defining the terms used in plastic industry	BIS
2003	Recycled Plastics Manufacture & Usage (Amendment) Rules	<ul style="list-style-type: none"> <li>• Regulation on the production, sale, usage and recycling of plastic bags</li> <li>• Mandates the minimum thickness of plastic carry bag to be 20 microns</li> </ul>	MoEFCC
2008	IS 17088:2008	Code listing the procedure for identification and labelling of plastics that are suitable for recovery via aerobic composting	BIS
2011	Plastic Waste (Management and Handling) Rules	<ul style="list-style-type: none"> <li>• Standard for management of plastic waste generated</li> <li>• Specifies thickness of plastic carry bag to be 40 microns</li> </ul>	MoEFCC
2014	IS 9833:2014	Provides a list of pigments and colourants accepted for food grade plastics	BIS
2016	Plastic Waste Management Rules	<ul style="list-style-type: none"> <li>• Plastic sheet or multi-layered packaging thickness should not be less than 50 microns</li> <li>• Producer having invalid or no registration from concerned Pollution Control Board, the manufacturer should not sell or</li> </ul>	MoEFCC

<b>Year</b>	<b>Legislation/Guidelines</b>	<b>Contents</b>	<b>Issuing Authority</b>
		provide plastic to be used as raw material to a producer <ul style="list-style-type: none"> <li>• Rules pertaining to thickness is not applicable to carry bags made up of compostable plastic and conforms to the Indian Standard (IS 17088:2008)</li> </ul>	
2018	Plastic Waste Management (Amendment) Rules	Substitution of ‘multi-layered plastics which are non-recyclable or non-energy recoverable or with no alternate use’ in place of ‘non-recyclable multi-layered plastics’	MoEFCC
Aug, 2021	Plastic Waste Management (Amendment) Rules	Prohibition of identified single-use plastic items having low utility and high littering potentials	MoEFCC
Sep, 2021	Plastic Waste Management (Second Amendment) Rules	Implementation of recycled plastics for storing, carrying, dispensing, or packaging	MoEFCC
2022	Plastic Waste Management (Amendment) Rules	Phasing out of certain single-use plastic products and mandate to increase the thickness of plastic carry bags to over 120 microns	MoEFCC

Despite the implementation of several guidelines and legislations in India, out of 9.46 MTPA of plastic waste generated, about 3.78 MTPA (40% by weight) are mismanaged [Rafey and Siddiqui, 2021]. Hence, there is a need of more stringent rules and regulation for plastic waste management.

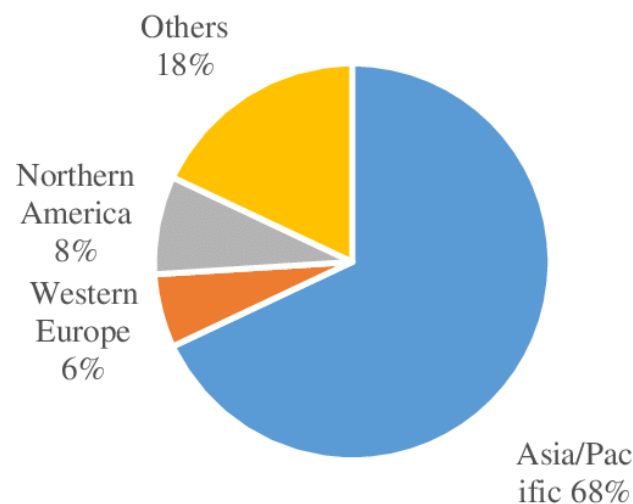
## **2.6. Present Scenario of Concrete, Aggregate and Water Demand**

In today’s world, urbanization and non-sustainable development has created a significant and increasing demand for construction materials. Concrete is one of the most common building materials used in the construction and infrastructure industries with a roughly estimated

global annual production of 25 billion ton in 2009, which means over 3.8 ton per person each year all over the world [Rouch, 2022]. The demand for concrete has rapidly increased in the last 50 years as a result of the population growth, which led to increase the need to implement residential and infrastructures projects, and it is still increasing to date.

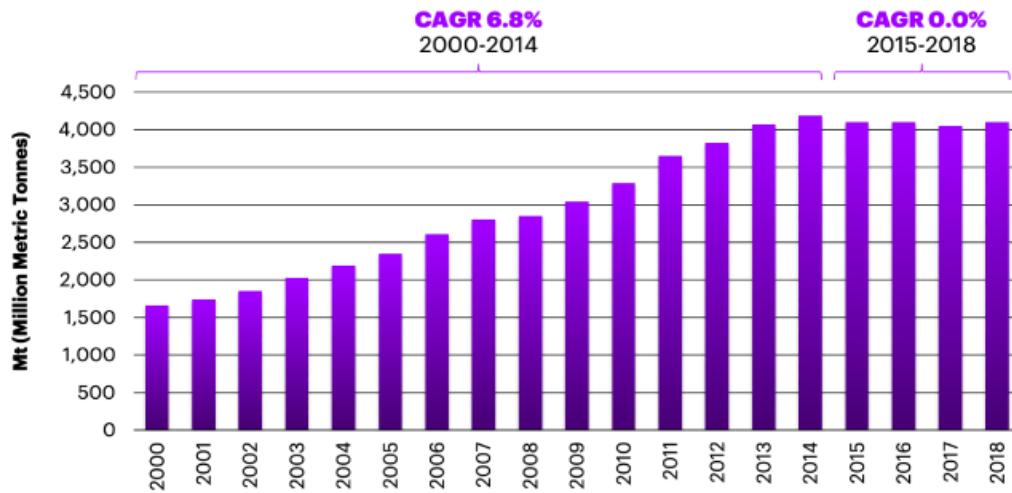
The development of concrete relies on aggregates sourced from natural rock, fossil deposits and river beds. Aggregates typically occupy 55 –80% of the volume of concrete [Alqahtani et al., 2021]. This constant increase of demand for concrete leads to the increase of the demand for the construction raw materials, especially the aggregates. Global consumption of these natural resources for use in concrete production was estimated to 48.3 billion metric ton in 2015 and it annually increases by about 5% [Mohammed and Najim, 2020].

These natural aggregates are neither unlimited, nor renewable resource and these are constantly depleting. With consideration of this clear increase in aggregate consumption, natural aggregate will no longer be able to meet the needs of construction industry in some counties in terms of both quantity and quality in future. The highest consumption was found to be in Asia and Pacific as shown in the Figure 2.8. This challenge will be further amplified in regions that already have depleted stocks of natural aggregates (e.g. China and India) as well as in countries where near-urban sources of quarry materials are rapidly depleting (e.g. Australia) [Gravina et al., 2021].



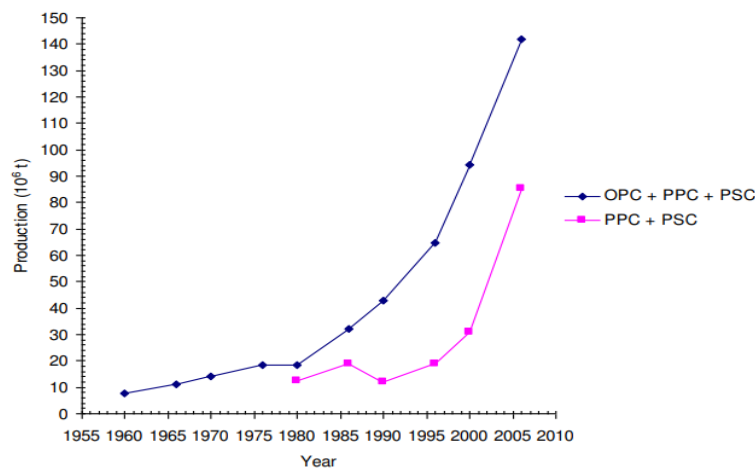
**Figure 2.8: Worldwide demand for construction aggregates (2015)** [Kamaruddin et al., 2020]

Another important constituent of concrete is cement, the binding material. The global production of cement has increased substantially since 2000 and reached 4100 million ton by 2019 [Rouch, 2022], which is further testimony to the increasing demand of concrete. The year wise global cement production starting from 2000 is given in Figure 2.9.



**Figure 2.9: Global cement production (2000-2018)** [Bjacek, 2019]

Again, the major cement producing global region is Asia and Pacific, primarily due to high production in China and India. India is the second largest cement producer worldwide with over 7% of the global installed capacity. According to IBEF (2022), India’s overall cement production accounted for 294.4 MT in 2019 and 329 MT in 2020. It is further increased by 7.8% in 2021 and expected to reach 419.92 MT by 2027. Figure 2.10 shows the trend of cement production in India.



**Figure 2.10: Trend of cement production in India (1956-2006)** [Bapat et al., 2007]

In addition, the impact of booming concrete production on worldwide water resources has been noticed too. According to Miller and Moore (2018), concrete production was responsible for 9% of global industrial water withdrawals in 2012, which is 1.7% of total global water withdrawal. Also, in 2050, 75% of the water demand for concrete production will likely to occur at predicted water stressed regions.

## **2.7. Adverse Environmental Effects of Extraction of Natural Aggregates**

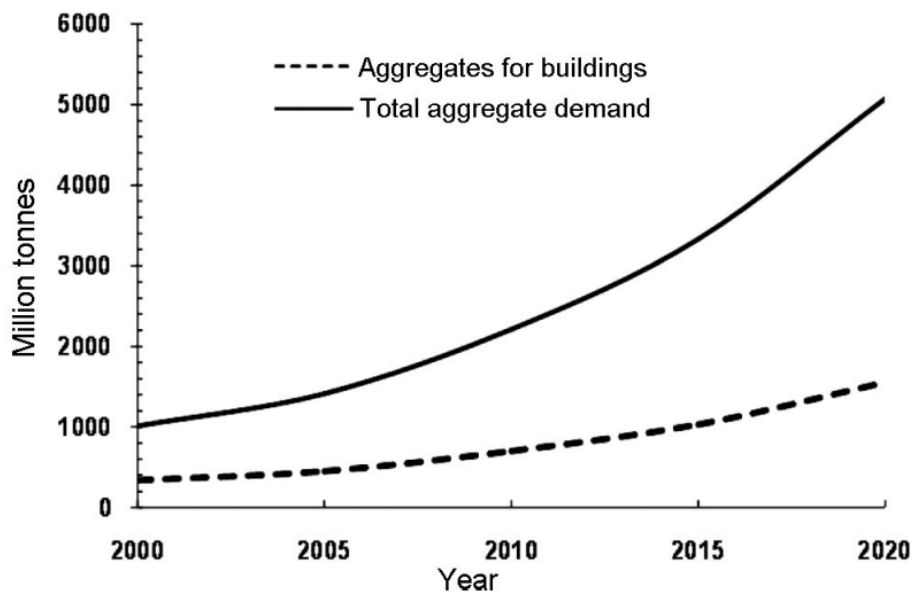
Human history has always been closely linked to the control, extraction and use of natural resources. Natural aggregate resources such as sand, gravel, and crushed stone rank first in order of amount and value of the global extracted mineral resources. Nearly every community, whether industrialized or agrarian, is dependent on aggregate resources to build and maintain their infrastructure. Over the past decades, however, the demand for natural resources has increased so much that it is now widely considered as a serious threat to our economic and social equilibrium. It has been estimated that globally each year, between 32 and 50 billion ton of aggregate (sand and gravel) are extracted [Steinberger et al., 2010]. The extraction of raw natural aggregate is presented in Figure 2.11.



*Figure 2.11: Extraction of natural aggregate* [Greenspec, 2023]

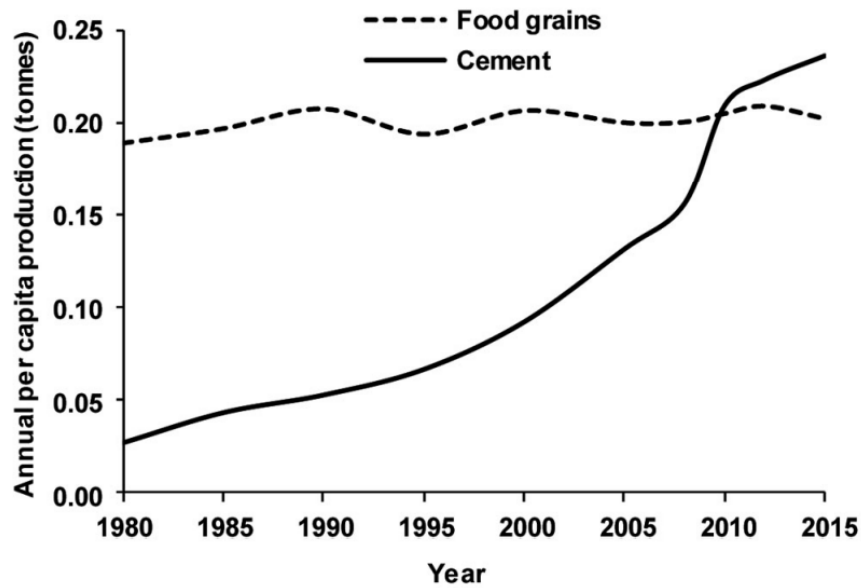
Aggregates are used for the construction of buildings as well as roads and other infrastructural projects. Total demand for aggregates in India is projected at slightly more than 5 billion ton [Reddy et al., 2016]. Figure 2.12 presents a graph showing the demand of total aggregates and the demand of aggregates for the purpose of building construction in India for the year 2000-2020. India is currently facing a severe shortage of aggregates. Mere

crushing of existing rock resources to generate aggregates leading towards serious ecological and environmental problems.



*Figure 2.12: Demand for aggregates in India* [Reddy et al., 2016]

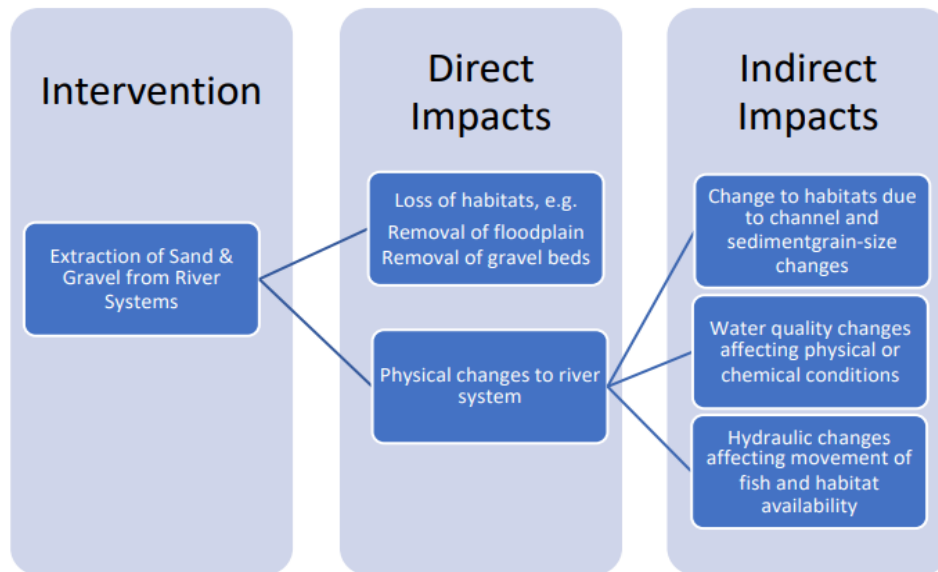
Construction materials are manufactured from mined resources and hence the challenge of shortage of natural resources was inevitable. Annual per capita consumption of construction materials is estimated at 1.8 and 3.6 ton in India and the world respectively. Aggregates constitute about 60% of the total materials consumed. So, in India per capita annual consumption of aggregates is about 1 ton in contrast to about 0.20 ton food grains consumption. The per capita food grain production remains nearly constant, whereas per capita cement production is growing at an exponential rate since the last three decades. The trends of food grains and cement production of India is shown in Figure 2.13. Also the consumption of cement has grown by leaps and bounds since the last three decades. A ton of cement requires 5–6 ton of aggregates. Meeting the demand for construction materials using only mined resource from the earth is posing serious environmental concerns and resulting in scarcity of natural raw materials [Reddy et al., 2016].



**Figure 2.13: Food grain and cement production in India** [Reddy et al., 2016]

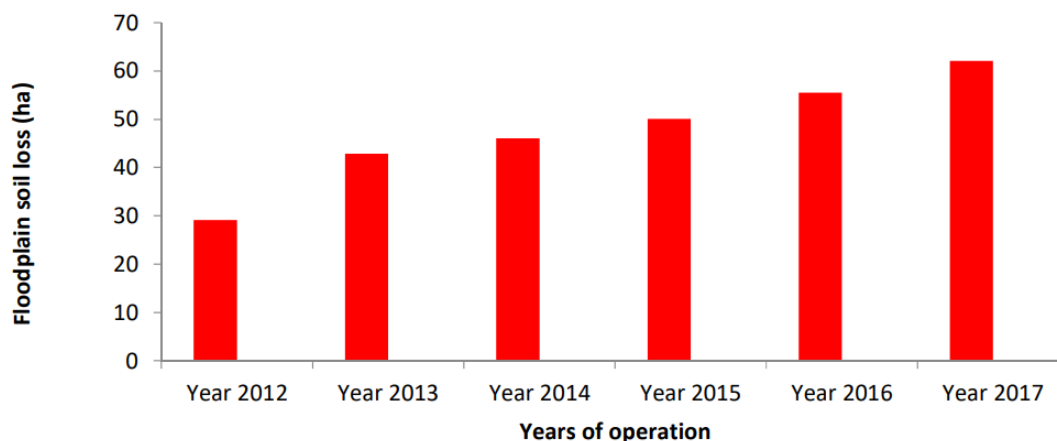
The potential environmental impacts in general associated with the aggregate extraction are the conversion of land use, changes to the landscape, loss of habitat, noise, dust, blasting effects, erosion, sedimentation etc. Most of the environmental impacts associated with aggregate mining are relatively benign. However, extracting aggregate from some areas may alter the geologic conditions, which, in turn, may alter the dynamic equilibrium of the area, resulting in cascading environmental impacts.

Sand mining is another big challenge from the environmental perspective. Demand of sand is very high in the construction sector. By 2020, 1.4 billion ton of sand was projected to be required in India only and rivers are the preferred source [Parasjoshe, 2022]. Excessive sand mining can alter the river bed, force the river to change course, erode banks and lead to flooding. It also destroys the habitat of aquatic animals and micro-organisms besides affecting groundwater recharge [Moudgil, 2018]. The direct and indirect impacts of extraction of sand and gravel from river ecosystem are shown in Figure 2.14.



**Figure 2.14: Impacts of extraction of sand and gravel from river ecosystem** [Koehnken and Rintoul, 2018]

In addition, extracting natural aggregates from flood plains resulted in a 112.9% of increase in land loss comparing to 2012. Between the years 2012 and 2017, 285.78 hectare floodplain land was lost due to aggregate extraction from the floodplains [Udom, 2018]. Figure 2.15 shows the trend of loss of land in flood plains due to the extraction of natural aggregates for the year 2012-2017.



**Figure 2.15: Land loss in flood plains** [Udom, 2018]

Apart from the direct effects, there are some indirect impacts too which have to be considered, such as the energy that is expended for converting the raw materials into useful construction products is significantly high. In addition, aggregate is a low-unit value, high bulk commodity. Consequently, excavation of aggregate near the point of use, which is

commonly at population centres, is most economical. But in these areas, conflicting land use, regulations, and citizen opposition further restrict the development of aggregate resources. In these cases, the construction materials and products are hauled over long distances which will further impact on the economic viability as well as consumption of fuel energy. Hence, finding a replacement of natural aggregates to use in construction centre is very much essential.

## 2.8. Existing Literatures on Use of Plastic in Concrete

One way to encounter the global issues of plastic waste management and excessive extraction of natural aggregates simultaneously is to use waste plastic based aggregates as partial replacement of natural aggregates in concrete. Some research works has already been done on this strategy and more research are still going on. Few notable research works along with its findings are given in Table 2.5.

*Table 2.5: Existing literature related to use of plastic in concrete*

Author	Year	Test	Result & conclusion
Sau, D. et al.	2023a	Test of M30 grade concrete properties using PE type plastic waste as replacement for natural aggregates in proportion of 5% to 40%.	<ul style="list-style-type: none"> <li>• Compressive strength decreases with an increase in PE aggregate</li> <li>• Split tensile strength of concrete increases for 5%–10% replacement</li> <li>• Acceptable for structural purposes up to 30% volumetric substitution</li> </ul>
Sau, D. et al.	2023b	Test of e mechanical and durability properties of concrete made up of PE and PET based aggregates as replacement for natural coarse and fine aggregates separately and simultaneously in proportion of 10, 20, 30 and 40%	<ul style="list-style-type: none"> <li>• Compressive strength reduces but permissible up to 30% of replacement</li> <li>• Significant increase in impact resistance</li> <li>• Alkaline, marine, and municipal wastewater do not show any adverse effect</li> </ul>

<b>Author</b>	<b>Year</b>	<b>Test</b>	<b>Result &amp; conclusion</b>
Shiuly, A. et al.	2022	Test of fresh and hardened properties of M20 and M25 grade concrete after volumetric substitution of natural coarse and fine aggregates by PE and PET based aggregates in proportion of 5% to 40%.	<ul style="list-style-type: none"> <li>• Significant increase in workability</li> <li>• Decrease in fresh and dry density of concrete composites</li> <li>• Can be used in the concrete production up-to certain replacement levels without compromising the mechanical properties</li> </ul>
Elango, A. and Kumar, A. A.	2018	Test of mechanical and durability properties on concrete samples using OPC 53, river sand, crushed aggregates and plastic in place of fine aggregates in proportion of 10%, 20% and 30%.	<ul style="list-style-type: none"> <li>• Decrease in strength of concrete but good results against acid attacks and increase in elasticity.</li> <li>• Can be used in places where the need is less compressive strength but more durability.</li> </ul>
Jaivignesh, B. and Sofi, A.	2017	Test of properties of concrete using plastic place of fine aggregates as well as coarse aggregates in proportion of 10%, 15 % and 20%, adding still fibre to the concrete.	Reduction in strength but can be used in favour of reduction of waste material.
Tamang, L. W. et al.	2017	Test of mechanical properties of concrete using plastic aggregates in proportion of 10%, 15%, and 20% in place of coarse aggregate.	<ul style="list-style-type: none"> <li>• Marginal reduction in strength.</li> <li>• The optimum result at 15% replacement.</li> </ul>
Amalu, R. G. et al.	2016	Test on concrete after using plastic as substitute of fine aggregates in proportion of 10%, 15%, 20% and 25%.	<ul style="list-style-type: none"> <li>• Reduction in strength of concrete.</li> <li>• Can be used as non-structural concrete as it shows higher workability and reduce environmental waste.</li> </ul>

<b>Author</b>	<b>Year</b>	<b>Test</b>	<b>Result &amp; conclusion</b>
Hossain, M. B. et al.	2016	Test of concrete properties after replacing coarse aggregates in proportion of 5%, 10% and 20% by waste plastic.	<ul style="list-style-type: none"> <li>• Lighter in weight but compressive strength is lesser than that of conventional concrete.</li> <li>• Concrete with 10% plastic aggregates shows strength nearly similar to the conventional concrete.</li> </ul>
Jibrael, M. A. and Peter, F.	2016	Strength and behavioural test of concrete after replacing fine aggregates with plastic bottles and plastic bags in varying proportions from 0% to 5%.	Can be used for non-structural purposes as it reduces the strength.
Harini, B. and Ramana, K. V.	2015	Test of concrete after replacement of plastic waste and silica fume as fine aggregate and cement respectively in concrete mixes. The plastic waste is replaced in the percentage 5%, 6%, 8%, 10%, 15%, 20% by volume and silica fume 5%, 10%, 15% by weight in concrete.	<ul style="list-style-type: none"> <li>• The degree of workability is high in all the replacement levels.</li> <li>• All the replacement levels of plastic waste as fine aggregate show reduction in compressive strength.</li> <li>• The tensile strength increases with partial replacement of fine aggregate by plastic up to 6% replacement, after that there is decrement in tensile strength.</li> </ul>
Subramani, T. and Pugal, V. K.	2015	Test of concrete with 5%, 10% and 15% replacement of aggregates in concrete with plastic.	<ul style="list-style-type: none"> <li>• Optimum results at 10% replacement of aggregates with plastic.</li> <li>• Further increase in plastic content decreases the strength of concrete.</li> </ul>

<b>Author</b>	<b>Year</b>	<b>Test</b>	<b>Result &amp; conclusion</b>
Vanitha, S. et al.	2015	Test of 7, 14 and 28 days strength of paver blocks and solid blocks of size 200 mm x 150 mm x 60 mm and 200 mm x 100mm x 65 mm casted with M20 grade of concrete with addition of plastic to a proportion of 2%, 4%, 6%, 8% and 10% in equal replacement of aggregates.	The optimum result for paver block is 4% replacement of aggregates with plastic aggregates and 2% in case of solid blocks.
Osei, D. Y.	2014	Test on concrete after replacing the coarse aggregates in concrete of ratio 1:2:4 by 25%, 50%, 75% and 100% with plastic.	<ul style="list-style-type: none"> <li>• Reduction in strength of concrete as well as density of concrete.</li> <li>• Replacement of aggregates more than 36% is not suitable for structural concrete.</li> <li>• Plastic can be a medium for production of light weight concrete.</li> </ul>
Sarwe, K.	2014	Test of mechanical properties of concrete after replacing fine aggregate by plastic waste at 0.2%, 0.4%, 0.6%, 0.8% by weight of cement and incorporating 0.1%, 0.2%, 0.3% 0.4% and 0.5% steel fibres in concrete mixes.	<ul style="list-style-type: none"> <li>• Decrease in compressive strength whereas marginal reduction in slump.</li> <li>• Highest compressive strength with 0.6% of waste plastic and 0.3% of steel fibre.</li> </ul>
Mathew, P. et al.	2013	Test on structural concrete using recycled plastic as coarse aggregate.	<ul style="list-style-type: none"> <li>• The optimum result at 22% replacement of coarse aggregates with plastic aggregates.</li> <li>• Concrete with plastic aggregates is weaker in fire resistance.</li> </ul>

<b>Author</b>	<b>Year</b>	<b>Test</b>	<b>Result &amp; conclusion</b>
Raghatate, A. M.	2012	Test of properties of concrete using plastic bags in form of fibre in proportion of 0.2%, 0.4%, 0.6%, 0.8% and 1% by weight.	Reduction of compressive strength with increase in plastic content, but increase in tensile strength with optimum strength at 0.8% addition.
Rai, B. et al.	2012	Test of M30 grade of concrete using plastic pallets in proportion of 5%, 10% and 15% by weight with and without plasticizer.	<ul style="list-style-type: none"> <li>• Reduction in density that can help in achieving low density or light weight concrete.</li> <li>• Reduction in slump and hence affects the workability but addition of plasticizers resolves the problem.</li> <li>• Reduction in compressive and flexural strengths but it was very low and can be allowed.</li> </ul>
Saikia, N. and Brito J. D.	2012	Test on concrete and mortar after replacement of coarse and/or fine aggregate with varying proportions of plastics from different origins.	<ul style="list-style-type: none"> <li>• Workability decreases on use of angular plastic aggregates but increases with use of smooth aggregates.</li> <li>• Irrespective of type of plastic, there was reduction of compressive strength, but the reduction of flexural and tensile strength was low as compared to compressive strength.</li> </ul>

From the existing literatures of using plastic in concrete, following conclusions can be drawn-

- Specific density of concrete decreases significantly with increase of plastic aggregate replacement, therefore can be recommended as light weight concrete.

- Compressive strength of the concrete is acceptable up-to certain percentage of replacement for structural purpose, but decreases with increase in percentage of plastic.
- Tensile strength of the concrete increases with addition of plastic up-to a certain extent.
- Marginal reduction in flexural strength of the concrete occurs with addition of plastic.
- Workability of the concrete decreases with increase in percentage of plastic in case of using angular plastic aggregate but increases with smooth plastic aggregate, results in low consumption of water during concrete preparation.
- Impact resistance increases with increases of plastic aggregate replacement.
- Durability tests such as sorptivity test, permeability test, impact resistance test show that plastic aggregate based concrete can be used in places where the need is less compressive strength but more durability.
- Fire resistance is low compared to conventional concrete.

## 2.9. Existing Literatures on Cost Analysis of Plastic Based Concrete

Even though many studies have been done on the mechanical properties of concrete after introducing plastic aggregates in it, the number of literature available on the cost analysis of this strategy is very few. Some of them are studied and relevant findings are summarized in Table 2.6.

**Table 2.6: Existing literature on cost analysis of using plastic aggregate in concrete**

Author	Year	Analysis	Result and conclusion
Alqahtani, F. K. et al.	2021	Estimation of cost of 24 different cases of construction of a building having G+2, G+3 and G+10 number of floors with span length of 3, 4, 5 or 6 meters using natural aggregates and Linear low-density polyethylene (LLDPE) based aggregates.	<ul style="list-style-type: none"> <li>• The cost of the slab form work quantity needed for the LLDPE based concrete is 13-21% less than that needed for conventional concrete.</li> <li>• Structures with slab spans of around 4 and 5 m benefit the most from the use of LLDPE based</li> </ul>

Author	Year	Analysis	Result and conclusion
		<p>Construction cost, maintenance cost, operation cost and end of life cost are considered.</p>	<p>Polylactic Acid (PLA), while those with smaller slab spans of 3 m benefit the least financially.</p> <ul style="list-style-type: none"> <li>• Because the LLDPE based PLA is more expensive than natural aggregates, the life cycle costs are most sensitive to it.</li> <li>• As the discount rate increases, the LLDPE based PLA results in more savings in the life cycle cost.</li> </ul>
Islam, M. J. and Shahjalal, M.	2021	<p>Estimation of total cost and economy index of 1 cubic meter concrete production using plastic aggregate made up of polypropylene as replacement of coarse aggregate made up of natural stone and burnt clay brick along with fresh and harden properties of concrete.</p> <p>Only the manufacture cost of polypropylene aggregate (PPA) was considered since aggregate was made up of waste plastic.</p>	<ul style="list-style-type: none"> <li>• Concrete with 10 % PLA exhibits higher compressive strength, modulus of rupture, and splitting tensile strengths, even, higher than that of the control stone aggregate concrete (SAC) and control brick aggregate concrete (BAC).</li> <li>• Though the cost is relatively reduced with increasing the percentage of PPA into the concrete mix, results of the economy index suggest that concrete containing 10% PP content might be the optimum limit both for SAC and BAC.</li> </ul>
Habib, M. Z. et al.	2017	<p>Estimation of cost of concrete production using 15% waste plastic aggregate.</p>	<p>Production cost of concrete is too high but its advantage on the environmental issue is significant.</p>

Author	Year	Analysis	Result and conclusion
		Cost of waste plastic aggregates including processing cost is considered.	
Lasiyal, N. et al.	2016	<p>Estimation of cost for making 1 cubic meter of concrete replacing 1%, 2% and 3% of fine aggregate by PET bottle flakes.</p> <p>The waste bottles for this project have been provided free of cost by the disposable unit of Municipal Corporation of the city.</p>	<ul style="list-style-type: none"> <li>• Costs saving per cubic meter are 4.72, 9.45 and 14.17 respectively for 1%, 2% and 3% replacement.</li> <li>• Considering the both, cost savings and strength reduction, 2% replacement of fine aggregate gives lesser reduction in strength and gives adequate cost savings.</li> </ul>

The results from different studies are inconclusive and contradictory to each other. Hence, more research work on this field needs to be done before coming to a definite conclusion.

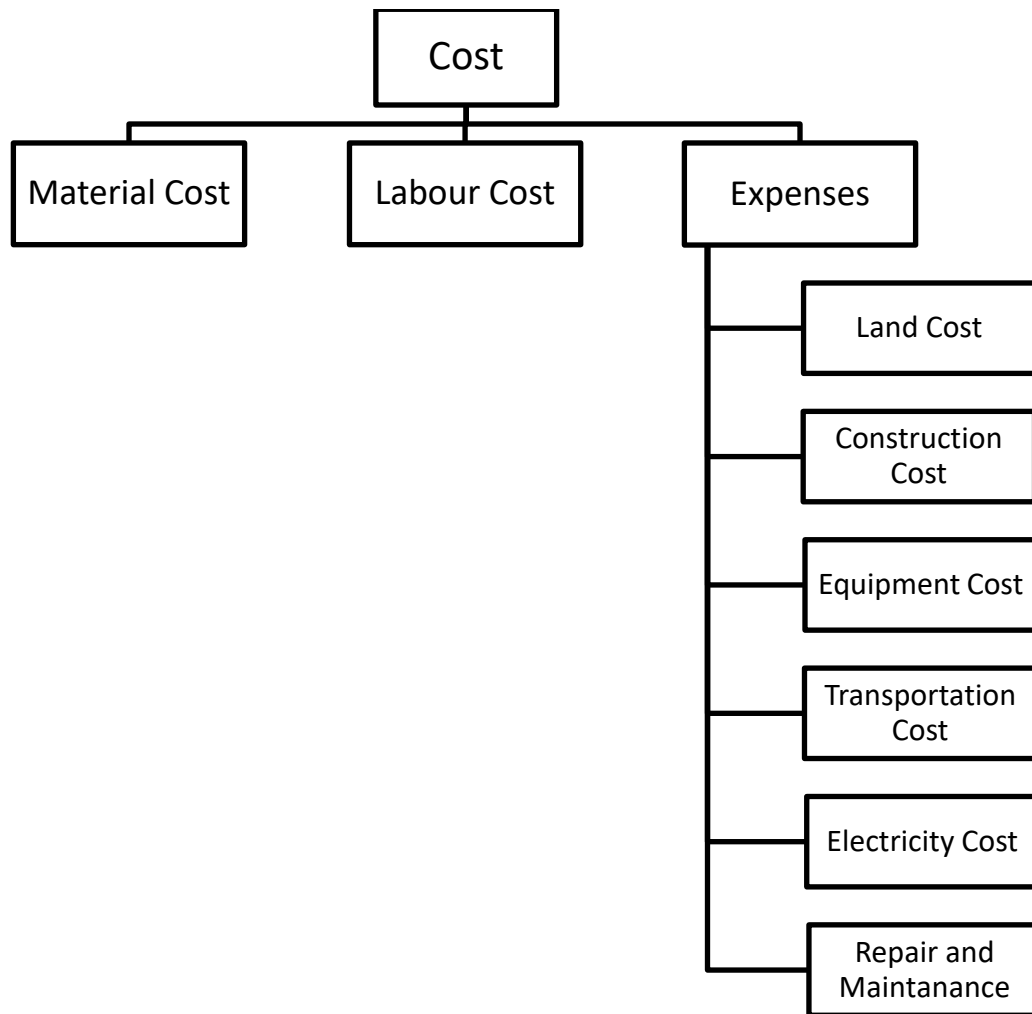
## 2.10. Classification of Costs

Money is one of the most, if not the most essential and important commodity of human life and human society. In the end everything comes down to money. So, it is very much important to calculate the costs and benefits of a project beforehand to make an assumption on the expenditure as well as identifying the opportunities to save and income some money.

Cost can be classified based on various factors. Classifications by two of those factors relevant to this study have been discussed here.

### 2.10.1. Classification by Nature

Based on the nature of the expenditure, cost can be classified into broadly three categories, namely Material Cost, Labour Cost and Expenses [Vedantu, 2023]. Expenses can be further classified into more divisions. The classification of cost based on nature has been presented in Figure 2.16.



*Figure 2.16: Classification of cost based on nature*

### **2.10.1.1. Material Cost**

The expenditure on the raw materials to use for production of goods is classified as Material Cost.

### **2.10.1.2. Labour Cost**

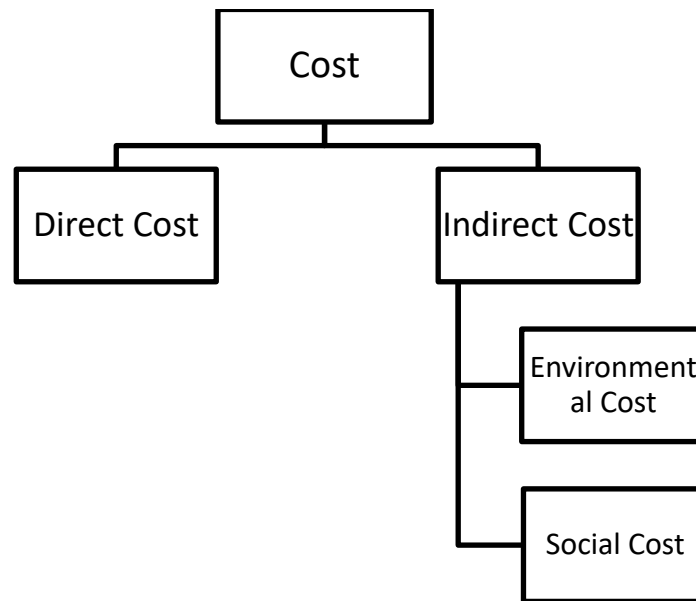
Labour Cost is the expenditure on the salary and wages of the permanent and temporary workers.

### **2.10.1.3. Expenses**

All the other expenditures associated with the production and selling of the goods are classified as Expenses. This consist expenditures on land, construction, equipment, transportation, electricity, operation and maintenance etc.

### 2.10.2. Classification by Traceability

Cost can be classified into two major categories based on the degree of traceability, namely Direct Cost and Indirect Cost [Vedantu, 2023]. Figure 2.17 represents the classification of cost based on the traceability.



*Figure 2.17: Classification of cost based on traceability*

#### 2.10.2.1. Direct Cost

The expenditures which can be directly tied to cost of a good or service and can be put in one specific cost centre, is known as Direct Cost. These can be traced to the cost objective.

#### 2.10.2.2. Indirect Cost

The expenditures which are not directly tied to cost of a good or service and cannot be put in one specific cost centre, is known as Indirect Cost. These cannot be traced to the cost objective.

For economic evaluation in this study, Indirect Costs are further classified into Environmental Cost and Social Cost.

##### 2.10.2.2.1. Environmental Cost

The costs which are incurred to prevent, reduce or repair damages to the environment arising from any activities, are known as Environmental Cost [Terna Driving Energy, 2023].

#### **2.10.2.2.2. Social Cost**

As the name suggests, social costs are the costs incurred by society as a whole. These are the sum of private costs and other external costs imposed on society by production or consumption of a good or service [FRBSF, 2002].

Non-market goods have no prices, but economic values can be estimated with several techniques. In addition to the Contingent valuation method (CVM), other common and widely accepted methods are travel cost, and hedonic pricing [Ekstrand and Draper, 2000]. Still CVM is the most used technique to evaluate economic values of various types of ecosystem and environmental services [Nautiyal and Goel, 2021], as it is based on stated preferences for goods, rather than observed behaviour of consumers.

According to Markandya and Ortiz (2011), contingent valuation is a stated preference method in which respondents are asked to state their preferences in hypothetical or contingent markets. In this survey based method, respondents are asked to state their Willingness to Pay (WTP) or Willingness to Accept (WTA). WTP is the maximum amount of money that respondents are ready to pay in exchange of a service where they gain a positive change. On the contrary, WTA is a minimum amount of money which people are ready to accept as a consequence of a negative change [Hasan-Basri et al., 2015].

### **2.11. Different Methods of Economic Analysis**

Some of the typical methods to calculate cost and benefit are-

- Cost-Benefit Analysis
- Life Cycle Cost Analysis

#### **2.11.1. Cost-Benefit Analysis**

##### **2.11.1.1. Introduction**

Cost-Benefit Analysis (CBA) is a systematic process to determine economic viability of a project or activity and a tool to determine which decisions to make. Generally, the sum of the potential benefits of a project or activity is estimated and then the total of all the associated costs is subtracted from that in the process to get the difference. A positive difference implies that the project or activity is economically beneficial, while a negative difference suggests the opposite.

### **2.11.1.2. Process**

There is no single universal standard method of conducting Cost-Benefit Analysis, but it is generally done with the following five stages [Hayes, A., 2023]:

#### **2.11.1.2.1. Identification of Scope**

The first step of CBA is to understanding the project and the goals to identify the scope and create a framework based on that. In this initial stage, planning is done with estimation of time, resource and workforce required for the project.

#### **2.11.1.2.2. Determination of Costs**

In this stage, all the costs associated with the project or activity, are determined. Alongside direct costs, indirect costs and intangible costs are also monetized and estimated in the stage two.

#### **2.11.1.2.3. Determination of Benefits**

After determination of costs, all the potential benefits come along with the project or activity, are determined. Similar to the previous stage, direct, indirect and all the other associated benefits are monetized and estimated in this stage.

#### **2.11.1.2.4. Computation of Analysis Calculations**

With the help of estimated costs and benefits, the analysis is conducted in this stage. To be more accurate, all the values are converted to the net present value here. The analysis usually performed with a simple subtraction or by determining the cost-benefit ratio.

#### **2.11.1.2.5. Recommendation and Implementation**

Based on the result of the previous stage, recommendations are made in this stage. Not only this helps to determine economic viability of a project or activity, but also helps to choose the best option from the alternatives from an economic point of view.

### **2.11.1.3. Advantages**

Following are the benefits of the CBA-

- Outcome is recommended based on data driven decision making

- Alongside direct costs and benefits, indirect and intangible ones are also considered
- Relatively simple and quick process compare to some other methods

## **2.11.2. Life Cycle Cost Analysis**

### **2.11.2.1. Introduction**

Life cycle cost analysis (LCCA) is a method to determine the most cost-effective option among different alternatives over the life span of a project or a long period of an activity. The purpose of this analysis is to estimate the overall costs of different options and recommending the one with the lowest value without compromising the quality. The analysis should be performed early so that there will be chances of refining the approach to ensure the reduction in life cycle total cost [Srivastav and Vaidya, 2023].

### **2.11.2.2. Process**

The approach to a typical LCCA analysis is composed of following six stages [Macedo et al., 1978; Brown and Yanuck, 1985]:

#### **2.11.2.2.1 Establishing Objectives**

The first step in LCCA analysis is to define requirements and establish basic objectives of the project. These requirements are generally developed from an analysis of the goals of that particular project. Also, any special constraints must be identified at this time.

#### **2.11.2.2.2. Defining Alternatives**

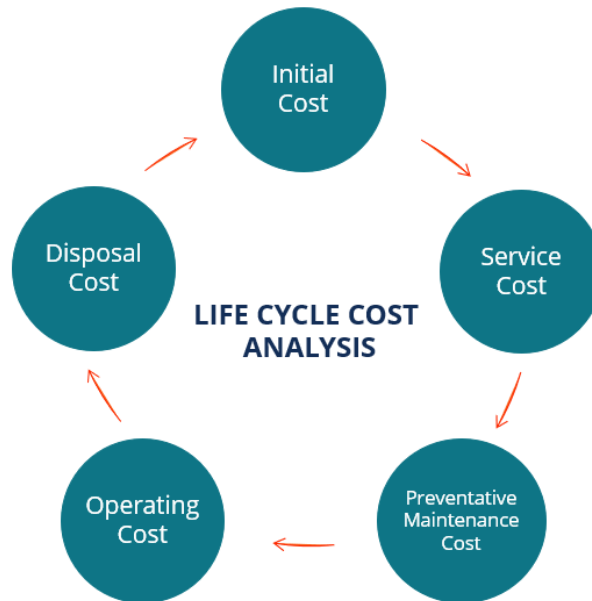
Based on the goal, a bunch of practical alternatives are chosen in this stage. Screening of the alternatives is also conducted to eliminate the ones which do not meet the requirements.

#### **2.11.2.2.3. Selection of Life Cycle**

This stage involves with selection of a specific number of years as the life cycle of the project, based on which future operations, maintenance and other costs are to be estimated.

#### **2.11.2.2.4. Estimation of Costs**

All the costs and revenues relevant to the comparison of alternatives are identified and estimated in this stage. Cost of a typical project can be classified into many groups. Figure 2.18 presents different types of costs of a typical project.



*Figure 2.18: Different types of cost considered in LCCA [CFI Team, 2022]*

#### **2.11.2.2.5. Computation of Present Values or Annual Equivalents**

As the various expenditures estimated take place at different times during the life cycle, the costs are adjusted to a common time period by converting to present values or annual equivalents in this stage. This is usually done by multiplying these costs by the appropriate discount factors.

#### **2.11.2.2.5. Sensitivity test of results**

In this stage, a sensitivity analysis is carried out to assess the results of the previous stage and all the alternatives are ranked based on that. Once these sensitivity tests are completed, the resulting lowest life cycle cost alternative is recommended for implementation.

#### **2.11.2.3. Advantages**

Following are the benefits of the LCCA [Srivastav and Vaidya, 2023]-

- Shows an accurate and realistic assessment of costs and revenue within a specified life cycle stage
- Promotes long-term worthwhileness
- Allows total incremental costs over the whole period
- Provides management awareness of the resources required to be purchased

## 2.12. Critical Literature Review

- Plastic waste management is one of the leading global issues at present. With constant increase of usage of plastic and lack of definite substitute, the situation is getting more severe day by day. Despite having management options like recycling and incineration, landfilling still remains the most prevalent approach as 56% of the globally generated plastic wastes are disposed at landfill [Tsakona et al., 2020]. This not only creates problem regarding land availability, but also pollutes the environment through generation of leachate and greenhouse gasses. Hence, a new sustainable approach is very much essential to manage plastic waste more efficiently.
- Excessive extraction of natural aggregates is another major global challenge, causing threat to the environment. Due to the rapid urbanization, usage of concrete has increased tremendously in last few decades. As 55-80% of concrete is typically occupied by aggregates [Alqahtani et al., 2021], natural resources are struggling to meet the demand. This unsustainable extraction of aggregates are leaving its negative imprint on the environment through changes to the landscape, loss of habitat, erosion, sedimentation, alteration of river bed and forcing the river to change course etc. So, a replacement of natural aggregates to use in concrete is very much needed.
- Using waste plastic based aggregate as partial replacement of natural aggregate in concrete encounters both of the previously mentioned global concerns to a great extent. The possibility of implementation of this innovative new strategy has been explored in many studies in terms of viability of the concrete mechanical properties [Jaivignesh and Sofi, 2017; Tamang et al., 2017; Subramani and Pugal, 2015]. Even though many studies concluded that the concrete can be used for structural and non-structural purposes [Sau et al., 2023a; Sau et al., 2023b; Shiuly et al., 2022; Hossain et al., 2016; Osei, 2014], still this has not been implemented at a large scale due to the uncertainties of the economic viability.

### 2.12.1. Research Gap

- The number of existing literature on the strategy of cost analysis of using plastic aggregate in concrete is very low.
- Results of the previous studies are mostly inconclusive and contradictory to each other.

- In earlier research works, only direct costs are considered while indirect and intangible costs such as environmental and social costs are ignored.
- In previous studies, it has been seen that the primary objectives are different while cost analysis is secondary part. For that reason, lots of farfetched assumptions are made during those analyses.

Hence, there is a huge need and opportunity for more detailed economic analysis, which will drive the policy makers to develop suitable methodologies regarding recycling plastic waste as partial replacement of natural aggregates in cement based concrete and help this strategy of managing plastic waste to be implemented at a larger scale.

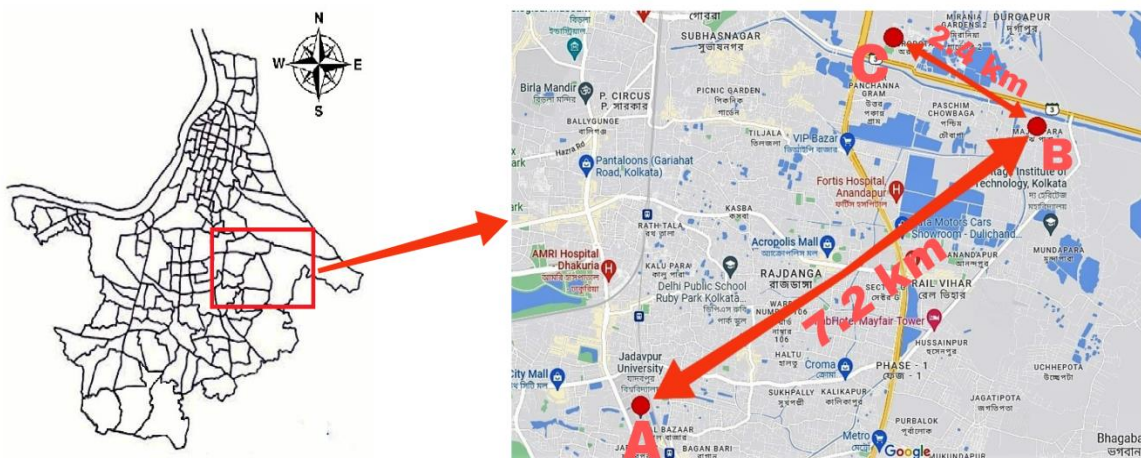
# Chapter 3: Study Area

## 3.1. General

The study has been conducted on the city of Kolkata [area under Kolkata Municipal Corporation], West Bengal, India. General information of the city along with a basic overview of the Municipal Solid Waste Management System of Kolkata has been presented in this chapter. Also the plastic waste management system along with the present deficiencies of the city has been highlighted here.

## 3.2. Basic Information

Kolkata is one of the largest metropolitan cities of India, located at 22°30' North latitude and 88°30' East longitude, at a distance of 120 Km from Bay of Bengal and stands on the eastern bank of river Hooghly (Ganga). It is spread over 206.08 sq. Km with population more than 4.5 million. The climate of the city is humid during summer and pleasant in winter with temperature ranges between 10 °C to 40 °C and average rainfall of 1400-1600 mm per year [Kolkata Municipal Corporation, 2022a]. Figure 3.1 represents the study area and some important locations relevant to this research work.



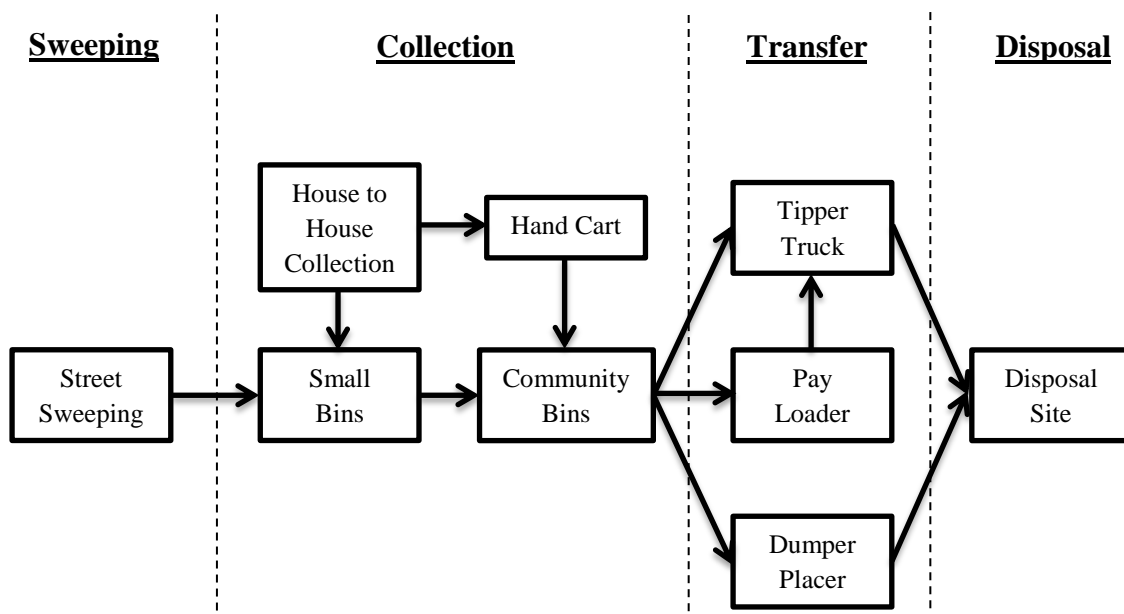
*Figure 3.1: Study area and few important locations*

From the locations marked at Figure 3.1, “A” represents Jadavpur University (22°29'49.8"N, 88°22'16.1"E), where casting of concrete and all the physical tests have been conducted; “B”

represents the location of the plastic aggregate processing unit which is located at Majhi Para, Chowbaga (22°31'37.9"N, 88°24'44.2"E); and “C” represents Dhapa solid waste disposal area (22°32'15.0"N, 88°23'51.4"E), from where the waste plastics are brought to the processing units. The distances that are shown between these locations are the shortest travel distances through roadway, estimated by using <https://www.maps.google.com>.

### 3.3. Municipal Solid Waste Management Service

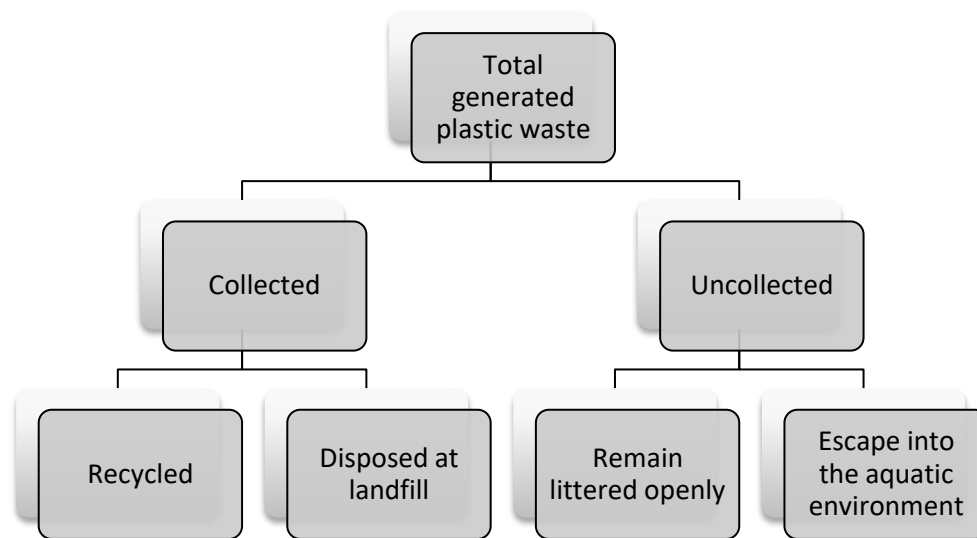
Kolkata Municipal Corporation (KMC) is responsible for the Solid Waste Management services of Kolkata. The city is divided into 16 boroughs and 144 wards [Kolkata Municipal Corporation, 2022a], which helps to run the operations smoothly. The whole operation can be divided into 4 parts – sweeping, collection, transportation and disposal. A schematic diagram of the general Municipal Solid Waste Management (MSWM) system of KMC area is shown in Figure 3.2 [Hazra and Goel, 2009].



**Figure 3.2: Schematic representation of MSWM system of KMC area**

Due to the lack of successful implementation of source segregation at Kolkata, the generated plastic wastes are mostly collected by the municipal corporations in mix condition with other municipal solid waste. It is then segregated at the disposal site and the waste plastics are primarily either recycled or disposed at landfill. From the remaining uncollected portion, some amount of plastic waste stays littered at open and a large portion from the rest escapes

into the aquatic environment. A general schematic representation of the fate of generated plastic waste has been shown in Figure 3.3.



***Figure 3.3: Fate of generated plastic waste***

Even though plastic waste is mostly recyclable, still at present a substantial amount of waste plastic is either disposed at landfill or remains uncollected at Kolkata and affecting the environment and the society negatively in various ways such as generation of leachate and greenhouse gasses, micro-plastic pollution, excessive breeding of mosquitoes, blockage of sewerage system, etc. Also, recycling plastic wastes has its own disadvantages. Moreover, the recycling sector of Kolkata is not much organised as many unregistered, informal facilities and rag-pickers are involved with the process. Hence, a new strategy is much required at present for sustainable plastic waste management.

# Chapter 4: Methodology

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## 4.1. General

In this chapter, a new sustainable plastic waste management strategy has been proposed to cover the present deficiencies and the methodology adopted for the present work to achieve the objective is described briefly and shown schematically. The whole work has been divided into 3 major stages. Overviews of the each stage along with the different associated aspects and the approaches taken to fulfil the objectives of those stages have been discussed in this chapter also.

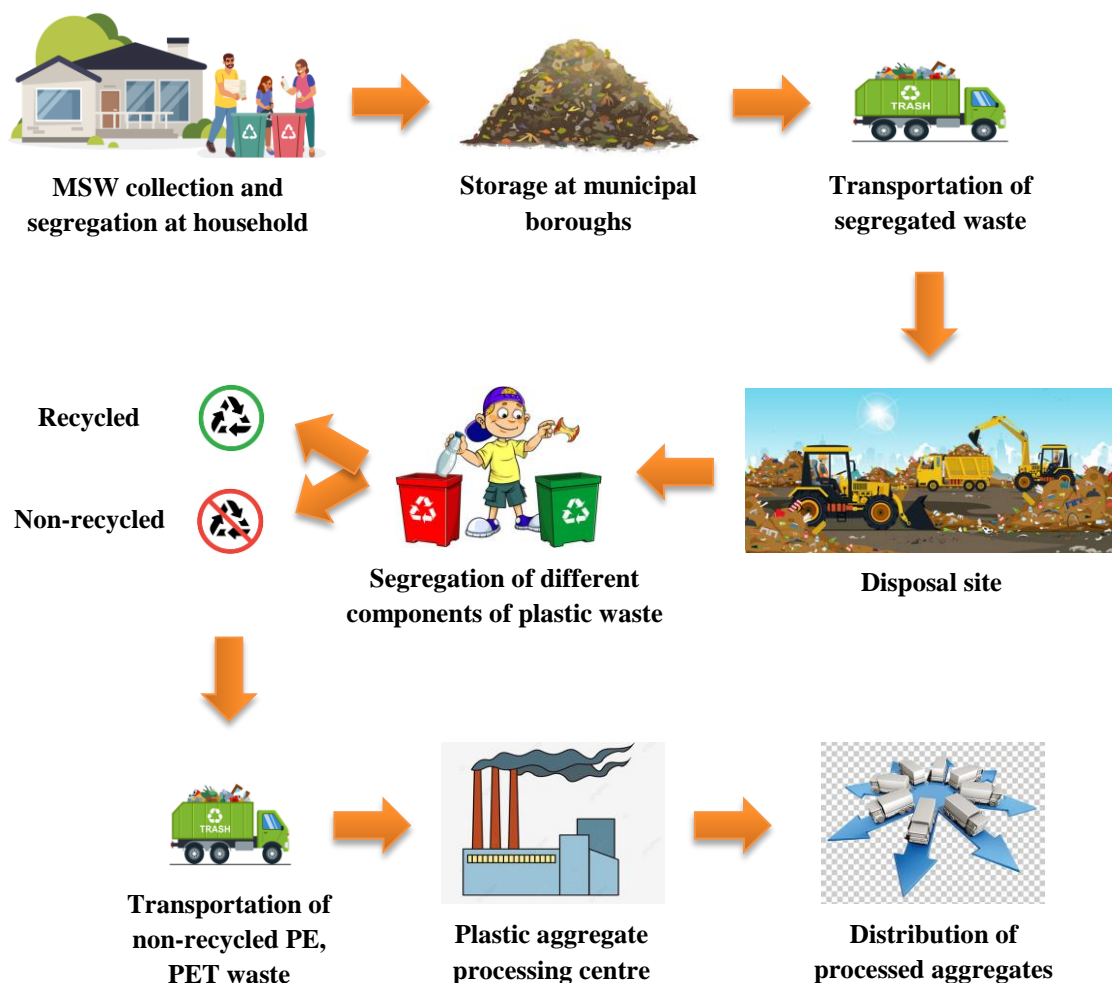
## 4.2. Proposed Strategy

The strategy that has been proposed in this study is to reduce the amount of uncollected and disposed plastic waste by increasing the collection and segregation efficiencies and then recycling PE and PET type waste from that additionally collected plastic waste as partial replacement of natural aggregates to produce green sustainable concrete. The replacement percentages have been considered as 10%, 20%, 30% and 40% of fine and coarse natural aggregates separately as well as simultaneously by PE based fine aggregate (PFA) and PET based coarse aggregate (PCA). Such types of aggregates are shown in Figure 4.1.



*Figure 4.1: (a) PE based fine aggregate; (b) PET based coarse aggregate*

As per the proposed strategy, the generated plastic waste along with municipal solid waste will be initially segregated and collected with higher efficiencies at household level and stored temporarily at municipal boroughs. From there, it will be brought to the landfill disposal site, where further segregation of different components of plastic waste will be done. Next, the segregated PE and PET waste, which are not recycled, will be sent to the plastic aggregate processing centres for processing. Lastly, the produced plastic aggregates will be distributed at the market as per the demand. Figure 4.2 represents a schematic diagram of the strategy that has been proposed in this study.



**Figure 4.2: Schematic diagram of the proposed strategy**

Successful implementation of this proposed strategy may potentially resolve the global challenges related to plastic waste management and unsustainable extraction of natural aggregates. It also spares the environment and the society from the various other negative effects, and may lead us to a sustainable and better future.

### **4.3. Overview of the Stages**

#### ***Stage 1: Quantity Estimation***

In this stage, the flow of plastic waste within the study area has been estimated and presented in form of a schematic diagram by using STAN. From there, the quantity of PE and PET waste which are either disposed at landfill or remain uncollected, has been determined for further calculations. Also, whether the full utilisation of this plastic waste is potentially possible or not, that has been checked by considering the demand of concrete at Kolkata to check the feasibility of the proposed strategy from the point of view of available quantity of raw material for plastic waste based aggregate.

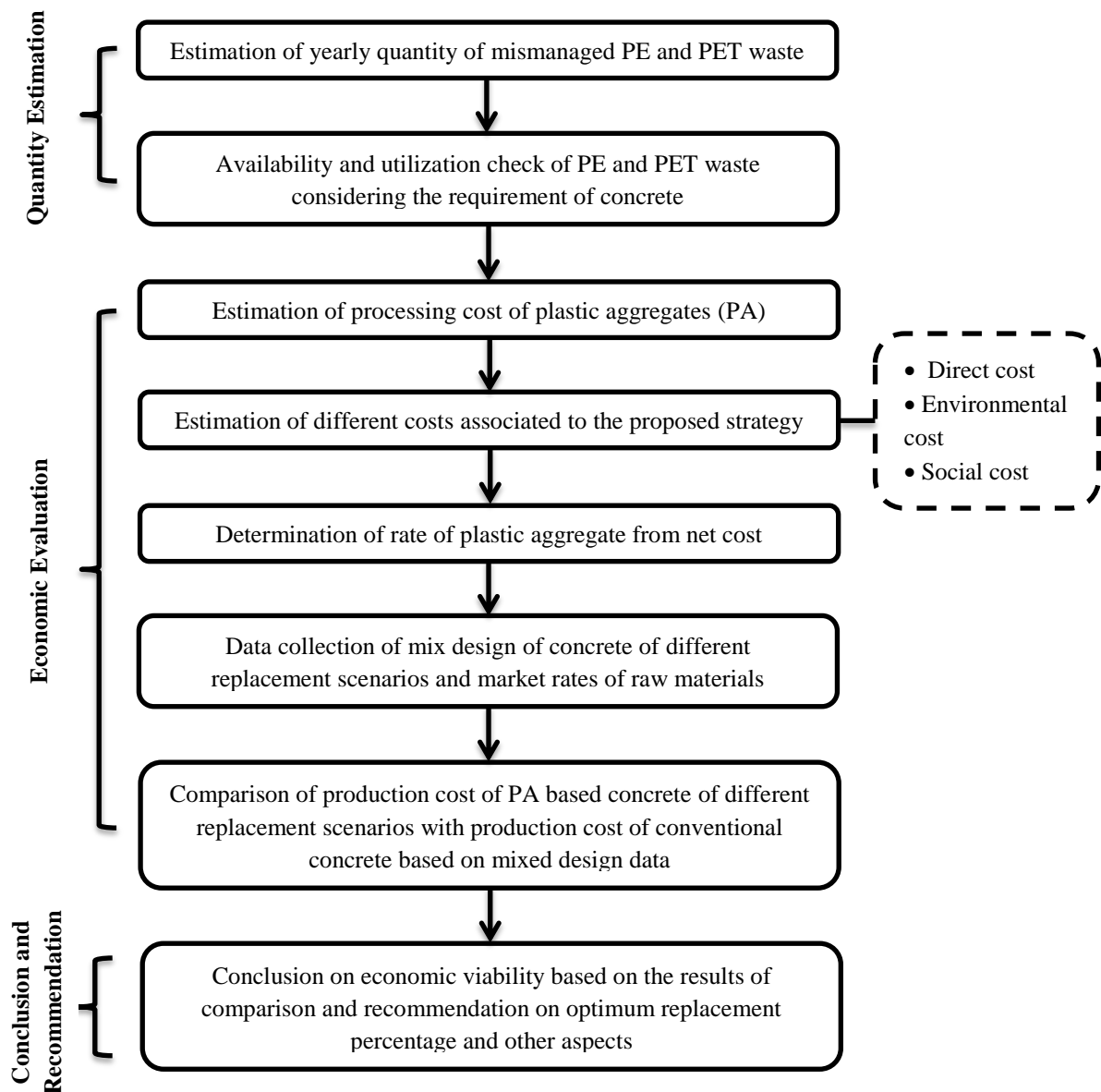
#### ***Stage 2: Economic Evaluation***

The processing cost of waste plastic based aggregates along with other associated direct, environmental and social costs and additional expenditures of the proposed strategy have been estimated in this stage. Next, the production cost of conventional concrete and plastic aggregate based concrete have been estimated after collecting data regarding the rates of raw materials and mix design, and compared to check the feasibility of the proposed strategy from the economic point of view.

#### ***Stage 3: Conclusion and Recommendation***

Based on the comparison done in the previous stage, a conclusion on the economic viability of the proposed strategy has been drawn in this stage. Also recommendations on optimum replacement percentage considering both economic aspect and mechanical aspect, responsibility of government and policy makers, etc. are given here. Future scope and potential challenges of this study are also mentioned in this stage.

Methodology of the proposed study is presented schematically in Figure 4.3.



*Figure 4.3: Schematic representation of methodology of the proposed study*

# Chapter 5: Quantity Estimation

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## 5.1. General

In this chapter, the flow of total plastic waste and PE, PET type plastic wastes separately have been evaluated for the city of Kolkata. The evaluation has been done based upon transfer coefficients and percentages assumptions using material flow analysis on the basis of primary survey data and secondary data collected from scientific literatures and relevant websites. The results of the estimation have been presented schematically by using STAN 2.7.101. Also, the feasibility of the proposed strategic changes has been checked from the point of view of utilisation of total relevant waste materials.

## 5.2. Flow of Plastic Waste

Kolkata is one of the highest plastic waste generating cities in India. According to Agarwal (2022), the quantity of plastic waste generation in Kolkata is 429.5 TPD, which is second highest among the metro-cities in India. So, the quantity of yearly generation is 156768 ton. Fate of this generated plastic waste is shown in Figure 3.3.

The collection efficiency of Municipal Solid Waste (MSW) is generally very high, especially in metropolitan cities. The quantity of plastic waste collected and the quantity that remains uncollected are derived from Equations 5.1 and 5.2 respectively.

$$B = A \times \frac{P_1}{100} \quad \dots\dots\dots (5.1)$$

$$C = A - B \quad \dots\dots\dots (5.2)$$

Where, A = Quantity of total generation of plastic waste in Kolkata, TPA

B = Quantity of collected plastic waste in Kolkata, TPA

P<sub>1</sub> = Collection efficiency of MSW in Kolkata in percentage

C = Quantity of uncollected plastic waste in Kolkata, TPA

According to the annual report by CPCB (2021), collection efficiency of solid waste in India is 95.4%. With consideration of same collection efficiency for Kolkata, 149557 ton plastic

waste is estimated to be collected while the rest 7211 ton remains littered or escapes into the aquatic environment every year.

In India, recycling percentage of plastic waste is high compare to world’s average. The remaining amount either goes to the landfill or remains uncollected. To calculate the quantity of plastic waste going into the landfill, Equation 5.3 is used.

$$D = A \times \left(1 - \frac{P_2}{100}\right) - C \quad \dots\dots\dots (5.3)$$

Where, D = Quantity of plastic waste going into the landfill in Kolkata, TPA

P<sub>2</sub> = Recycling rate of plastic waste in Kolkata in percentage

According to Central Pollution Control Board (CPCB) for the year 2016-17, around 9.4 MTPA of plastic waste was generated, out of which nearly 5.6 MTPA plastic waste was recycled which is around 60% [Mohanty, 2018]. The rest, accounting for 40%, either went to landfill or remains uncollected. The similar trend has been observed in last few years. So, in total, 62707 TPA plastic wastes either disposed at landfill or remain littered or escape into the environment. Hence, the total amount of the plastic waste which is ending up at landfill is determined to be 55496 ton per year.

The major disposal ground in Kolkata is Dhapa (21.47 ha), located in the eastern side of the city. It receive about 3000 ton of solid waste per day while another site at Garden Reach (3.52 ha) receive about 100 ton of solid waste per day [Paul et al., 2014]. So, the disposal rate at Garden Reach is around 3.2% of the total while the majority portion i.e. 96.8% goes to Dhapa. Even though at present the quantity of disposal per day has increased, it is assumed that the percentage remained same. As the percentage of waste going to the Garden Reach landfill site is very low, it is considered that the total quantity is disposed to the Dhapa site for simplification.

West Bengal is one of the highest contributors of plastic waste in India and subsequently a large amount of plastic waste goes to the marine environment from here, same goes for Kolkata. The amount of plastic waste openly dumped in Kolkata is estimated by using Equation 5.4.

$$F = C - E \quad \dots\dots\dots (5.4)$$

Where, E = Quantity of plastic waste going into the marine environment from Kolkata, TPA

F = Quantity of plastic waste stays littered in Kolkata, TPA

India is estimated to release 0.09–0.24 million ton/year of litter into the marine environment [Rafey and Siddiqui, 2021]. Average of the two extreme ranges is has been for further calculation, i.e. 0.165 million ton/year. According to the annual report by CPCB (2020), Waste Bengal contributes around 9% of total plastic waste generation in India. Due to the lack of available data, the assumption that West Bengal contributes 9% of total plastic waste that is going into the ocean has been taken, which accounting up-to 14850 TPA. Now, according to the annual report on plastic wastes management for the year of 2020-2021 by WBPCB (2021), generation of plastic waste in West Bengal is 1645 TPD which is 3.83 times of the generation of Kolkata. So, the quantity of plastic waste escaping into the ocean from Kolkata is estimated to be 3877 TPA while 3334 TPA wastes are dumped openly.

The consumption of plastic in India is much diversified and different types of plastics are being used. Out of those, PE and PET are two of the major types. Recycling of plastic waste is hugely dependent on formal and informal rag-pickers. As they are not much interested in single use plastic waste due to less potential of recycling, it mostly ends up in landfill or escapes into the environment. The amount of PE and PET disposed at landfill, escapes into the ocean and stays littered in Kolkata are calculated using Equations 5.5, 5.6 and 5.7 respectively.

$$X = D \times \frac{P_3}{100} \dots\dots\dots (5.5)$$

$$Y = E \times \frac{P_3}{100} \dots\dots\dots (5.6)$$

$$Z = F \times \frac{P_3}{100} \dots\dots\dots (5.7)$$

Where, X = Quantity of PE and PET going into landfill in Kolkata, TPA

P<sub>3</sub> = Consumption of PE and PET out of total plastic usage in percentage

Y = Quantity of PE and PET going into marine environment in Kolkata, TPA

Z = Quantity of PE and PET dumped openly in Kolkata, TPA

The consumption of different types of plastics in India for the year of 2019 has been given in Table 5.1 [Tiseo, 2022].

**Table 5.1: Plastic consumption in India by type** [Tiseo, 2022]

<b>Type of plastic</b>	<b>Consumption in million ton</b>	<b>Percentage of total</b>
Polyethylene	5.3	33.2
Polypropylene	5.08	31.8
Poly Vinyl Chloride	3.31	20.8
Polyethylene Terephthalate	1.64	10.3
Styrenics	0.38	2.4
Acrylonitrile-Butadiene- Styrene	0.24	1.5
<b>Total</b>	<b>15.95</b>	<b>100</b>

So, the consumption rate of PE and PET together is 43.5% of total in India. The assumption of same percentage in case of Kolkata for further calculations has been taken.

Hence, Quantity of PE and PET going into landfill in Kolkata is calculated as 24141 TPA, quantity of PE and PET escaping into marine environment in Kolkata is calculated as 1687 TPA and quantity of PE and PET staying littered in Kolkata is estimated as 1450 TPA. A flow chart of quantification of PE and PET waste flow relevant to this study has been presented by using STAN 2.7.101 in Figure 5.1.

STAN (short for subSTance flow ANalysis) is a freeware that helps to perform material flow analysis according to the Austrian standard ÖNorm S 2096 (Material flow analysis - Application in waste management) [Stan2web, 2012].

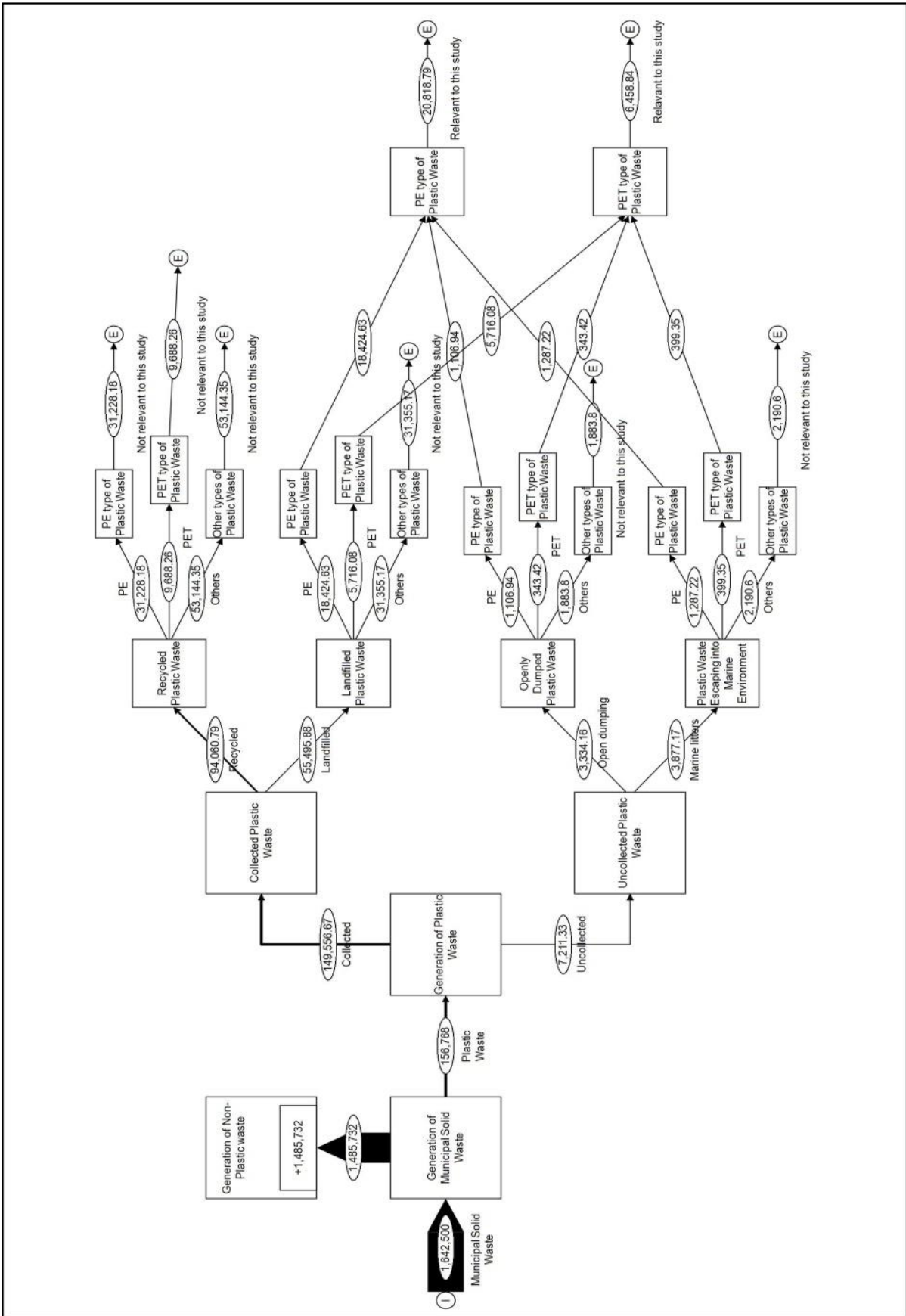


Figure 5.1: Estimated flow of plastic waste at Kolkata using STAN 2.7.101

So, the total quantity of mismanaged PE and PET waste at Kolkata is 27278 TPA, of which 20819 TPA is PE waste and the rest 6459 TPA is PET waste.

### 5.3. Quantity Wise Feasibility Check

According to Capital Market (2019), the rate of consumption of cement in India is around 235 Kg per capita. On the other hand, the total area under KMC is 206.08 sq. Km with population density of 24252 per sq. Km. So, the total population is 4997853 [Kolkata Municipal Corporation, 2022a]. Hence, the total yearly consumption of cement in Kolkata is around 1174496 ton.

The main usage of cement is to make concrete for structural development. To be on the safer side, standard M30 grade concrete mix is considered for further calculations. So, the ratio of cement, sand and coarse aggregate is 1:0.75:1.5 [Prasiddha, 2023]. Hence, the yearly demands of natural coarse and fine aggregates are estimated to be 1761744 ton and 880872 ton respectively.

According to Shiuly et al. (2022), aggregates made of PE can be used as replacement of fine aggregate and PET as replacement of coarse aggregate up-to 30% without compromising mechanical strengths of concrete. The amount of coarse aggregate (CA) and fine aggregate (FA) that can be replaced by plastic aggregates are estimated by using Equations 5.8 and 5.9 respectively.

$$R_1 = Q_1 \times \frac{SG_1}{SG_3} \dots\dots\dots (5.8)$$

$$R_2 = Q_2 \times \frac{SG_2}{SG_4} \dots\dots\dots (5.9)$$

Where,  $R_1, R_2$  = Amounts of CA and FA that can be replaced by plastic aggregates respectively, TPA

$Q_1, Q_2$  = Quantity of PET and PE available to replace natural aggregates respectively, TPA

$SG_1, SG_2, SG_3, SG_4$  = Specific gravity of natural CA, natural FA, PET based aggregate and PE based aggregate respectively

Again, as per Shiuly et al. (2022), the specific gravity of natural CA, natural FA, PET based aggregate and PE based aggregate are 2.76, 2.66, 0.85 and 0.8 respectively. Hence, the estimated yearly amount of CA that can be replaced by PET based aggregate is 20973 ton,

which is 1.19% of total yearly demand and the estimated yearly amount of FA that can be replaced by PE based aggregate is 69224 ton, which is 7.86% of total yearly demand.

As both of the required replacement percentages are well below the percentages of intended replacement, the proposed strategy is feasible quantity wise and all the mismanaged PE and PET waste of Kolkata potentially can be utilised in the proposed fashion.

# Chapter 6: Economic Evaluation

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## 6.1. General

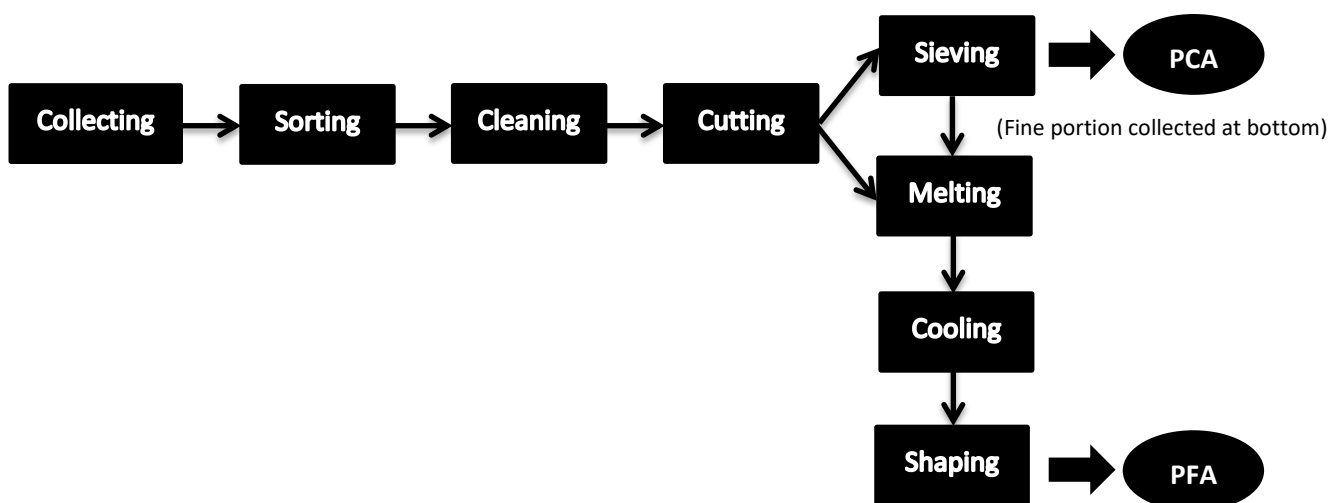
In this chapter, the processing cost of plastic aggregates has been estimated by conducting an industrial survey. Next, the direct and environmental benefits and additional expenditures related to the proposed strategy have been monetized largely based on secondary data collected from scientific literatures and relevant websites, while the social cost has been estimated by conducting a WTP survey to estimate the net cost. Also, a feasibility check of the proposed strategy from the economic point of view has been done in this chapter after comparing the production cost of conventional concrete with plastic aggregate based concrete of different replacement percentages.

## 6.2. Cost Estimation

All the costs associated to the proposed strategy are estimated in this section.

### 6.2.1. Processing Cost of Plastic Aggregates

To produce waste plastic based aggregates, waste plastic needs to be processed at a plant. The cost of processing is estimated in this section. The general flow chart for processing of both PE based fine aggregates (PFA) and PET based coarse aggregates (PCA) are presented in Figure 6.1.



*Figure 6.1: Flowchart showing the processing of plastic aggregates*

The different segments of expenditures associated with processing of PCA and PFA are estimated by interviewing the owners of processing plants located at Chowbaga road, Majhipara, Kolkata-700105 and collecting secondary data. Daily production of each processing plant is around 2000 Kg and with 26 working days per month, yearly production of a processing plant is estimated as 624 ton.

#### **6.2.1.1. Land cost**

The requirement of land area for a single processing plant of similar capacity including storage area is about 2.5 Katha, i.e. 1800 sq. ft. According to WBSIDCL (2022), the rate of lease at Kolkata for 30 years is 3450 INR per sq. ft. So, the total cost of the land is determined to be 62,10,000 INR. Hence, the yearly cost is 2,07,000 INR [1 USD = 81.29 INR on 15<sup>th</sup> January, 2023].

#### **6.2.1.2. Raw material cost**

From the KMC boroughs, segregated municipal solid wastes are sent to Dhapa landfill site where further segregation of different components of plastic wastes is done. From there, PE and PET wastes are brought to the processing centre for processing. As the PE and PET based aggregates are being made from waste plastic, the raw material cost is considered zero.

#### **6.2.1.3. Setup and equipment cost**

For a plastic waste recycling plant in India, the manufacturing setup can cost in between INR 5 and 10 lakhs (1 million = 10 lakhs), with machinery ranging from 3.5 lakhs to 35 lakhs [Corpbiz, 2023]. The average value is considered for both which adds up to 26.75 lakhs INR. Figure 6.2 represents some pictures of the equipment used at processing centres.



*Figure 6.2: Different equipment for processing of plastic aggregates*

With consideration of 10 years lifetime and no salvage value to be on the safer side, the yearly depreciation comes out to be 2,67,500 INR.

#### **6.2.1.4. Transportation cost**

From Dhapa landfill site, PE and PET wastes are brought at the processing centre located at a distance of 2.4 Km (Figure 3.1). Mini trucks with an average payload of 4 ton and average mileage of 7 Kmpl are being used for the transportation purpose, having an average valuation of 14 lakhs (online market survey) and 10 years lifetime [Rydell, 2021]. So, the yearly depreciation of the vehicle is 1,40,000 INR.

In total, 156 numbers of trips are needed yearly to transport the total amount of PE and PET waste from Dhapa to processing site. Hence, the total distance needs to be covered is 749 Km and 107 litres of diesel are required yearly. At present, the price of diesel in Kolkata is 92.76 INR per litre [The Economic Times, 2022]. So, the total yearly fuel cost is estimated as 9926 INR.

Hence, the total yearly expenditure for the purpose of transportation is considered as 1,49,926 INR.

#### **6.2.1.5. Labour cost**

The requirement of worker is 8 per processing centre (primary data through manual interviews). According to the Office of the Labour Commissioner (2022), the minimum rate of wages in West Bengal at areas under municipal corporations is 9239 INR per month. So, the total yearly expenditure on wages of workers per processing centre is 8,86,944 INR.

#### **6.2.1.6. Electricity cost**

The average monthly electricity bill of a processing plant is around 75,000 INR (primary data through manual interviews). So, the yearly expenditure on electricity is 9,00,000 INR.

#### **6.2.1.7. Repair and maintenance cost**

According to Post (2022), the assumption of total maintenance and repair costs over the life of the machine should be equal to 75% of the new cost of the machine. Hence, the repair and maintenance cost per year for setup, machinery and the vehicle together is estimated as 3,05,625 INR.

#### **6.2.1.8. Working Capital**

Similar to the research work of Tam (2008), the working capital is considered as 15% of the operating cost which includes maintenance, fuel, labour and electricity cost. Hence, the working capital per year is considered as 299,624 INR.

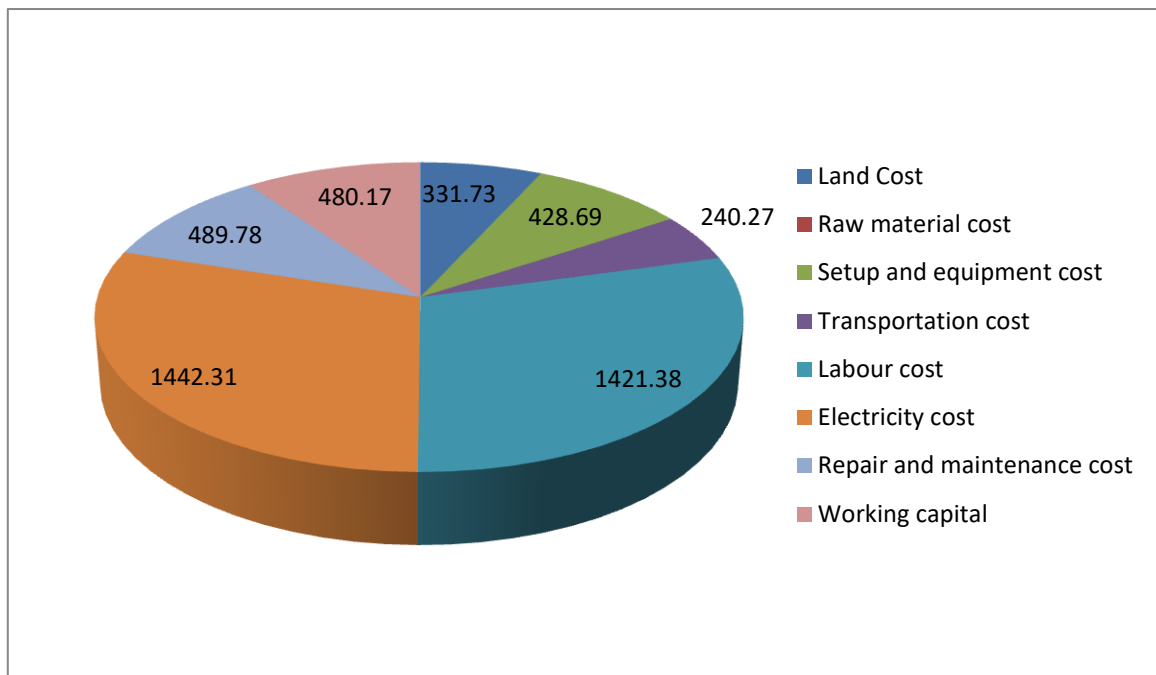
### **Summary of processing costs of plastic aggregates**

All the different direct cost components related with production of plastic aggregates are given in a tabular form in Table 6.1 and shown in Figure 6.3.

*Table 6.1: Different cost components of processing of plastic aggregates*

<b>Type of cost</b>	<b>Cost (INR)</b>	<b>Cost per ton production (INR)</b>	<b>Percentage of total cost (%)</b>
Land cost	207000	331.73	6.86
Raw material cost	0	0	0

Type of cost	Cost (INR)	Cost per ton production (INR)	Percentage of total cost (%)
Setup and equipment cost	267500	428.69	8.87
Transportation cost	149926	240.27	4.97
Labour cost	886944	1421.38	29.4
Electricity cost	900000	1442.31	29.84
Repair and maintenance cost	305625	489.78	10.13
Working capital	299624	480.17	9.93
<b>Total</b>	<b>3016619</b>	<b>4834.33</b>	<b>100</b>



**Figure 6.3: Pie chart showing the cost components of processing of plastic aggregates**

With the production cost of 4834.33 INR (59.47 USD on 15<sup>th</sup> January, 2023) per ton, the yearly production cost of plastic aggregates for the available 27278 ton of PE and PET waste at Kolkata is estimated as 13,18,70,854 INR and 44 numbers of processing plants of similar capacity will be required in total, which will create at least 352 direct job opportunities.

Some similar kind of studies have been conducted before to estimate the processing and selling cost of recycled concrete aggregate (RCA). According to the study of Ohemeng and

Ekolu (2020), the average processing cost of coarse RCA is 16.38 US\$ per ton; as per the study of Tam (2008), finished products of 7, 10, 20 and 75 mm aggregate are produced and sold at the rate of about \$14.8, \$20, \$22, and \$15.4 per ton; while the study of Makul (2020) concludes that finished products are sold at prices ranging from \$14 to \$22 dollars.

**6.2.2. Associated Costs to the Proposed Strategy**

Different costs directly and indirectly associated to the proposed strategy except the processing cost of plastic aggregates are estimated in this section.

**6.2.2.1. Direct Cost**

**6.2.2.1.1. Landfill disposal cost**

Landfill disposal cost is one of the most essential costs related to solid waste management which encompasses the capital and operating costs that will be incurred over the life of a landfill. This generally includes-

- Land cost
- Operational costs
- Management, administration and organisational overhead costs
- Development costs
- Cost of rehabilitation and aftercare, etc.

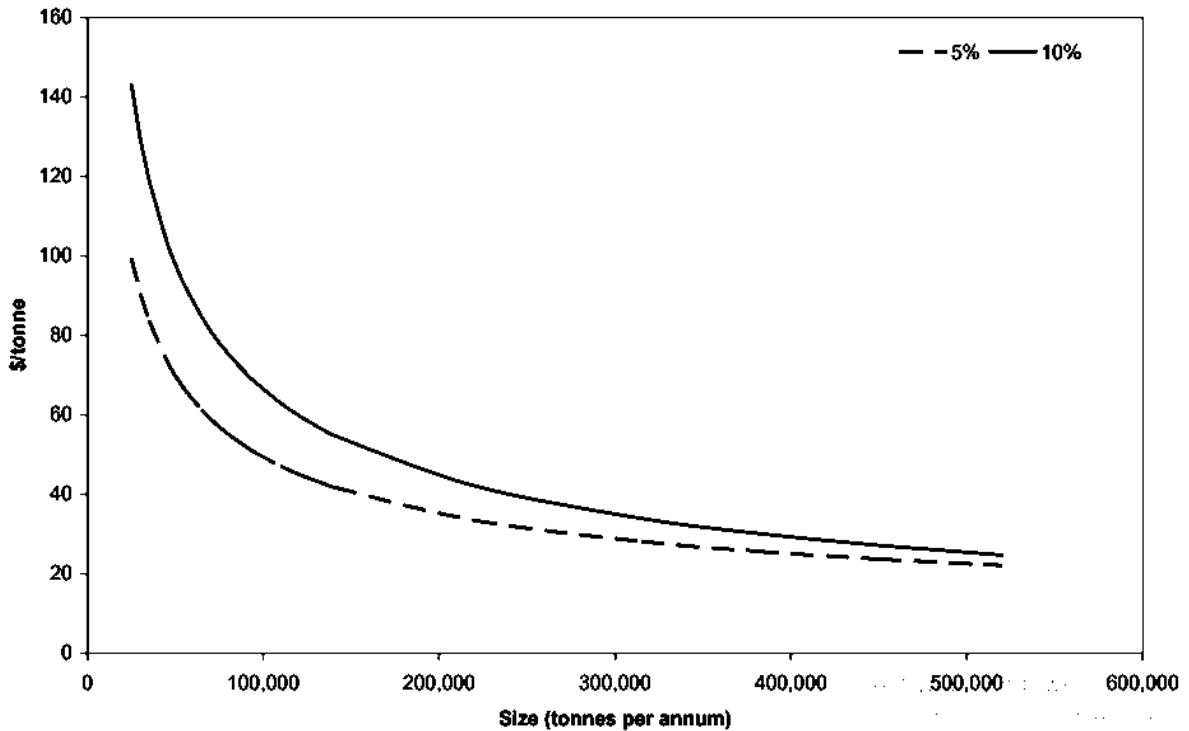
The cost of the landfill disposal that can be saved by not disposing PE and PET into the landfill at Kolkata is derived using Equation 6.1.

$$S_1 = X \times C_1 \dots\dots\dots (6.1)$$

Where,  $S_1$  = Yearly landfill disposal cost saved by recycling and reusing PE and PET in Kolkata, INR

$C_1$  = Landfill disposal cost per ton of waste, INR

Disposal cost of MSW in landfill heavily relies on the amount of waste disposed. The variation in disposal costs with landfill size in New Zealand is given in Figure 6.4 [Covec, 2007].



**Figure 6.4: Costs of landfill disposal based on quantity of incoming waste with 5% and 10% discount rate (NZD, 2007) [Covec, 2007]**

The quantity of waste generation in the KMC area is 4500 TPD, i.e. 1642500 TPA [The Kolkata Municipal Corporation, 2022a]. After consideration of collection efficiency, it is estimated that Dhapa landfill site receives around 1566945 ton wastes per year. So, from the extension of the curve it can be derived that the cost of landfill disposal is 20 New Zealand Dollar (NZD) (2007) per ton of waste in this case. The present value of this in terms of Indian currency comes out as 1650 INR.

On the other hand, in 2005, the National Landfill Division (2005) estimated that the costs of a large best-practice landfill in a capital city would be about 25 Australian Dollar (AUD) (2005) per ton of waste, which is equivalent to 2647 INR at present.

For conversion of different currencies to Indian currency, <http://www.bookmyforex.com> website has been used. After that, <https://www.inflationtool.com> website is used to counter the inflation and to get the present value (15<sup>th</sup> January, 2023) of a data from the past.

Using the average of two values, the yearly avoided direct cost of landfill disposal comes out as 5,18,66,939 INR due to recycling and reusing of mismanaged PE and PET waste in Kolkata as per the proposed strategy.

### 6.2.2.1.2. Collection and transportation expenditure of uncollected PE, PET waste

Management of MSW resulting from rapid urbanization has become a serious concern for people. At present, a huge proportion of the total expenditure is incurred on collection, while a bit lesser on transportation and a very little amount on disposal. The expenditure on collection and transportation of the uncollected PE and PET waste at Kolkata is estimated using Equation 6.2.

$$S_2 = (Y + Z) \times C_2 \times \frac{P_4}{100} \dots\dots\dots (6.2)$$

Where,  $S_2$  = Extra yearly expenditure on collection and transportation of the uncollected PE and PET waste at Kolkata, INR

$C_2$  = Municipal solid waste management expenditure for per ton of waste, INR

$P_4$  = Budget allocated for collection and transportation of MSW out of total budget in percentage

According to Hanrahan et al. (2006), municipal solid waste management expenditure in cities with population above 1.5 million is 1050 INR per ton on average. On the other hand, according to Chattopadhyay (2009), KMC spends around 72.87% of the total budgetary allocation on primary collection of the solid waste and 22.34% on transportation in terms of Operation and Maintenance (O&M) expenditure and capital expenditure. After addition of these two values, the expenditure on collection and transportation for per ton of waste comes out to be 1000 INR (2006), which is equivalent to 3100 INR at present.

Hence, the additional total yearly expenditure on collection and transportation of uncollected PE and PET waste at Kolkata is estimated as 97,24,700 INR.

### 6.2.2.2. Environmental Cost

#### 6.2.2.2.1. Landfill gas emission cost

Landfill is one of the important sources of greenhouse gases. It is a roughly 50/50 mixture of methane and carbon dioxide by volume with trace amounts of many other compounds. Emission of landfill gases are generally expressed in terms of carbon dioxide equivalent ( $CO_2e$ ) and the equivalency of methane is taken as 21 since its Global Warming Potential

(GWP) is 21 times of the GWP of CO<sub>2</sub>. Not only landfill, these gases also generate from openly dumped wastes too in a similar way.

To derive the avoided cost of gas emission from landfills and open dumping sites due not disposing PE and PET into the landfill or dumped openly in Kolkata, Equation 6.3 is used.

$$S_3 = X \times \frac{G_1}{1000} \times C_3 \quad \dots\dots\dots (6.3)$$

Where, S<sub>3</sub> = Yearly gas emission cost saved by recycling and reusing PE and PET in Kolkata, INR

G<sub>1</sub> = Greenhouse Gas (GHG) emission from landfill and dump sites for per unit of PE and PET waste, Kg CO<sub>2</sub>e/ton

C<sub>3</sub> = Value of reduction of per ton of CO<sub>2</sub>e, INR

According to Ma et al. (2020), the flows of PET waste in China are 15.9, 22.55, 34.75 and 4.4 million ton respectively for the years of 2000-2005, 2006-2011, 2012-2017 and 2018.

In China, on an average only about 17% of the plastic used are recycled in some shape or form [Lai, 2022]. On the other hand, between 2006 and 2013, on an average 16% MSW was incinerated in China [Ji et al., 2016]. Also, according to Chu et al. (2022), 11% of global plastic waste goes to aquatic ecosystem. So, the assumption has been taken that the rest 56% plastic wastes are going into the landfill.

According to Chu et al. (2022), the emission of GHG from landfills in China in the PET life cycle for the years of 2000-2005, 2006-2011, 2012-2017 and 2018 are respectively 1.9, 4.1, 6.6 and 1.26 Tg CO<sub>2</sub>e.

According to Chen and Lin (2008), emission factor of PET and other plastic products are almost same. Using these data, the GHG emission from landfill due to PET waste in China has been calculated in Table 6.2 and the result is used for further estimation of GHG emission from landfill and open dumped sites of Kolkata due to presence of PE and PET waste.

**Table 6.2: GHG emission from landfill due to PET waste in China**

<b>Year</b>	<b>Total flow of PET (MT)</b>	<b>PET going to landfill (MT)</b>	<b>GHG from landfill (Tg CO<sub>2</sub>e)</b>	<b>GHG emission from landfill per unit of plastic (Kg CO<sub>2</sub>/ton)</b>	<b>Weighted avg. GHG emission from landfill per unit of plastic (Kg CO<sub>2</sub>/ton) [(a*6+b*6+c*6+d)/19]</b>
2000-2005	15.9	8.9	1.9	213.5 (a)	304
2006-2011	22.55	12.63	4.1	324.6 (b)	
2012-2017	34.75	19.46	6.6	339.2 (c)	
2018	4.4	2.46	1.26	512.2 (d)	

Hence, the amount of CO<sub>2</sub>e emission from landfill that potentially can be avoided with the proposed strategy is 7338864 Kg.

In India, there is currently a commodity exchange market known as the Multi Commodity Exchange (MCX). The MCX currently only trades carbon credits based on carbon equivalents. One carbon emissions reduction (CER) credit is equivalent to 1 metric ton of CO<sub>2</sub>. In the present study CER value is considered as same as United States Environment Protection Agency (USEPA) 2009 i.e. \$13.82, which is equivalent to 1619 INR at present [Sprague et al., 2009].

So, the avoided yearly landfill gas emission cost saved by recycling and reusing PE and PET in Kolkata is determined as 1,18,81,621 INR.

#### **6.2.2.2.2. Leachate emission cost**

Landfill leachate is a highly contaminated liquid with organic, inorganic compounds and heavy metals resulted from physical and biochemical breakdown of landfill waste due to percolation of rainwater and moisture through waste in landfills. When migrates it contaminates the subsurface water, water bodies and surrounding soil.

According to Productivity Commission (2006), groundwater quality can be maintained if landfill leachate emission is not more than 1000 L/ha/day. If the seepage amount is more, the cost is estimated using Equation 6.4.

$$S_4 = X \times C_4 \quad \dots\dots\dots (6.4)$$

Where,  $S_4$  = Yearly landfill leachate emission cost saved by recycling and reusing PE and PET in Kolkata, INR

$C_4$  = Leachate cost per ton of waste, INR

According to Basak (2011), at present, the quantity of leachate is being generated every year from Dhapa landfill is about 900 L/m<sup>2</sup>. The area of Dhapa is part of the wetlands, of which the landfill site is spread over the area of approximately 21.47 hectares [Paul et al., 2014], out of that, 0.316 hectare is determined to be occupied by PE and PET. So, the quantity of leachate generation at Kolkata due to PE and PET waste is estimated as 2844000 L/year or 24657.5 L/ha/day.

As the leachate emission rate at Dhapa landfill site is higher than 1000 L/ha/day, leachate cost needs to be considered. Valuation of impact of leachate emissions from landfills is given in Table 6.3 [BDA Group, 2009].

**Table 6.3: Valuation of impact of leachate emissions from landfills** [BDA Group, 2009]

<b>Location</b>	<b>Range of values (AUD 2008/ton of waste)</b>	<b>Avg. (AUD 2008/ton of waste)</b>
United States	0-2	1
European Union	0-3	1.5
Nederland	0-5	2.5
United Kingdom	0-2	1
Australia	0.0004-0.02	0.25
	0-1	
New Zealand	1-36	18.5
<b>Net average</b>		<b>4.125</b>

So, the net average cost of landfill leachate per ton of waste from Table 4 comes out as 4.125 AUD (2008), which is equivalent to 405.6 INR at present.

Hence, the total amount of yearly landfill leachate emission cost saved by recycling mismanaged PE and PET waste in Kolkata is determined as 97,91,590 INR.

### 6.2.2.2.3. Cost of gas emission from transportation

The transportation sector is one of the largest contributors to anthropogenic greenhouse gas emission. The Indian transport sector is responsible for 13.5% of India’s energy related CO<sub>2</sub> emissions, with road transport accounting for 90% of the sector’s total energy consumption [Climate Action Tracker, 2020]. The quantity of generated gas due to transportation of aggregates is estimated by using Equation 6.5.

$$G_2 = \frac{2 \times H}{I} \times G_3 \dots\dots\dots (6.5)$$

Where, G<sub>2</sub> = Gas emission from transportation of per unit of aggregates, Kg CO<sub>2</sub>e/ton

H = Distance between the source of aggregate and destination, Km

I = Average of the mileages of the vehicle when fully loaded and when fully empty, Km/L

G<sub>3</sub> = Generation of CO<sub>2</sub> from fuel consumption, Kg/L

J = Payload of the vehicle, ton

The environmental cost of CO<sub>2</sub> emission that potentially can be saved by using plastic aggregates instead of natural aggregates at Kolkata is the difference between the emission cost of present management system and the proposed management strategy. To determine the emission cost, Equation 6.6 is used.

$$S_5 = K \times \frac{G_2}{1000} \times C_3 \dots\dots\dots (6.6)$$

Where, S<sub>5</sub> = Gas emission cost due to transportation of aggregates, INR

K = Quantity of aggregates to be transported, ton

The average Gross Vehicle Weight (GVW) of the mostly used trucks which carry aggregates in India is about 28 ton, having payload of 20 ton. The average fuel consumptions of this type of trucks are given in Table 6.4 [International Council of Clean Transportation, 2017].

**Table 6.4: Fuel consumption of 25 to 31 ton trucks**

GVW (ton)	Axle Configuration	Speed of vehicle (Km/hr.)	Fuel consumption (L/100 Km)		Avg. fuel consumption (L/100 Km)	
			Upper weight limit	Lower weight limit	Upper weight limit	Lower weight limit
25-31	8×2	40	22.1	19.5	26.1	21.8
		60	26.4	24.2		
	8×4	40	20.1	15.7		
		60	35.7	27.8		

According to Singh et al. (2021) and Gajjar et al. (2015), 1 L consumption of diesel generates 2.64 Kg of CO<sub>2</sub>.

***CO<sub>2</sub> generation due to transportation of natural aggregates***

Natural aggregates used for construction purpose in Kolkata, are generally mined at Sainthia, West Bengal. The distance between the source and Jadavpur University through a distributor is around 196 Km. So, the fuel consumption for a round trip is 93.9 L and subsequently the CO<sub>2</sub> generation is 247.9 Kg Hence, the generation of CO<sub>2</sub> for transportation of each ton of natural aggregates is 12.4 Kg So, the quantity of CO<sub>2</sub> emission that occurs due to transportation of a total amount of 90197 ton of equivalent natural aggregates which is proposed to be replaced by PE and PET based aggregates, comes out to be 1118443 Kg.

***CO<sub>2</sub> generation due to transportation of PE and PET waste and plastic aggregates***

The primary source of the plastic waste is Dhapa landfill site, from where it goes to the processing centre located at Chowbaga road, near Majhipara Seven Star Club. The distance from Dhapa to the processing centre is 2.4 Km and the distance between the processing centre and Jadavpur University is about 7.2 Km (Figure 2). So, the fuel consumption for a round trip is 4.6 L and subsequently the CO<sub>2</sub> generation is 12.15 Kg. Hence, the generation of CO<sub>2</sub> for transportation of each ton of plastic aggregates is 0.61 Kg. So, the quantity of CO<sub>2</sub>

emission that will occur due to transportation of a total amount of 27278 ton of plastic aggregates which is proposed to be used as replacement comes out to be 16640 Kg.

***CO<sub>2</sub> generation due to transportation of previously uncollected PE and PET waste after collection***

It has been considered that all the uncollected PE and PET wastes will be collected at the KMC boroughs and from there, will be taken to Dhapa and later will be transported to processing plants. The distances between boroughs and Dhapa are given in Table 6.5 [Kolkata Municipal Corporation, 2022b].

***Table 6.5: Distance between Dhapa landfill site and KMC boroughs***

<b>Borough no.</b>	<b>Office address</b>	<b>Distance from Dhapa (Km)</b>	<b>Avg. distance from Dhapa (Km)</b>
I	10, B. T. Road, Kolkata – 700002	11	10.78
II	79, Bidhan Sarani, Kolkata – 700006	9.5	
III	109, Moulana A. K. Azad Sarani, Kolkata – 700054	7.1	
IV	213B, C. R. Avenue, Kolkata – 700007	9.2	
V	22, Surya Sen Street, Kolkata – 700009	9	
VI	1, Hogg. Street, Kolkata – 700087	8.4	
VII	9/1A, A. J. C. Bose Road, Kolkata – 700017	5.9	
VIII	172/5, Rash Behari Avenue, Kolkata - 700029, (Triangular Park)	6.6	
IX	11, Belvedere Road, Kolkata – 700027	9.6	
X	28, Prince Anwar Shah Road, Kolkata – 700033	10	

<b>Borough no.</b>	<b>Office address</b>	<b>Distance from Dhapa (Km)</b>	<b>Avg. distance from Dhapa (Km)</b>
XI	Baghajatin Mkt. Complex, Unit - 3, Baghajatin Stn. Road, Kolkata	9.7	
XII	97 & 98, Garfa Main Road, Kolkata – 700075	7.4	
XIII	2, Raja Ram Mohan Road, Kolkata – 700008	14	
XIV	516, Diamond Harbour Road, Kolkata – 700034	15	
XV	E/3, Circular Garden Reach Road, Kolkata – 700024	19	
XVI	Diamond Park, P.O. Joka, Kolkata – 700104	21	

So, the fuel consumption for a round trip is 5.16 L and subsequently the CO<sub>2</sub> generation is 13.62 Kg. Hence, the generation of CO<sub>2</sub> for transportation of each ton of plastic aggregates is 0.68 Kg. So, the quantity of CO<sub>2</sub> emission that will occur due to transportation of a total amount of 3137 ton of plastic wastes which remain uncollected comes out to be 2133 Kg.

Total yearly amount of CO<sub>2</sub> that can be avoided at Kolkata from the transportation sector with implementation of the proposed strategy is estimated and presented in Table 6.6.

**Table 6.6: Yearly reduction of CO<sub>2</sub> generation at transportation sector**

<b>Activity</b>	<b>Quantity (ton)</b>	<b>Average one way distance (Km)</b>	<b>Fuel consumption per round trip (L)</b>	<b>CO<sub>2</sub> generation per trip (Kg)</b>	<b>CO<sub>2</sub> generation per ton of material (Kg)</b>	<b>Total CO<sub>2</sub> generation per year (Kg)*</b>
Transportation of natural aggregates from mining site to consumers via distributor	90197	196	93.9	247.9	12.4	(-) 1118443

Activity	Quantity (ton)	Average one way distance (Km)	Fuel consumption per round trip (L)	CO <sub>2</sub> generation per trip (Kg)	CO <sub>2</sub> generation per ton of material (Kg)	Total CO <sub>2</sub> generation per year (Kg)*
Transportation of uncollected PE and PET wastes from boroughs to landfill site	3137	10.78	5.16	13.62	0.68	(+) 2133
Transportation of PE and PET wastes from landfill to processing plant	27278	2.4	1.15	3.04	0.15	(+) 4092
Transportation of PE and PET based aggregates from processing plant to consumer	27278	7.2	3.45	9.11	0.46	(+) 12548
Total						(-) 1099670

Note: \*(-) stands for potential reduction and (+) stands for extra generation

Hence, the avoided yearly CO<sub>2</sub> emission cost from the transportation sector of Kolkata due to the changes from the proposed strategy is estimated as 17,80,366 INR.

#### 6.2.2.2.4. Cost of gas emission due to processing of PA

Conversion of PE and PET waste to aggregate is an energy intensive process and it produces a bad odour. To estimate the cost of gas emission which will occur due to processing of PE and PET based aggregates, Equation 6.7 is used.

$$S_6 = \frac{(X+Y+Z)}{L} \times M \times G_4 \times C_3 \quad \dots\dots\dots (6.7)$$

Where, S<sub>6</sub> = Additional cost of gas emission from processing plants, INR

L = Yearly production of a processing plant, ton

M = Yearly consumption of electricity due to processing, MWh

G<sub>4</sub> = CO<sub>2</sub> generation for consumption of per MWh electricity, ton

Average monthly electricity bill of a processing plant is 75000 INR. According to CESC (2022), the cost of using 1 KWh electricity usage in Kolkata for industrial use is given in Table 6.7.

**Table 6.7: Charge of electricity usage for industrial purpose at urban area**

Monthly consumption (KWh)	Energy Charge (INR/KWh)
First 500	6.77
Next 1500	7.47
Next 1500	7.87
Above 3500	8.07

Hence, the monthly consumption of electricity is estimated as 9523 KWh, i.e. 114.3 MWh/year. On the other hand, according to Central Electricity Authority (2011), the average emission factor in India is 0.85 tCO<sub>2</sub>/MWh.

So, the additional yearly generation of CO<sub>2</sub> due to processing of plastic aggregates in Kolkata is calculated as 4247106 Kg and the incurred cost of it is estimated as 68,76,065 INR as additional expenditure of the proposed strategy.

### 6.2.2.3. Social Cost

As per the proposed strategy, efficiency of collection and segregation of plastic waste need to be increased. Hence, the social cost for providing better and more efficient plastic waste management system has been estimated here by using Contingent Valuation Method (CVM).

This method has been adapted previously by many researchers for their respective studies. According to the study of Abas et al. (2021), 62% of people of rural area of Kelantan, Malaysia are willing to pay for better solid waste management, while as per the study of Niringiye and Omortor (2010), the demand for improved waste management is only significantly related to the age of the household head. Again according to Chung and Yeung (2019), monthly willingness to pay (WTP) of Hong Kong residents for waste disposal is 38.4 Hong Kong Dollar (HKD) while as per the study done by Kayamo (2022), average WTP of residents of Hawassa city, Ethiopia was 26.57 Ethiopian Birr (ETB)/ month. Apart from solid waste management, CVM has been used for other services too, such as Bogale and Urgessa (2012), Makwinja et al. (2019) assessed residents' WTP for improving drinking water quality, Roe et al. (2001) studied consumers' willingness to pay for green electricity etc.

### 6.2.2.3.1. Societal benefits from implementation of proposed strategy

#### 6.2.2.3.1.1. Reduction in cases of mosquito borne diseases

Plastic pollution is one of the major reasons of breeding of mosquitoes. The small pools of water created in plastic litter due to holding the rainwater or clogged drainage system caused by plastic pollution are ideal breeding grounds for mosquitoes. With these convenient breeding grounds, mosquitoes reproduce in great numbers and infests heavily in polluted areas. Malaria and dengue are two of the most common diseases which are carried by mosquitoes.

According to National Center for Vector Borne Diseases Control (2022a), the number of cases of dengue in West Bengal for the years of 2015, 2016, 2017, 2020 and 2021 are 8516, 22865, 37746, 5166 and 8266 respectively while the numbers of deaths are 14, 45, 46, 0 and 7 for those respective years.

On the other hand, according to Kanwal (2022), the number of cases of malaria in West Bengal for the years of 2014, 2015, 2016, 2017, 2018, 2019, 2020 and 2021 are 26484, 24208, 35236, 31265, 26440, 25928, 14049 and 19237 respectively. Between those periods of time, the mortality rate of malaria in India was 0.034% [National Center for Vector Borne Diseases Control, 2022b]. So, the number of deaths occurred due to malaria between 2014 and 2021 in West Bengal is 69.

According to the World Population Review (2022), the population of West Bengal in 2022 is 101562085 while, the total population under KMC area is 4997853 [Kolkata Municipal Corporation, 2022a], which is 4.92% of West Bengal. Based on this, the numbers of cases and deaths due to dengue and malaria at Kolkata have been given in Table 6.8.

**Table 6.8: Numbers of cases and deaths due to dengue and malaria at Kolkata**

Disease	Year	West Bengal		Kolkata		Avg./Year (Kolkata)	
		Cases	Deaths	Cases	Deaths	Cases	Deaths
Dengue	2015-2021 (NR 2018, 2019)	82557	112	4062	6	813	2
Malaria	2014-2021	202847	69	9981	4	1248	1
Total						2061	3

According to a consulted doctor, it takes around two weeks of time for proper treatment and rest to recover from malaria and dengue. The standard working hours is considered 8 hours a day. Hence, the total yearly loss of working hours is estimated as 2,30,832 hrs. and the number of yearly death is 3 due to dengue and malaria at Kolkata.

With proper management of plastic waste as per the proposed strategy where uncollected plastic wastes are to be collected and reused or recycled, the number of cases and deaths caused by dengue and malaria will come down significantly.

#### **6.2.2.3.1.2. Saving of land area**

The availability of land for constructing new landfills has become one of the major concerns for solid waste management due to rapid increase of urbanization. So, saving the future requirement of landfill areas is one of the highest priorities. To estimate the land area that can be saved potentially due to not disposing PE and PET waste at landfills in Kolkata, Equation 6.8 can be used.

$$S_7 = X \times N \quad \dots\dots\dots (6.8)$$

Where,  $S_7$  = Landfill area saved due to not disposing PE and PET waste at landfills in Kolkata, ha.

$N$  = Landfill area requirement for per TPA waste, ha.

According to Basak (2011), for 1000 TPD capacity landfill facility, area requirement is 67 ha. Hence, the land area that can be saved potentially by not disposing 55496 TPA plastic waste is determined as 10.19 ha., of which 4.43 ha. would have occupied by PE and PET waste.

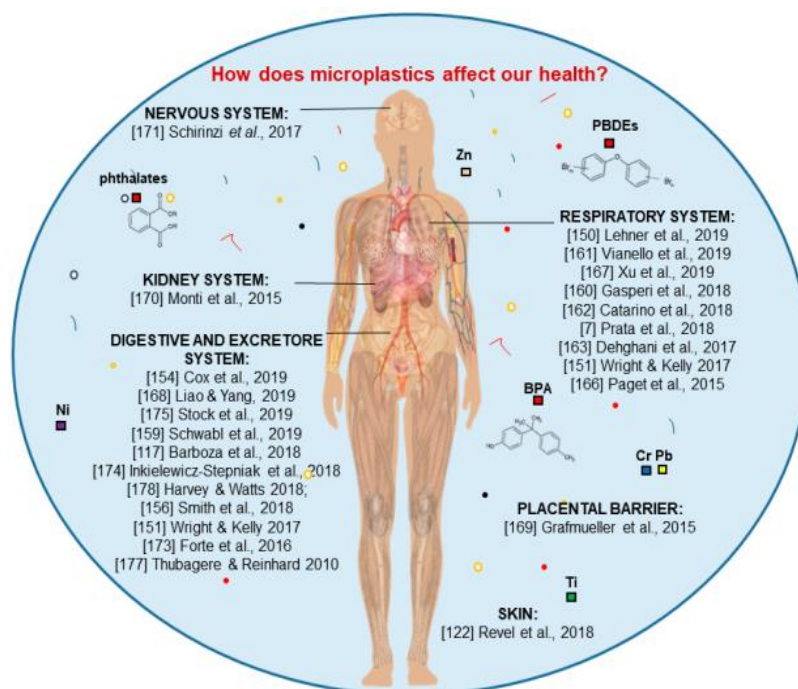
#### **6.2.2.3.1.3. Reduction in micro-plastic pollution**

Uncollected plastic waste is the foremost reason for secondary micro-plastic pollution. The last sink of plastic garbage is the oceans. According to a study in 2012, around 165 million ton of plastic waste were estimated to be present in the oceans with about 5 trillion plastic pieces floating on the ocean [Alabi et al., 2019]. Degradation of these marine plastics contributes heavily in micro-plastic pollution. Due to their small size, these micro-plastics are ingested by marine organisms and these are found in many species intended for human consumption including invertebrates, crustaceans, and fish [Smith et al., 2018]. Based on the consumption of foodstuff, the estimated intake of micro-plastics is 39,000–52,000

particles/person/year, and this estimation goes up-to 74000 and 121000 based on age and gender when inhalation is considered [Cox et al., 2019].

Another major source of micro-plastic pollution is landfill leachate. Plastic wastes buried in landfill are gradually broken and decomposed into micro-plastics under physical, chemical and biological effects and contaminate the surrounding soil and water sources in form of leachate [Shen et al., 2022]. The abundance of micro-plastics in landfill leachate is 4-13 items/L as per Su et al. (2019), while according to Perumal and Muthuramalingam (2022), micro-plastic concentration in India in different aquatic environments are 3096 items/Kg in marine sediments, 59 items/L in seawater, 33.9 items/L in lake water, 336 items/Kg in lake sediments, 288 pieces/m<sup>3</sup> in river water, and 328 items/Kg in river sediments.

After the exposure by ingestion, inhalation or dermal contact, the effects of micro-plastic on human health can lead to respiratory distress, cytotoxic and inflammatory effects, and autoimmune diseases in men [Campanale et al., 2020]. Not only that, it also may causes damage to the kidney and digestive system as well as the nervous system. According to Prata et al. (2020), micro-plastics may lead to oxidative stress, cytotoxicity and translocation to other tissues, while their persistent nature limits their removal from the organism, leading to chronic inflammation, which increases the risk of cancer. The effects of micro-plastic on human health are shown in Figure 6.5 [Campanale et al., 2020].



**Figure 6.5: Effects of micro-plastic on human health** [Campanale et al., 2020]

With higher efficiency of collection of plastic waste as per the proposed plan, this major issue of micro-plastic pollution will be solved to a great extent.

#### **6.2.2.3.1.4. Relief from other social inconveniences**

With the implementation of the new proposed strategy, society will be relieved largely from the following inconveniences and nuisances which are commonly caused by uncollected plastic waste-

- Blockage of drainage system
- Production of foul smells
- Deterioration of natural beauty
- Reduction of productivity of agricultural lands, etc.

#### **6.2.2.3.2. Determination of social cost**

In this study, to estimate the social cost of this research work, CVM method is used and a survey has been conducted on individuals of different age, gender and economic background from Kolkata where they state the maximum amount which they are willing to pay to obtain the proposed service of collection of uncollected plastic wastes to avail all the benefits stated before.

##### **6.2.2.3.2.1. Design of survey experiment**

###### *Determination of sample size*

The sample size for this work has been estimated using Equation 6.9, suggested by Yamane (1967).

$$n = \frac{p}{1+p(e)^2} \dots\dots\dots (6.9)$$

Where, n = Sample size

p = Population size

e = Margin of error

According to Kolkata Municipal Corporation (2022a), total population under KMC area is 4997853 and according to Knoema (2011), the average household size in Kolkata is 4.39. Hence, the total number of household under KMC area is estimated to be 1138464 which is

the population size in this case as the survey is conducted on the basis of per household. On the other hand, 90% (i.e.  $e = 0.1$ ) precision level is considered. Hence, for this present study, the sample size comes out to be 100.

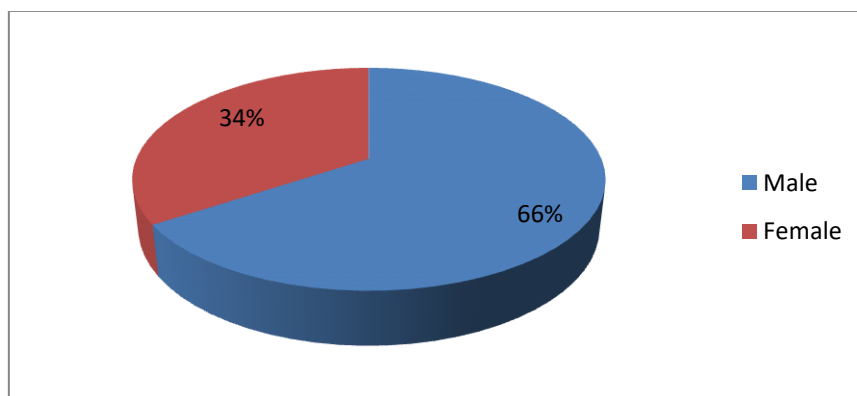
### ***Questionnaire design***

To prepare the questionnaire, first the demographic questions are listed. The address of the respondents are asked first as only the citizens of Kolkata are needed to be considered for this survey and then the respondents are asked about their gender and age to correlate these with their economic choices later. Next, a question is asked about the monthly income of the respondents to learn about their socio-economic background and the influence of it on their final choices. Finally, their willingness to pay for better and efficient plastic waste collection and segregation system has been asked in payment card format, based on which the social cost is estimated.

Payment card format is a type of elicitation technology, where respondent chooses a value from a list of predetermined values [Ke et al., 2022]. This format is easy for respondent to make a selection and non-response rate is relatively lower compare to other formats.

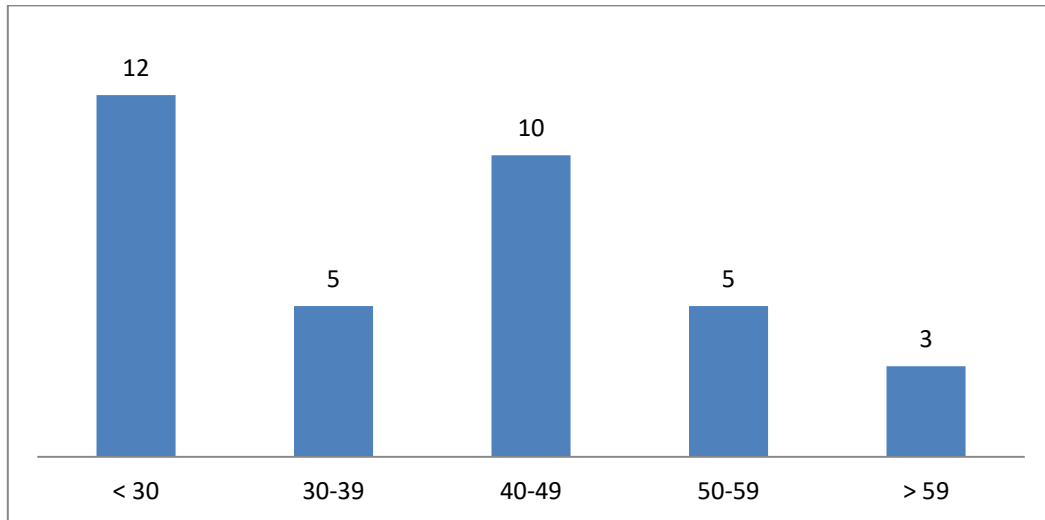
#### **6.2.2.3.2.2. Collection of data**

Though more than 100 households from Kolkata were invited randomly through e-mail to participate in this survey, only 35 members of different households participated. The primary database collected through the survey consist data of the gender, age group and family income of the respondents and their willingness to pay for more efficient collection and management of plastic waste. The summary statistics of the information collected are shown in Figure 6.6, 6.7, 6.8 and 6.9.



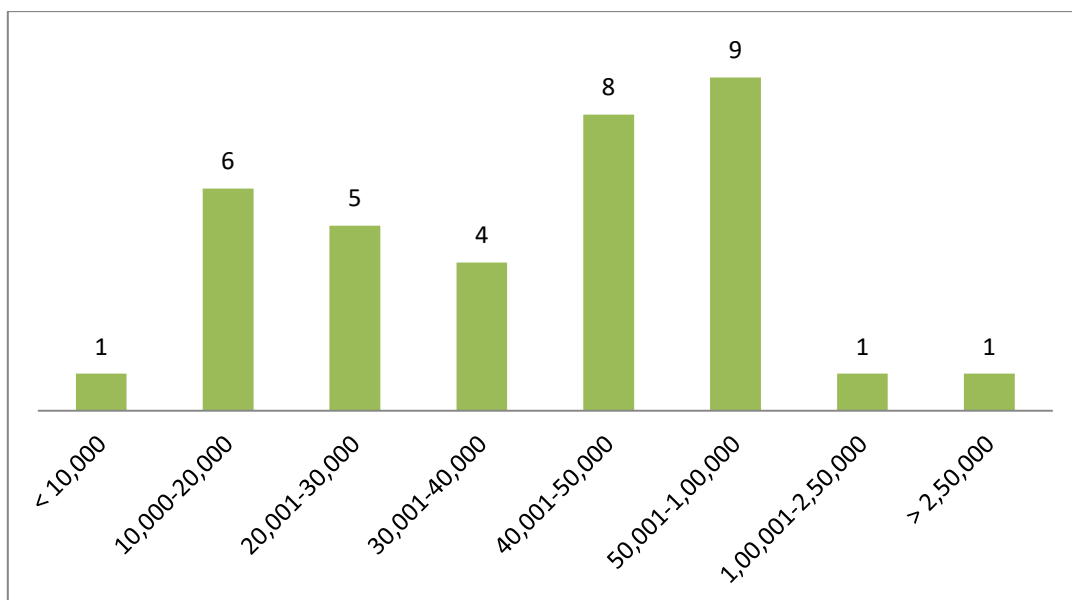
***Figure 6.6: Gender of the respondents***

Out of the 35 respondents, 23 (65.7%) are male while the rest 12 (34.3%) are female respondent. The survey has been targeted to the earning member of family, which caused this significant difference between number of male and female respondents.



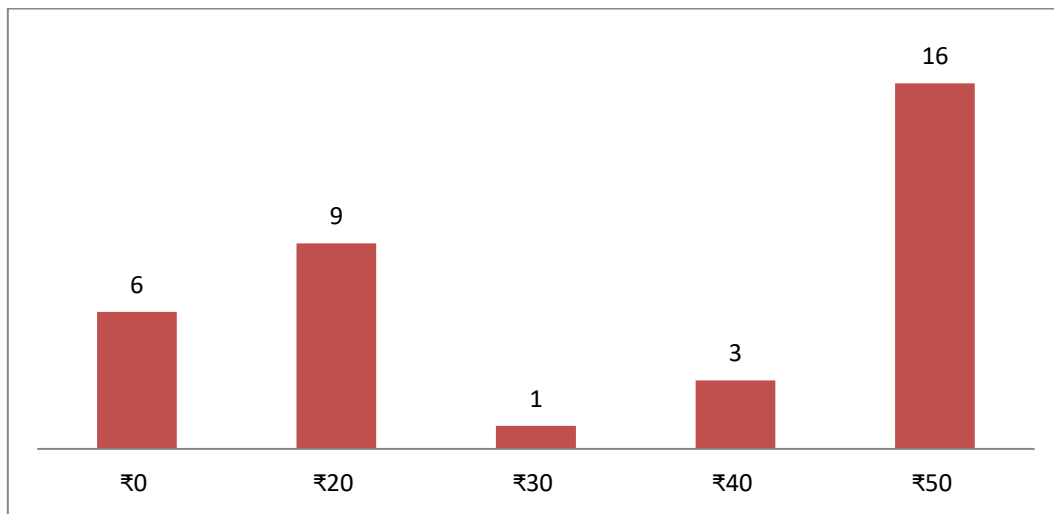
**Figure 6.7: Age group of the respondents**

According to Nagarajan (2013), the median age of India is just 24, which coincides with this study as the highest number (12) of responses came from the age group of less than 30, followed by the 40 to 49 age group (10). The lowest number (3) of responses belongs to the age group of more than 59.



**Figure 6.8: Family income of the respondents (INR per month)**

On the other side, according to Gupta and Sidhartha (2022), in metro cities of India, 13% people belong to the rich category (monthly family income more than 2.5 lakh), 55% belong to the middle class category (monthly family income between almost 40 thousand and 2.5 lakh), 32% belong to the aspirer category (monthly family income between almost 10 thousand and 40 thousand) and less than 1% are in the destitute category (monthly family income less than 10 thousand). The responses of our survey follow this pattern to a great extent with highest number of respondents (9 responses) opted for the income category of 50 thousand to 1 lakh, followed by the division of 40 thousand to 50 thousand (8 responses).



**Figure 6.9: Willingness to pay of the respondents for more efficient collection and management of plastic waste (INR per household per month)**

After asking about the gender, age and family income to get the socio-economic background of the respondents, they were asked whether they want to pay a monthly fee from their household for better and more efficient collection and management of plastic waste with explanation of all the societal benefits come with it. Total 29 respondents opted for yes while the rest 6 did not want pay any amount. Out of the 29, 9 respondents were willing to pay 20 INR, 1 respondent wanted to pay 30 INR, 3 people wanted to pay 40 INR and the rest 16 respondents opted for 50 INR.

#### **6.2.2.3.2.3. Analysis of data**

The statistical test of these collected data is done by using one way ANOVA. Analysis of Variance (ANOVA) is a statistical technique that is used to check if the means of two or more groups are significantly different from each other. ANOVA checks the impact of one or more factors by comparing the means of different samples. The statistics measures whether

the means of different samples are significantly different or not is called the F-Ratio. Lower the F Ratio, more similar are the sample means and vice-versa. Table 6.9 represents the results obtained from ANOVA.

**Table 6.9: Result of ANOVA**

		Sum of Squares	Df	Mean Square	F	Sig.
Age	Between Groups	1552.599	4	388.150	2.829	0.042
	Within Groups	4115.972	30	137.199		
	Total	5668.571	34			
Income	Between Groups	14978467261.9	4	3744616815.48	1.888	0.138
	Within Groups	59502604166.7	30	1983420138.89		
	Total	74481071428.6	34			
Gender	Between Groups	0.663	4	0.166	0.689	0.605
	Within Groups	7.222	30	0.241		
	Total	7.886	34			

The ANOVA result revealed that between the 3 factors governing WTP values, significance of age is the highest, followed by Income and all the co-relations are positive.

With consideration of 0 in case of those 6 people who did not want to pay, the average WTP comes out 32.29 INR per household per month. Hazra et al. (2013) and Hazra et al. (2015) presented WTP values starting from INR 67 to 227 per household per year for various attributes related to better solid waste management in KMC area. According to Kolkata Municipal Corporation (2022), total population under KMC area is 4997853 and according to Knoema (2011), the average household size in Kolkata is 4.39. Hence, the total number of household under KMC area is 1138464 and according to the WTP survey, the social cost is estimated to be 3,67,61,035 INR. As the consumption of PE and PET together is 43.5% of the total usage of plastic [Tiseo, 2022], the social cost for this study is estimated as 1,59,91,051 INR.

### 6.2.3. Net Cost of Plastic Aggregates

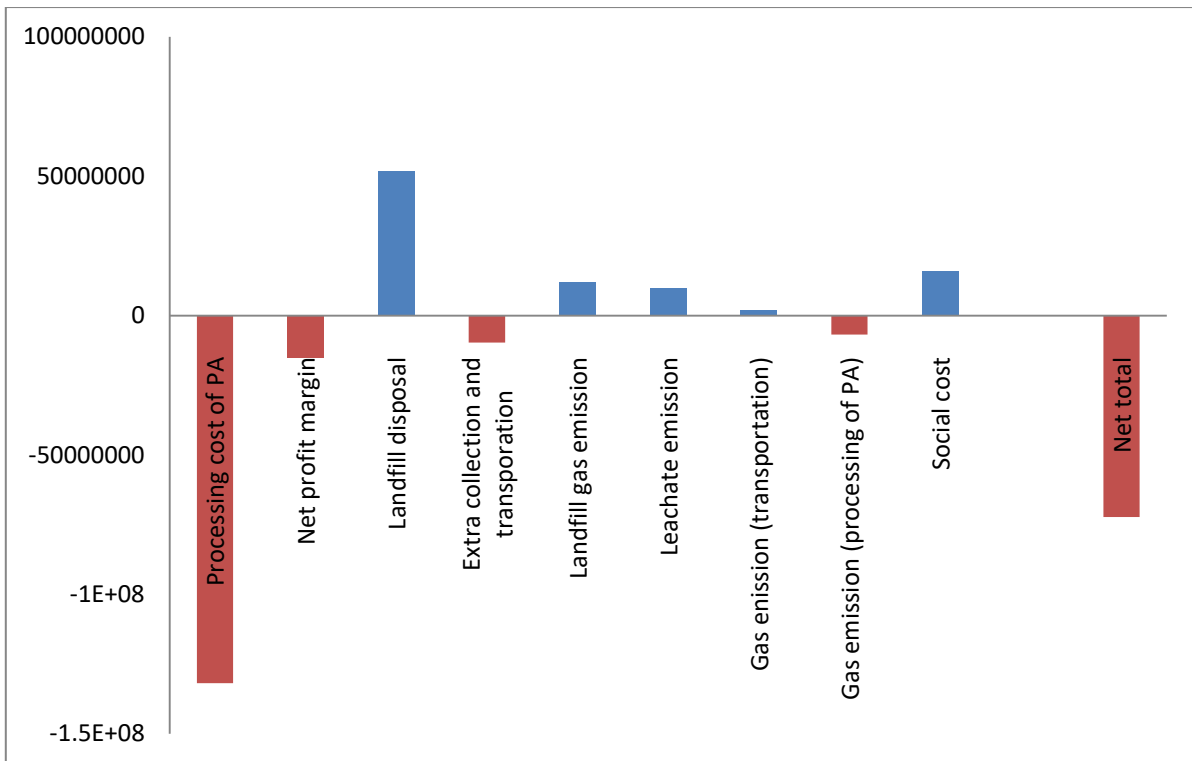
Total processing cost of 27278 ton plastic aggregates is estimated as 13,18,70,854 INR in the section 6.2.1. According to Damodaran (2023), the average net profit margin for building

material processing industry is 10.30%. Hence, an additional cost of net profit of 1,51.42,362 INR has been considered.

All the costs associated with the proposed strategy of partially replacing natural aggregates with PE and PET based plastic aggregates in concrete at Kolkata have been presented in Table 6.10 and Figure 6.10.

**Table 6.10: Summary of the associated costs of the proposed strategy**

Type	Description	Related costs (INR)	
		Benefit (+)	Expenditure (-)
Market price of plastic aggregate	Processing cost		13,18,70,854
	Net profit margin		1,51.42,362
Direct costs	Landfill disposal cost	5,18,66,939	
	Collection and transportation cost of remaining uncollected waste		97,24,700
Environmental costs	Landfill gas emission cost	1,18,81,621	
	Leachate emission cost	97,91,590	
	Cost of gas emission from transportation	17,80,366	
	Cost of gas emission due to processing of plastic aggregates		68,76,065
Social cost	WTP for better and more efficient collection and management of plastic waste	1,59,91,051	
Net cost		(-) 7,23,02,414	



**Figure 6.10: All the associated costs with the proposed management system**

Since the yearly total net cost for 27278 ton of PE and PET based plastic aggregates is 7,23,02,414 INR, so the rate of plastic aggregate is estimated as 2650 INR/ton.

### 6.3. Economic Feasibility Check

Whether the proposed strategy is feasible from the economic point of view or not, that has been evaluated in this section.

#### 6.3.1. Mix Design of Concrete

For this study, mix design of M30 grade concrete has been done for 13 different cases based on IS 10262:2019 (Revised), IS 456: 2000, IS 383: 2016 and IS 9103: 1999. The detail mix design and mechanical and durability properties of PA based concrete are described in Sau et al. (2023a) and Sau et al. (2023b). It has been observed that the fresh and dry density of concrete decreases up-to 8.16% and 8.6%, while workability increases up-to 20% at 40% replacement. On the other hand, though compressive strength reduces with increase of plastic aggregates, it is permissible up-to 30% replacement. Further, the tensile strength of concrete increases up-to 10% before declining while impact resistance and resistance against acid attack, alkaline, marine, and municipal wastewater also increases significantly. So, this

concrete is viable to use as green sustainable lightweight concrete. Obtained values from mix design have been presented in Table 6.10.

### 6.3.2. Data Collection on Rate of Raw Materials

**Cement:** According to Mahajan (2023), the average price of 53 grade OPC cement in India is 400 INR per bag. Hence, the rate of cement is taken as 8 INR/Kg.

**Water:** For consumption up-to 10,000 litres of treated water for industrial use, tariff will be calculated at the rate of 33.60 INR per 1,000 litres [The Hindu, 2020]. Hence, the rate of water is taken as 0.0336 INR/Kg.

**Gravel:** The rate of gravel is taken as 2.25 INR/Kg after conducting a local market survey.

**Sand:** The rate of sand is taken as 1.5 INR/Kg after conducting a local market survey.

**Admixture:** The rate of admixture is taken as 60 INR/Kg on the basis of online prices.

**PCA and PFA:** The rates of plastic aggregates are taken as 2.625 INR/Kg (section 6.2.3).

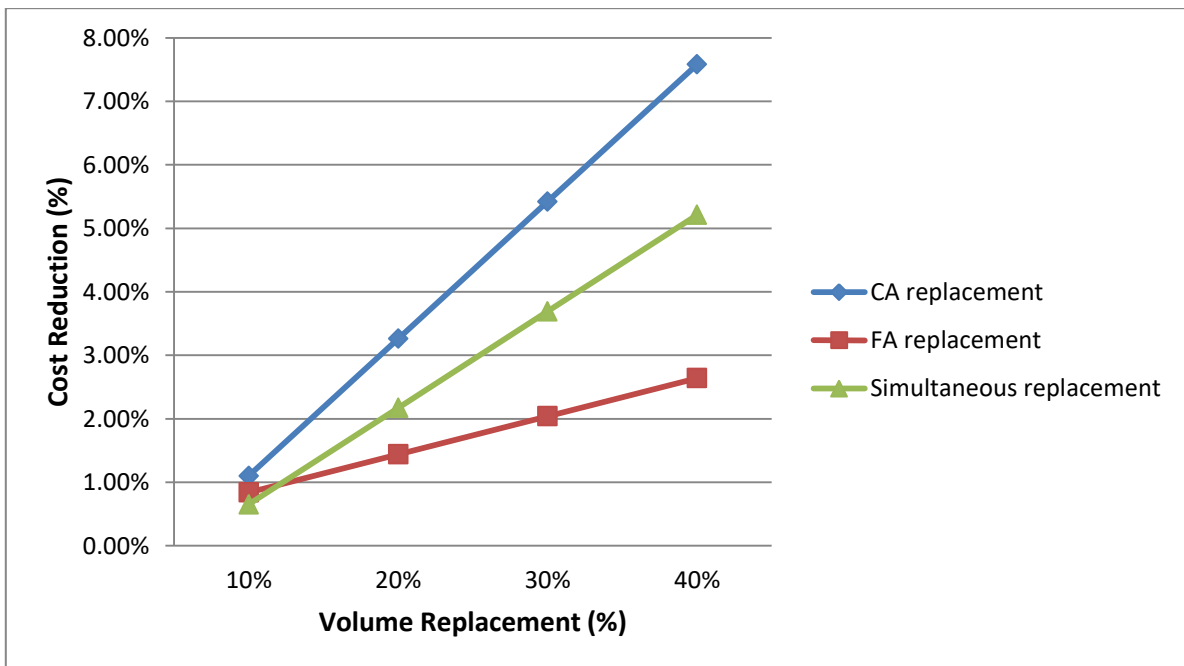
### 6.3.3. Comparison of Production Cost of Concrete

Concrete production costs of 13 cases of this study are estimated and presented in Table 6.11 and the changes in cost reductions based on volume replacements are shown in Figure 6.11 in a graphical form. The mix design data and the rate of materials are taken from Sau et al. (2023b) and section 6.3.2 respectively to estimate the production costs of concrete.

**Table 6.11: Estimation of production cost of concrete**

Volume replacement by plastic aggregates	Cement (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	Sand (Kg/m <sup>3</sup> )	Gravel (Kg/m <sup>3</sup> )	Admixture (Kg/m <sup>3</sup> )	Plastic coarse aggregate (Kg/m <sup>3</sup> )	Plastic fine aggregate (Kg/m <sup>3</sup> )	Cost (INR/m <sup>3</sup> )	Comparison of cost with conventional concrete
No replacement	410	165	690	1170	4.08	-	-	7197.84	-
10% CA replacement only	410	165	690	1083.24	4.08	43.61	-	7118.2	- 1.11%
20% CA replacement only	410	165	690	962.88	4.08	87.22	-	6962.96	- 3.26%
30% CA replacement only	410	165	690	842.52	4.08	130.83	-	6807.71	- 5.42%

Volume replacement by plastic aggregates	Cement (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	Sand (Kg/m <sup>3</sup> )	Gravel (Kg/m <sup>3</sup> )	Admixture (Kg/m <sup>3</sup> )	Plastic coarse aggregate (Kg/m <sup>3</sup> )	Plastic fine aggregate (Kg/m <sup>3</sup> )	Cost (INR/m <sup>3</sup> )	Comparison of cost with conventional concrete
40% CA replacement only	410	165	690	722.16	4.08	174.43	-	6652.44	- 7.58%
10% FA replacement only	410	165	610.83	1170	4.08	-	22.09	7137.63	- 0.84%
20% FA replacement only	410	165	542.96	1170	4.08	-	44.18	7094.36	- 1.44%
30% FA replacement only	410	165	475.09	1170	4.08	-	66.27	7051.09	- 2.04%
40% FA replacement only	410	165	407.22	1170	4.08	-	88.34	7007.77	- 2.64%
6% CA, 4% FA replacement	410	165	654.01	1131.38	4.08	26.17	9.3	7150.96	- 0.65%
12% CA, 8% FA replacement	410	165	626.76	1059.17	4.08	52.33	18.6	7041.58	- 2.17%
18% CA, 12% FA replacement	410	165	599.51	986.95	4.08	78.49	27.91	6932.21	- 3.69%
24% CA, 16% FA replacement	410	165	572.26	914.73	4.08	104.66	37.21	6822.83	- 5.21%



*Figure 6.11: Relation between cost reduction and volume replacement*

From Table 6.11 and Figure 6.11 it can be concluded that the production cost reduction of waste plastic aggregate based concrete varies from 0.65% to 7.58% compare to conventional concrete and the reduction is proportional to the percentage of volume replacement. It has been seen that the reduction rate is highest in case of coarse aggregate replacement and lowest in case of fine aggregate replacement.

The number of studies that has been conducted previously on the economic analysis of using plastic aggregate in concrete is very limited. According to Islam and Shahjalal (2021), concrete containing 10% replacement with polypropylene plastic particles is optimum for both of stone aggregate concrete and brick aggregate concrete. As per another study by Alqahtani et al. (2021), cost of the slab formwork quantity needed for the LLDPE based concrete is 13% to 21% less and savings in life cycle costs reached up to 5.9%. Again, according to Lasiyal et al. (2016), cost saved per cubic meter of concrete are 4.72, 9.45 and 14.17 INR respectively for 1%, 2% and 3% replacement of fine aggregates by PET flakes.

# Chapter 7: Conclusion and Recommendation

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## 7.1. General

In this chapter, a conclusion has been made regarding viability of the proposed strategy based on economic evaluation considering all the aspects. Furthermore, some biggest challenges of this proposed strategy are discussed here along with some practical recommendations to overcome those challenges and to help for successful implementations which may help the environment and to society in various ways. Future scope of this study is also mentioned in this chapter.

## 7.2. Conclusion

Even though the production cost of recycled PA is more compare to natural aggregates, still it has been seen that the introduction of PE and PET based aggregates as partial replacement of natural aggregates in concrete reduces the production cost of it without compromising the mechanical strength when the environmental and social benefits of the proposed strategy are monetized and requirement of aggregate is considered. The cost reduction varies between 0.65% and 7.58% depending upon the percentage and type of replacement, but as the maximum permissible replacement percentage is 30% based on the changes in mechanical properties, hence the maximum reduction of the production cost of concrete that can be achieved without compromising the strength is 5.42%. Based on this result, it can be concluded that the proposed strategy is not only economically viable but it is economically beneficial too. Further, the net cost of plastic based aggregates will come down even more when the other environmental benefits associated with the proposed strategy apart from the ones which have been monetized in this study, would be considered during the estimation of cost. Additionally, it will create substantial amount of job opportunities.

Apart from that, the proposed strategy is also hugely beneficial to the environment and it reduces the severity up-to a great extent of two serious global challenges- (i) mismanagement of plastic waste and associated issues of leachate and GHG generation from landfill, micro-plastic pollution, increase in mosquito borne diseases, blockage of drainage system,

requirement of extra landfill area etc., and (ii) shortage of natural aggregates and associated issues of noise and dust pollution, land loss, alteration of river course and subsequent effects to the water quality and aquatic habitats, erosion etc. The total potential reduction in carbon emission as CO<sub>2</sub>e resulted from the proposed strategy is estimated as 4191427 Kg per year. With successful implementation of the proposed strategy at a larger scale, these associated benefits will certainly push the society forward towards a sustainable future.

### **7.3. Challenges**

- Many authors such as Jaivignesh and Sofi (2017), Amalu et al. (2016), Jibrael and Peter (2016), Sarwe (2014) have raised their concern regarding the reduction of compressive strength of the concrete with introduction of plastic in their respective studies. Hence, plastic aggregate based concrete should be used in such a way that it does not compromise with the safety.
- As the plastic aggregate processing plants are totally dependent on the collection and segregation by municipality for the supply of raw materials, uncertainty of feed may prove to be a challenge in a longer run.
- The proposed strategy is presented on the basis of collection of the uncollected plastic wastes and prevention of waste plastics going into the landfill and aquatic system. Making it happen in reality is certainly one the biggest challenges of this study.
- Convincing the common people to use plastic waste based concrete and industrial owners to invest on it by overcoming a mental barrier against this needs to be done by giving assurance of safety and showing all the benefits. It is very essential for success of the proposed strategy.

### **7.4. Recommendations**

- As the production cost of all 12 cases of plastic aggregate based concrete is less than the conventional one and it reduces further with increased percentage of replacement, the changes in mechanical properties of concrete are also need to be considered. Hence, the optimum percentage of replacement should be recommended based on the changes in mechanical properties.
- As the proposed strategy is hugely beneficial to the environment, the policy makers should develop suitable methodology and specifications regarding using waste plastic as replacement of natural aggregates in concrete.

- With implementation of such policy, the plastic aggregates will be produced in mass quantity, which will result in further reduction of the production cost and will make the proposed strategy more economically beneficial and lucrative.
- Government should put efforts to spread awareness regarding the benefits of the proposed strategy and the vast opportunity lies in this fairly untapped market to generate interest and also recommended to provide subsidy on the electricity bill at processing centres as it is the highest contributor to the processing cost of plastic aggregates to encourage the investors to invest on this industry.

### **7.5. Future Scope**

- During quantity estimation and economic evaluation, certain assumptions have been made based on a large set of secondary data. Attempt may be made to do the economic viability study based on less number of assumptions and more primary data for better accuracy.
- To compute the environmental cost of plastic waste based aggregates, benefits from less generation of leachate and greenhouse gasses have been monetized. Other environmental benefits associated to the proposed management strategy, such as prevention of land loss, change of river course, noise and dust pollution, etc. due to less extraction of natural aggregates may also be monetized and considered during calculation of environmental cost. Further, a Life Cycle Assessment study may be conducted to identify any potential of global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation during the aggregate preparation from plastic waste.
- For the estimation of social cost using WTP survey, required number of sample size was 100 and even though 100 emails were sent to randomly chosen people from different households of the study area, the number of response was only 35. This estimation may be made based upon more number of responses and a larger domain of collected data for more precision.
- The whole study has been conducted upon the mismanaged waste plastics while the recycled plastic wastes have not been considered as it already has a stable market. But as recycled plastic wastes pollute the environment more than virgin plastics, attempt may be made to conduct a LCCA to identify the better strategy between conventional recycling and the proposed one to go forward.

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