CHAPTER- I

INTRODUCTION

1.1 GENERAL BACKGROUND

India is an agricultural-based developing country, which is shifting towards urbanization at a fast rate. As the country's standard of living is increasing, its waste generation also raising. Urbanization, economic development, and population growth all have a significant impact on waste generation. As a result, a sustainable solution that leads to a healthy, resilient, and pollution-free environment is required. Landfills or open dumping is the easiest and most convenient approach to dispose of waste in most underdeveloped/developing countries. The current situation emphasizes the 4R's technique, which is to reduce, reuse, recycle, and recover, but these techniques may require more energy, labor, time, and people's acceptance. Most of the waste generated is not recycled, reused, or treated because of poor management or handling of waste, and it eventually lands in a landfill.

1.1.1 Scenario of Waste Generation

The world is evolving into a new era, leaving behind the unresolved generated waste problem. The world's population rose dramatically from 3.1 billion in 1960 to approximately 7 billion in 2010 and is expected to reach 9.3 billion by 2050. (FAO, 2013). Global waste generation has increased from 635 MT (million metric tonnes) in 1965 to 1999 MT in 2015, and it is expected to reach 3539 MT by 2050. Current trends show a continuous increase in waste production with unsustainable treatments, with landfilling being the most prevalent (Chen et al., 2020). According to the world bank (2018), the expanding population significantly generated 2.01 billion tonnes of waste in 2016 and is expected to reach 3.40 billion tonnes by 2050. Out of the total waste generated only 33% of the waste could be managed or collected. The quality and quantity of waste are heavily influenced by the country's income. High-income countries account for only 16% of the global population but generate approximately 34% of the total waste. Low-income countries generate more waste as compared to high-income countries. The data of the top 20 waste-generating countries, along with their GDP, are shown in Figure 1.1, with India ranking third being the low-income country. In low-income countries, the percentage of waste collected is incredibly low, at around 48% in cities and only 26% in rural areas. Even the quality of waste varies greatly, with high-income countries producing 32% of food waste and 51% of recyclable waste, while low-income countries produce 53% of food waste and 56% of green waste, respectively. Some landfills receive approximately 37% of total waste; 8% (sanitary landfill); 33% (open dump); 19% (recycle or compost); and 11% (other) (incinerated). Open dumping is around 93% in low-income countries, compared to only 2% in high-income countries (World Bank, 2018).

India's urban population is 471 million, accounting for approximately 34.5% of the total population as per the 2011 Census of India. According to the Planning Commission 2014 report, this urban population generates approximately 62 million metric tonnes of municipal solid waste (MSW) per year, which is expected to increase to 165 and 436 MT/year by the end of 2031 and 2050. CIPET (Central Institute of Plastic Engineering and Technology, Chennai) conducted a study in 59 city-states where MSW generation was approximately 50,592 TPD (tonnes per day) in 2009-2010, increasing to 1,27,486 TPD in 2010-2011, of which only 70% was collected and only 12.45% was treated (CPCB, 2013). In general, waste in India is composed of 40% to 60% compostable material, 30% to 50% inert material, and 10% to 30% recyclable material (Joshi and Ahmed, 2016). Indian MSW is not suitable for thermal treatments such as incineration and pyrolysis due to its high organic content and low calorific value (800-1,100 kcal/kg) (Sebastian and Alappat, 2016). The world waste composition or characterization (average) is shown in Figure 1.2 (a), with biodegradable waste accounting for the majority (44%) (consisting of food and green waste), whereas India generates 47.5% of biodegradable waste (Figure 1.2 (b)). Many authors have also mentioned the physical and chemical characterization of Indian waste with the population (Sharholy et al., 2008; Singh et al., 2011; Gupta et al., 2015; Malav et al., 2020).

Solid waste is widely regarded as an urban issue, with urbanization, economic wealth, living standards, and consumption of goods and services all contributing to an increase in the amount of waste generated (Marshall and Farahbakhsh, 2013). The global urban population grew, from 751 million in 1950 to 4.2 billion in 2018, while the rural population has declined. Now, the population residing in urban areas is approximately 55% of the world's population, compared to 1950 which was only 30% and it is predicted that by 2050, 68% of the world's population will be urban (UN DESA, 2018). Even in India, urbanization increased from 27.8% in 2001 to 31.6% in 2011, with up to 50% of the Indian population expected to live in cities within the next ten years (Devi et al., 2016; Gupta and Arora, 2016). According to the World Bank (2018) report, the country with the highest urbanization rate (82%), generates approximately 2.21 kg/capita/day, while the country with the lowest urbanization rate (38%) generates 0.46 kg/capita/day.

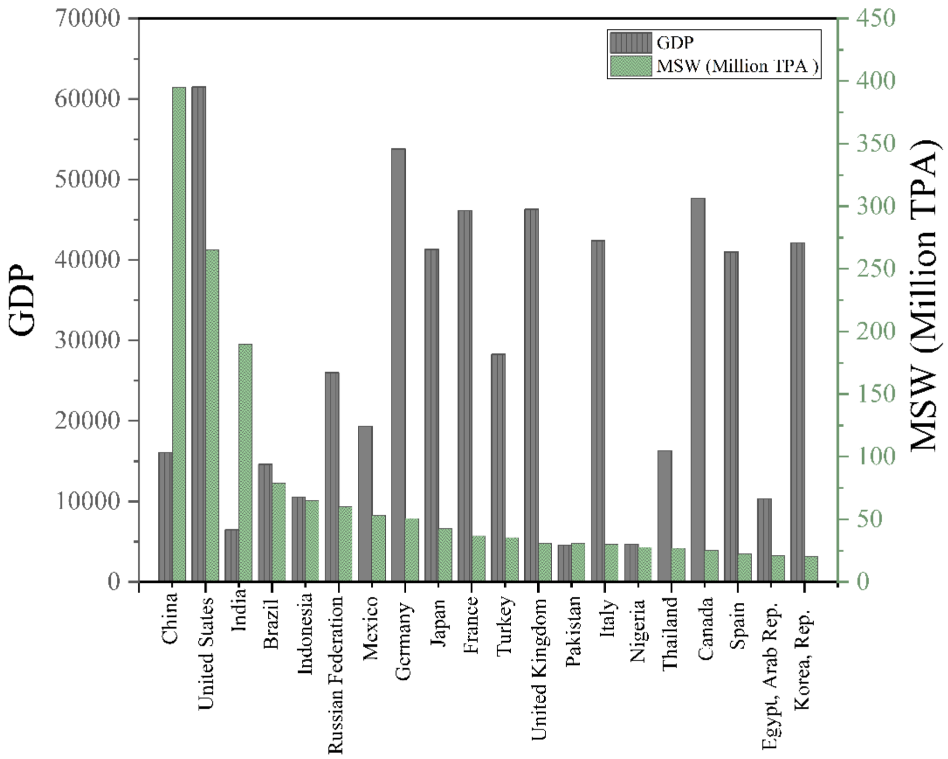
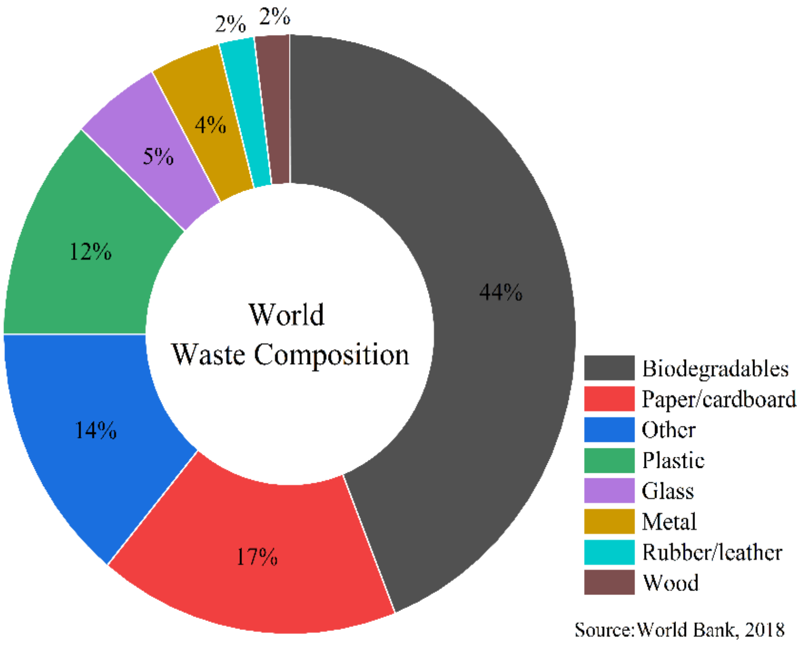
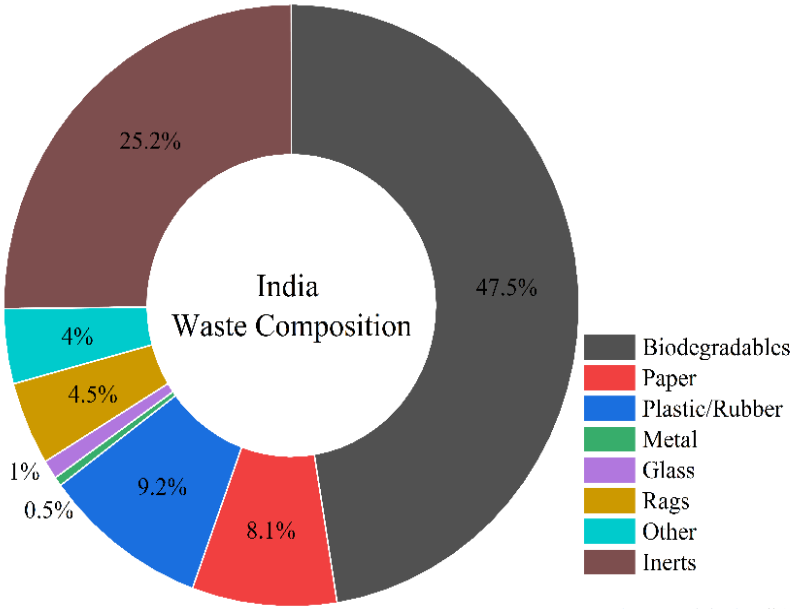


Figure1.1 Top 20 waste generating countries with their GDP



Source: World Bank, 2018

(a)



Source:Manual on Municipal Solid Waste Management Part 2, Ministry of Urban Development 2016

(b)

Figure 1.2 Waste composition of **(a)** world **(b)** India

1.1.2 Solid Waste Management (SWM) in India

The major challenge for India is its unorganized waste collection system. The average MSW collection efficiency in any large city in India is about 70% (Khan, 1994; Maudgal, 1995; Gupta et al., 1998; Rathi, 2006; Siddiqui et al., 2006; Saxena et al., 2010). One of the biggest challenges faced by the authorities in SWM is the segregation of waste before even going for the treatment process. There are various authorities involved in regulating the waste management system. The Ministry of Environment, Food, and Climate Change is overviewing the country's application of solid waste management (SWM) standards. The Central Pollution Control Board (CPCB) gathers data from State Pollution Control Boards (SPCBs) and Pollution Control Committees (PCCs) and submits an annual report to the MoEF &CC on the state of SWM in the country.

The Municipal Solid Wastes (Management and Handling) Rules of 2000 established waste segregation as a legal mandate and policy pillar, but due to a lack of awareness, not much progress was made. The Ministry of Environment, Forest, and Climate Change (MoEF &CC) notified the Solid Waste Management (SWM) Rules of 2016, which state that waste must be separated at the source and useful waste should be recovered, reused, and recycled. The rule also states that food waste from hotels and restaurants must be composted or biomethanated. Landfills should only be used for non-recyclable, non-biodegradable, non-combustible, and non-reactive inert waste, as well as pre-processing rejects and residues from the waste processing facilities. Even though it is now mandatory to treat waste before dumping it, only 20% of collected waste is treated and processed; the remainder is dumped in open landfills (MoHUA, 2016-17). Some waste-to-energy (WtE) technologies like incineration, pyrolysis, composting, refuse-derived fuel, and biomethanation have recently been adopted in some parts of India, but the country still lacks resources and technical expertise (Mondejar-Jimenez et al., 2016). These WtE technologies are investigated with highly positive results in developing countries, but in India, this is still a challenge due to its installation cost and sustainability (Sharholy et al., 2008), and even in many cities, they are unsuccessful due to various operational and design issues, lack of consciousness, insufficient funding, irresponsibility, and lack in terms of technical aspects (Kalyani and Pandey, 2014).

There are currently 209 composting, 207 vermicomposting, 82 biomethanation, and 45 Refuse derived fuels (RDF) operating units in India (CPCB, 2016). For the generation of electricity from MSW, six plants with a combined capacity of 65.75 MW are in operation (MNRE, 2018). The country has the potential to generate 2.55 GW of energy from MSW from urban waste and 1.68 GW from industrial waste. The collective urban waste of all cities can generate approximately 50.50 GW of energy, which can be increased to 1.12 GW by 2031 and 2.78 GW by 2050. The installed capacity of WtE plant was 43.45 MW in 2007, and it had grown to 138.30 MW by the end of 2018. (Paulraj et al., 2019).

India still needs to improve its solid waste management system, there could be numerous reasons for its failure (specially WtE projects), some of them could be insufficient waste collection techniques, lack of source segregation, litigation challenges, waste quality, viable technology, insufficient financial support, lack of public participation and lack of policies. Some of the major challenges faced by the country regarding SWM/WtE projects are as follows (Malav et al., 2020):

- India is a diverse country in respect of its large geographical area, huge population with different standards of living, diverse topography, and variable climate. This diversity also affects the quality/quantity and characteristics of the generated waste. This forces policymakers to rely on limited data, and as a result, they are unable to provide alternative solutions based on the waste type.
- The WtE technologies are still a new concept for a country like India. The country still needs to build the required capacity to train skilled laborers, become familiar with the latest technologies applied worldwide to SWM, financial incentives for determining novel techno-viable alternatives, and refine decision-making processes that can result in rapid and effective decisions regarding the implementation of such technologies in a smooth manner.
- Another issue is the lack of financial investment in waste management, which limits the infrastructure needed to provide proper solutions.
- The country also requires an integrated solid waste management system that includes generation, transfer, segregation, sorting, recovery, treatment, and disposal with cost-effective resource utilization and maximization.

- The inadequate implementation of rules and regulations because of the poor coordination between the center and state leads to delays in projects on the ground level.
- The segregation of the waste itself is a most challenging and time taking process and requires mass involvement and awareness.
- Appropriate technological solutions are required through research & development (R&D). Public and private partnerships with subject experts and corporations are required to achieve management and effective handling using cutting-edge technologies.

Despite advanced waste management technologies and methods, landfilling remains the most popular and cost-effective method in developing countries. Sanitary landfilling is the final step in SWM after all other treatments have been exhausted. Although approximately 51% of waste in India is classified as biodegradable (Ahluwalia et al., 2018), only 6-7% is converted to compost, with the remainder being dumped in landfills (Annepu, 2012). According to the CPCB annual report for 2019-20, there are 3151 existing dumpsites, with 14 of them converted to sanitary landfills. Because this waste is a growing issue, 1359 new sites have been identified to meet future demand (Figure1.3). The report also stated the 5-year data or the percentage of waste that has been treated and landfilled. The gap in solid waste management has been reduced to 23% by 2020, and approximately 50% of the waste collected gets treated (Figure 1.4). Although the data in the report only pertains to municipally collected waste, there are no records of waste that is openly dumped illegally. It is assumed that the area of land required to dispose of MSW by the end of 2047 will be 1400 km^2, which is nearly equivalent to the combined area of Hyderabad, Mumbai, and Chennai (Sharma and Jain, 2019). There will undoubtedly be a severe scarcity of land soon, which must be addressed. This necessitates long-term landfill management, in which open dump sites are converted to sanitary landfills. Landfill mining could be one of the most effective methods for reclaiming land and reaping economic benefits from old and closed landfills.

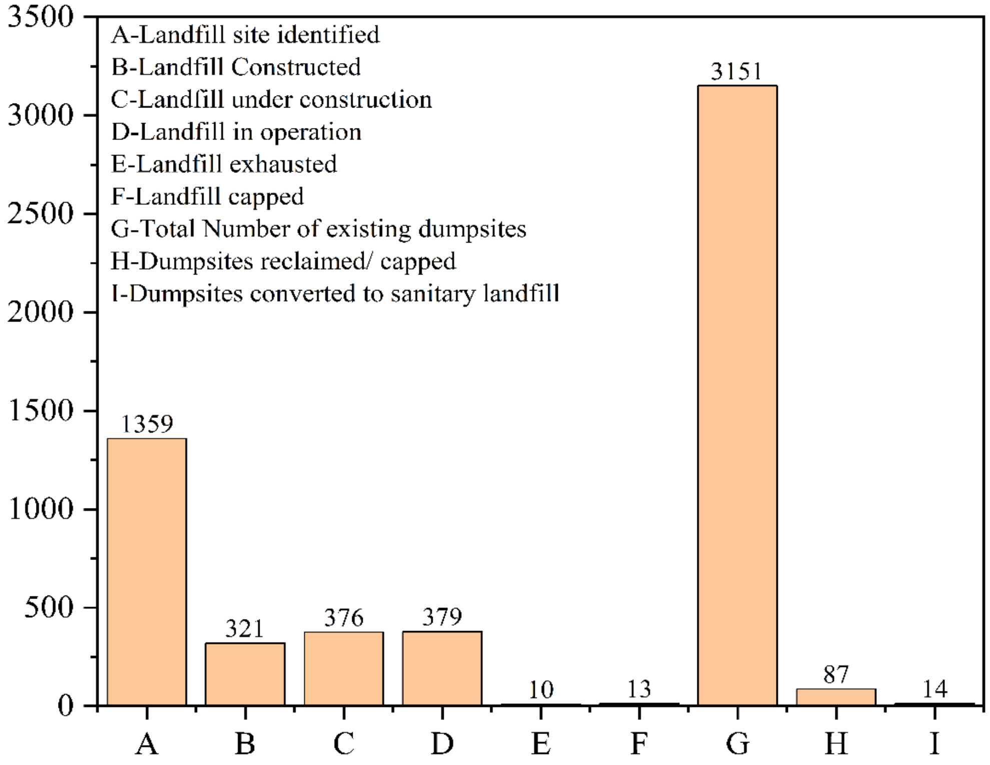


Figure 1.3 Indian landfill data (Source@ CPCB annual report (2019-20)

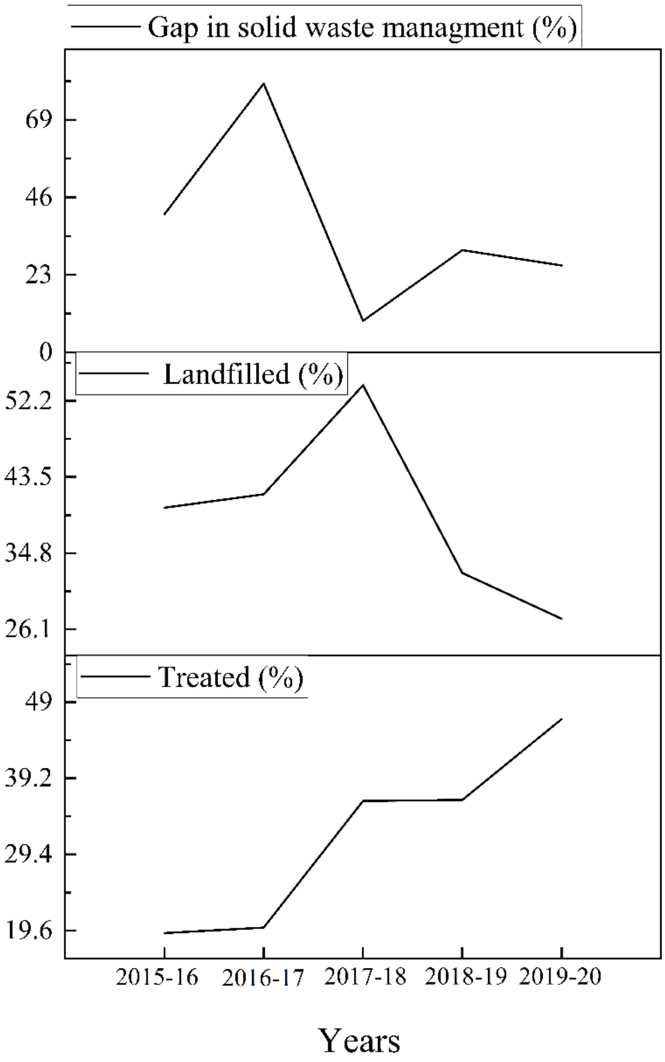


Figure 1.4 Indian solid waste management data
(Source@ CPCB annual report (2019-20)

1.1.3 Landfill Mining

A landfill is a large area designed specifically to receive waste. Landfill mining (LFM) is defined as "the excavation and treatment of waste from an active or inactive landfill for one or more of the following purposes: landfill space conservation, landfill area reduction, elimination of potential contamination sources, energy recovery from excavated waste, reuse of recovered material, waste management system cost reduction, and site redevelopment" (Cossu et al., 1996). It is also defined as "a process for extracting materials or other solid natural resources from previously disposed of waste materials by burying them in the ground" (Krook et al., 2012). Now the focus has been shifted from landfill mining (LFM) to enhanced landfill mining (ELFM) which is an advanced level of LFM. LFM is limited to the reclamation of landfill space, methane, and a few valuable metals such as copper or aluminium. However, LFM is not always carried out with a focus on resource recovery. It has also been used to simply restructure the landfill due to insufficient gas and leachate collection systems or slope instability. ELFM, on the other hand, focuses on full valorization (completely closing the circle of waste) of all landfilled waste as both materials and energy and eventually regaining the land (Danthurebandara, 2015).

Every landfill mining project is unique due to its unique site-specific and environmental conditions, project objective, waste quality, and waste composition. There are also several unknowns at the project level. Baas et al. (2010) identified four major types of uncertainties associated with landfill mining projects, namely (none of which have been adequately addressed) landfill waste composition, the efficiency of materials processing technologies, markets for materials recovered from landfills, and environmental and health risks associated with the excavating landfills. Landfill mining could be a great source of materials, but due to the heterogeneity of the fill, sorting, segregating, and recovering materials could be a time-consuming and expensive task. Referring to the environmental point of view and the growing human population and their need for land for living, food, agriculture, or even waste disposal has compelled us to focus on new approaches for dealing with the waste dump yards, enhanced landfill mining (ELFM) could be one solution.

1.2 AN OVERVIEW AND PROBLEM IDENTIFICATION

The old dumps and closed landfills become a serious problem as not only do they cover a large land area but also create a concern for the environment. There are various comprehensive studies around the world on landfill waste which include characterization of waste, basic physical, chemical, and geotechnical characterization, shear strength and settlement analysis, and aging effects of waste (Gabr and Valero, 1995; Zekkos, 2005; Zekkos et al., 2013a, b; Zhan et al., 2008; Singh et al., 2009; Chen et al., 2009; Babu et al., 2010; Reddy et al., 2011; Bareither et al., 2012; Gomes et al., 2013; Babu and Lakshmikanthan, 2015; Abreu and Vilar, 2017). Most of these laboratory and field studies focus on the stability and settlement of the waste in the landfills and how these landfills (if closed) can be further made suitable to use for future development. Although the other perspective could be to mine this waste and reutilize it further after processing. The characterization studies of the waste from most landfills around the world validate that 60% or more of mined waste from the landfills appears to be soil-like material (Mönkäre et al., 2016; Havangi et al., 2017; Somani et al., 2018). Most of these fine materials are redeposited as soil covers in the same landfills without treatment, whereas these soil-like materials can be recycled and used in the fields with additional treatments (Wanka et al., 2017). If its physicochemical parameters are within the allowable limits, it can be used in the geotechnical field, as a backfill/embankment material, or even as a construction material for brick manufacturing/concrete mix. Even there are various studies (field and laboratory) on the dynamic characterization or parametric studies of landfill waste to check the behaviour and stability of the waste fills under earthquakes or other vibrations due to traffic or construction activities (Zekkos et al., 2008; Ramaiah et al., 2016 (a, b, and c); Alidoust et al., 2018; Keramati et al., (2016, 2018); Naveen et al., 2014a). The studies on the soil-like portion or MSW fines (considered in this study) are very limited to its physical and chemical characterization (Kurian et al., 2003; Somani et al., 2018; Quaghebeur et al., 2013; Singh and Chandel, (2021,2022a)). Thus, it is important to investigate the static and dynamic characterization of MSW fines to check its reusability as geomaterial like fill material in embankments/ backfills (field applications).

There are even immense studies have been carried out for reinforced soils. Soil reinforced with randomly distributed fibers has a wide range of successful applications, including retaining structures, embankments, subgrade stabilization, and so on. Various studies also show that adding geosynthetics and bio-based fibers (natural fibers) to soil improves its physical and mechanical properties (Haeri et al., 2000; Yetimoglu and Salbas, 2003; Punthutaecha et al., 2006; Tang et al., 2010; Fatahi et al., 2013; Hamidi and Hooresfand, 2013; Chen et al., 2015; Kumar and Gupta, 2016; Debnath and Dey, 2017; Yoo and Abbas, 2020). Even some studies also show reinforcement increases liquefaction resistance and dynamic characteristics of soils (Krishnaswamy and Isaac, (1994, 1995); Ye et al., 2017; Ghadr et al., 2020). Geotextiles are used in the design of municipal solid waste landfills for a variety of purposes, including separation, filtration, drainage, reinforcement, and cushioning. Sometimes even the landfill's foundation soil requires stabilization and reinforcement with geotextiles, geogrids, or randomly distributed fiber reinforcements. There are no studies regarding the behaviour of reinforced MSW fines under monotonic or dynamic loadings and their field applications. MSW differs from conventional soils in terms of particle size and shape, as well as mechanical, chemical, and engineering behaviour. The engineering behaviour of reinforced MSW may differ from that of the reinforced soils. Because the theories applicable to reinforced soils may not be exactly applicable to reinforced MSW, long-term field monitoring is required to examine the engineering performance of the reinforced waste (Ke et al., 2021).

1.3 OBJECTIVES

Based on the problems stated in the above discussion following objectives have been considered for the present research:

- To study the physical, morphological, mineralogical, chemical, and geotechnical characteristics of MSW fines (soil-like material).

- To study the static strength and consolidation characteristics of the unreinforced and fiber-reinforced MSW fines.
- To study the dynamic characteristics of the unreinforced and fiber-reinforced MSW fines under different relative compaction, confining pressure, frequency of loading, and amplitude of cyclic shear strain.
- To study the stiffness characteristics of the unreinforced and fiber-reinforced MSW fines under low-strain conditions.
- To propose generalized relationships for liquefaction potential evaluation of unreinforced and fiber-reinforced MSW fines by energy method and pore water pressure ratio (r_u) model.
- To develop empirical strain-dependent modulus reduction and damping correlations for unreinforced and fiber-reinforced MSW fines.
- To develop prediction models for dynamic shear modulus of unreinforced and fiber-reinforced MSW fines through machine learning applications.

1.4 SCOPE OF THE STUDY

To accomplish the objective noted above the considered MSW fines, i.e., the soil-like material (particle size < 4.75mm) collected from the Ramana site, Varanasi (India) have been segregated and processed from the rest of the waste. The considered material then was further investigated in the laboratory for its geotechnical (specific gravity, grain size analysis, Atterberg limit, standard proctor, vibratory table, consolidation, permeability, and static triaxial tests), morphological, mineralogical, and chemical characteristics.

The liquefaction potential and dynamic properties of the MSW fines were studied by conducting a series of strain-controlled cyclic triaxial tests. The effect of various parameters like frequency of loading, the amplitude of cyclic shear strain, confining pressure, and relative compaction of the sample on liquefaction potential and dynamic properties of the MSW fines were studied. The results have been compared with the different soils of the same category.

The behaviour of reinforced MSW fines under static as well as dynamic loading conditions was investigated. The considered reinforcing materials were randomly distributed fibers which were a part of the waste collected from the Kasarda WtE plant, Varanasi (India).

The bender element tests on the unreinforced and reinforced MSW fines were carried out to investigate the shear velocity of the material and low-strain shear modulus (G_{max}). The study provides empirical correlations for the unreinforced and reinforced MSW fines to predict the dynamic parameters and cyclic behaviour which can be used in further numerical analysis to check the seismic response of the considered material when used in geotechnical structures.

1.5 ORGANIZATION OF THE THESIS

This thesis is organized into seven chapters. The outlines of the chapters are presented below:

Chapter I describes the background, motivation towards this research topic, objectives, and scope of the research.

Chapter II provides a review of the previous work on the physical, chemical, mineralogical, morphological, geotechnical, static/cyclic strength, liquefaction, and dynamic properties of MSW, similar soils, and other wastes, i.e., coal and MSW ashes.

Chapter III describes the source of the MSW used, the segregation process of obtaining MSW fines and fibers from the waste, the laboratory testing program, the material characteristics, the sample preparation technique, details of static and cyclic triaxial tests performed, bender element test details, the test procedure adopted, and the details of the equipment used.

Chapter IV presents the field and laboratory experimental results of the MSW fines under consideration. The basic geotechnical (specific gravity, grain size analysis, Atterberg limit, standard proctor, consolidation, permeability, and static triaxial tests) morphological, mineralogical, and chemical characteristics of the MSW fines are studied in the laboratory. The results of the strain-controlled cyclic triaxial tests are also discussed. The effect of various parameters such as loading frequency, the amplitude of cyclic shear strain, confining pressure, and relative compaction on the liquefaction potential and dynamic properties of MSW fines is reported. The chapter also includes the results of the laboratory analysis on reinforced MSW fines with fibers (waste). The analysis of shear wave velocity and low-strain shear modulus from the bender element test of unreinforced and reinforced MSW fines are presented.

Chapter V presents all the correlation studies for unreinforced and fiber-reinforced MSW fines considering the data collected from strain-controlled cyclic triaxial test and bender element test for small-strain shear modulus.

Chapter VI presents the machine learning-based models to predict the dynamic shear strength of the unreinforced and reinforced MSW fines. It also includes the sensitivity analysis of the considered parameters on the dynamic shear modulus of the considered material.

Chapter VII summarises the research and presents the major findings and limitations of the current study and further future research directions are suggested.

Finally, the references used in this study are organized alphabetically.