Università degli studi di Milano-Bicocca

Data Science Lab for Smart Cities

Final Essay

From Waste to Resource: A Holistic Analysis of Waste Management and Recycling Practices in Singapore

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Abstract

Waste management and recycling are crucial components of sustainable environmental practices, aimed at minimizing the impact of waste materials on human health and the environment. Ethical and social implications of waste management need to be included in the decision-making process, focusing on the adoption of policies to reduce waste production and promote recycling. Indicators, such as waste generation, recycling rates, landfill diversion, and waste-to-energy conversion, are useful in measuring and evaluating waste management practices in smart cities. In this paper, we present an analysis of waste management in Singapore, focusing on waste generation, disposal, recycling, and the ethical and social implications associated with these practices.

Using a comprehensive dataset spanning the last two decades, we examine the historical trends and indicators of waste management in Singapore. We explore Singapore's waste management roadmaps and their impact on waste generation and disposal patterns. Additionally, we investigate the contribution of different materials to waste disposal and analyze the environmental value of recycling efforts. Through quantifying energy savings and greenhouse gas reductions achieved through recycling, we assess the significance of recycling initiatives and compare them to the energy produced by waste-to-energy centers. Furthermore, we conduct a forecast analysis to provide insights into future waste generation trends in Singapore. By considering population growth and other relevant factors, we offer a glimpse into potential future scenarios and the challenges that lie ahead.

The ethical responsibility for waste management falls on individuals, businesses, and governments to minimize waste generation, promote resource recovery, and protect ecosystems for present and future generations. Social implications encompass the need for equitable waste collection infrastructure, fair labor practices, and inclusive integration of informal waste pickers into formal waste management systems. Policy measures such as banning unnecessary packaging, promoting item reuse through second-hand marketplaces, preventing planned obsolescence, and leveraging AI technologies in recycling can help improve how smart cities deal with waste. These policy suggestions aim to address ethical concerns, conserve resources, reduce waste disposal, create economic opportunities, and foster a circular and sustainable economy. However, the implementation of these policies should be guided by stakeholder engagement, transparency, and careful consideration of potential challenges and environmental impacts. Through comprehensive and inclusive waste management strategies, cities can strive towards a cleaner, healthier, and more sustainable future for all.

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1 Smart City, Waste Management and Recycling

1.1 Waste Management and Recycling

Waste management and recycling are critical aspects of sustainable environmental practices. Waste management involves the collection, transportation, disposal, and recycling of waste materials to minimize their impact on human health and the environment. Recycling, in particular, focuses on the process of converting used materials into new products, reducing the need for extracting and producing virgin resources[1]. Waste management encompasses various activities aimed at effectively handling waste materials. It involves proper waste collection methods, including curbside pickup, waste sorting, and segregation to separate recyclable materials from non-recyclable waste. The collected waste is then transported to treatment facilities, such as recycling centers, composting sites, or landfill disposal sites, depending on the nature of the waste and available infrastructure [2].

Recycling is a key component of waste management that focuses on converting used materials into new products through various processes. Recycling helps conserve natural resources, reduce energy consumption, and decrease pollution associated with the extraction and production of virgin materials. Commonly recycled materials include paper, plastics, glass, metal, and organic waste. Through recycling, waste materials are processed to extract valuable resources that can be used to manufacture new products. This reduces the amount of waste sent to landfills, conserves resources, and minimizes the environmental impact of resource extraction and waste disposal [3].

1.1.1 Waste Disposal and Handling

When trash is improperly managed, it can lead to pollution of air, water, and soil. Decomposing organic waste in landfills produces methane, a potent greenhouse gas that contributes to climate change [4]. The release of methane during the decomposition process can also contaminate groundwater and emit foul odors [5]. Additionally, when rainwater passes through landfills, it can pick up harmful chemicals and contaminants, forming a toxic liquid called leachate, which can contaminate nearby water bodies and groundwater quality [6].

A solution adopted in order to manage waste in many countries is open burning waste, particularly in developing countries, which releases emissions which are deemed in some cases hazardous [7]. This is particularly true when considering the open burning of plastic waste [8]. Burning waste, particularly in open fires or uncontrolled incineration processes, can have severe environmental consequences. The combustion of waste releases various pollutants into the air, including particulate matter, sulfur dioxide, nitrogen oxides, and toxic chemicals [9]. These pollutants contribute to air pollution, which can harm human health and ecosystems. Particulate matter, for example, can cause respiratory problems and cardiovascular diseases [10]. Toxic chemicals released during the burning process can contaminate the air and potentially accumulate in the environment, posing long-term risks to both human and ecological health, showing a link with birth defects and cancer [11].

1.1.2 Effects of Recycling

Aside from the clear health benefits to the population, recycling plays a crucial role in conserving resources and it can lead to cut costs in various aspects. Firstly, recycling reduces the need for raw materials, which can be expensive to extract and process. By using recycled materials, industries can lower their production costs and potentially offer more affordable products [12]. Additionally, recycling reduces the amount of waste sent to landfills, which can help municipalities save on landfill disposal fees and related expenses [13]. Moreover, recycling can create economic opportunities by generating jobs in the recycling industry and related sectors [14]. This can contribute to local economic growth and reduce unemployment rates.

Furthermore, reducing the need for extracting and processing raw materials helps conserve natural resources. When materials such as paper, plastic, glass, and metal are recycled, they can be transformed into new products, reducing the demand for virgin materials. This saves energy, water, and other resources associated with extraction, manufacturing, and transportation [12]. For example, recycling one ton of paper can save around 17 trees, 7,000 gallons of water, and large amounts of energy [15]. By diverting waste from landfills through recycling, valuable materials are recovered and reused, reducing the environmental impact of resource extraction and promoting a more sustainable circular economy.

1.2 Waste Management Indicators

Waste management has become a pressing issue in urban environments, with significant environmental, economic, and social implications. As cities strive to become smarter and more sustainable, the development and implementation of effective waste management strategies become paramount. Indicators are a tool to be used in measuring the problem of waste management in the context of smart cities [16]. Specifically, the indicators of waste generation, recycling rates, landfill diversion, and waste-to-energy conversion rate can shed light on the challenges and progress in waste management practices [17].

The **amount of waste generated** by a city serves as a crucial indicator to assess the scale of the problem. This indicator quantifies the total volume or weight of waste produced within a given timeframe, such as per capita waste generation rates. By tracking waste generation trends, policymakers and stakeholders can identify patterns, evaluate the effectiveness of waste reduction initiatives, and develop targeted strategies to minimize waste at its source [18].

Measuring **recycling rates** provides insights into the success of waste management systems in diverting recyclable materials from landfills. Recycling rates indicate the percentage of waste materials that are collected, sorted, and processed for reuse or recycling. Higher recycling rates signify effective recycling infrastructure, public awareness, and engagement. Monitoring changes in recycling rates over time helps evaluate the impact of recycling programs and identify areas for improvement, such as increasing the accessibility of recycling facilities or enhancing public education campaigns [19].

Landfill diversion measures the proportion of waste that is diverted away from traditional landfills. This encompasses various waste management practices, including recycling, composting, and waste-to-energy conversion. A higher landfill diversion rate suggests a more sustainable waste management system, reducing the burden on landfills, minimizing environmental pollution, and maximizing resource recovery. Monitoring landfill diversion rates enables cities to assess the efficiency of their waste management infrastructure and identify strategies to further reduce waste disposal in landfills [20].

Another important indicator in measuring the problem of waste management is the **waste-to-energy conversion rate**. This indicator assesses the proportion of waste that is used as a source of energy through processes such as incineration or anaerobic digestion[21]. Waste-to-energy conversion can help address two challenges simultaneously: waste reduction and energy production. By converting waste into energy, cities can reduce the volume of waste destined for landfills while simultaneously generating renewable energy. Monitoring the waste-to-energy conversion rate provides insights into the efficiency and utilization of waste as a valuable resource. It allows policymakers to assess the effectiveness of waste-to-energy facilities, evaluate their environmental impact, and explore opportunities for increasing energy recovery from waste streams [22].

The measurement and analysis of indicators related to waste management play a vital role in evaluating the effectiveness of strategies implemented in smart cities. By tracking waste generation, recycling rates, landfill diversion, and citizen participation, policymakers and stakeholders can gain valuable insights into the challenges and progress in waste management practices. These indicators enable the identification of areas for improvement, the formulation of targeted interventions, and the promotion of sustainable waste management systems. Through the continued monitoring and analysis of these indicators, smart cities can enhance their waste management practices and move towards a more sustainable and circular economy [23].

1.3 Ethical and Social Implications

Waste management is a pressing global issue with significant ethical and social implications. By understanding these implications, cities can develop informed strategies that prioritize environmental responsibility, social equity, and community well-being [24].

Effective waste management raises ethical questions regarding environmental stewardship and inter-generational justice. The indicators, such as Waste Generation per Capita and Recycling Rate, shed light on the responsibility of individuals, businesses, and governments to minimize waste generation and maximize resource recovery. Ethical considerations involve reducing the environmental impact of waste, mitigating pollution, and protecting ecosystems for present and future generations. Additionally, promoting environmental awareness and responsible consumption fosters a sense of ethical responsibility and accountability among citizens [25].

Waste management has direct and indirect social implications that affect communities, particularly vulnerable populations. Lack of proper waste collection infrastructure disproportionately impacts marginalized communities, leading to environmental injustice and public health risks [26]. Moreover, the presence of informal waste pickers underscores social inequalities and the need for fair labor practices, decent working conditions, and integration of informal workers into formal waste management systems.

The indicators discussed above serve as valuable tools for assessing the social and ethical dimensions of waste management. They provide quantitative measurements that allow policymakers to monitor progress, identify areas for improvement, and allocate resources effectively. For instance, monitoring Waste Diversion Rate helps evaluate the success of recycling and waste reduction initiatives, promoting circular economy principles [27]. Assessing Waste Composition reveals the types of waste generated, enabling targeted interventions and educational campaigns to address specific waste streams [28].

However, it is essential to recognize the limitations of indicators and ensure their alignment with ethical considerations. For example, while the Waste-to-Energy Conversion Rate may offer energy recovery benefits, it should be evaluated alongside potential environmental and health impacts [28]. Ethical and social implications should guide decision-making processes to ensure that waste management strategies prioritize the well-being of communities, minimize harm, and foster inclusive and sustainable development. With a comprehensive and ethical approach to waste management, cities can work towards a cleaner, healthier, and more sustainable future for all.

2 The Singapore Dataset, Analysis and Policies

Singapore has established itself as a global leader in sustainable practices, and the National Environment Agency (NEA) has played a crucial role in ensuring a clean and environmentally friendly city-state. To gain insights into the waste generation, disposal, recycling, and associated environmental benefits, we have analyzed three primary datasets, as well as used some secondary datasets for time series forecasting[29].

This section of the rapport presents an analysis of the trends and patterns observed in waste generation, waste recycling, and recycling rates in Singapore. The data is examined with the aim of gaining insights into the effectiveness of waste management and recycling practices. This section will touch on the topic of waste disposal, waste-to-energy centers and energy conversion. Further, it looks at environmental impact of recycling, and a forecaster analysis on predicted data of waste generation in the decides to come. The analysis aims to provide a comprehensive understanding of the progress made in sustainable waste management and to identify areas for improvement. The rapport ends with discussing policies for waste management and recycling, and their ethical implications.

2.1 Dataset

Waste Generation, Disposal, and Recycling Datasets (2003-2017 & 2018-2022): The first two datasets, created with data from the NEA, provide detailed information on waste generation, disposal and recycling across various waste categories. These datasets cover a wide range of waste materials, including paper/cardboard, ferrous metal, plastics, construction & demolition waste, food waste, horticultural waste, wood waste, ash & sludge, textile/leather waste, used slag, non-ferrous metal waste, glass waste, and scrap tires. Spanning from 2003 to 2017 and subsequently from 2018 to 2022, these datasets enable us to analyze trends and patterns in waste management over time. [30]

Environmental Impact Dataset: The third dataset focuses on the environmental impact of recycling efforts. It provides information on the amount of energy, crude oil barrels, greenhouse gas pollution, and landfill space saved per ton of recycled waste material. The waste materials covered in this dataset include plastic, glass, ferrous metal, non-ferrous metal, and paper. The dataset allows us to evaluate the broader environmental benefits associated with recycling specific waste materials. Understanding the energy savings, reduction in crude oil consumption, greenhouse gas emissions reduction, and reduced landfill usage can help to quantify the positive impact of recycling on Singapore's sustainability goals[31][32].

Economy and Population Datasets: Additionally, to enhance our understanding of waste generation trends, we have incorporated three temporal datasets obtained from Macrotrends.net[33]. These datasets cover significant aspects of Singapore's economy and population, including GDP (Gross Domestic Product), GDP per capita, percentage change in GDP, population, population growth rate, consumer spending in total, consumer spending per capita, and percentage change in consumer spending. Spanning from 1960 or 1970 until 2021, as well as future predictions for population by the UN, these datasets provide a comprehensive historical overview. The datasets are combined with the aim to perform correlation analysis and develop a time series forecast model to predict future trends in waste generation in Singapore.

2.2 Historical Data Analysis

2.2.1 Singapore's Waste Management Roadmaps

Singapore has set ambitious waste management goals to ensure sustainable and efficient waste management practices. Over the years, the country has implemented several plans and initiatives to address waste management challenges and achieve these goals. The first comprehensive waste management plan of interest was introduced in 2002, known as the "Singapore Green Plan 2012." This plan focused on waste minimization, recycling, and resource recovery. It aimed to reduce waste disposal and increase recycling rates through public education, infrastructure development, and industry collaboration[34].

Following the Singapore Green Plan 2012, the government launched the "Sustainable Singapore Blueprint" in 2009, which was revised up until 2016. This blueprint outlined the nation's environmental sustainability goals across various sectors, including waste management. It emphasized waste reduction, recycling, and resource conservation as key strategies for sustainable waste management. Under the Sustainable Singapore Blueprint, Singapore aimed to increase its overall recycling rate and reduce the amount of waste sent to landfill. The blueprint also introduced initiatives to promote sustainable consumption and production, encourage the adoption of environmentally friendly technologies, and enhance public awareness and participation in waste management practices[34].

In recent years, Singapore has further strengthened its commitment to sustainable waste management with the introduction of the "Zero Waste Masterplan" in 2019. This plan sets out a comprehensive roadmap to transform Singapore into a zero-waste nation. The Zero Waste Masterplan focuses on three key strategies: reducing waste generation, increasing recycling rates, and harnessing waste as a resource. It includes initiatives such as the mandatory reporting of packaging waste, extended producer responsibility schemes, and the development of a robust circular economy. To support these waste management plans, Singapore has invested in advanced waste management infrastructure and technologies. The country has established state-of-the-art waste-to-energy incineration plants and implemented a comprehensive recycling infrastructure network. Additionally, Singapore actively promotes research and development in waste management technologies, encouraging innovation and sustainable practices[34][29].

Analyzing Singapore's waste data and evaluating the effectiveness of these plans and initiatives will provide valuable insights into their success and areas for improvement. It is essential to assess factors such as waste generation trends, recycling rates, landfill diversion, and public engagement to determine the progress made towards achieving waste management goals. By studying the data and analyzing the alignment between the goals and initiatives outlined in the various plans, it is possible to evaluate Singapore's waste management performance and the effectiveness of its strategies. The analysis will take a look at the historical waste data to inspect Singapore's achievements, challenges, and potential areas for further improvement in waste management practices.

2.2.2 Waste Generation and Recycling Trends

Figure 1 shows the temporal data for waste generation, disposal and recycling rate between the years of 2003 and 2022. The data shows a consistent upward trend in waste generation over the earlier years of the 2000's. This trend signifies the impact of Singapore's population growth, urbanization, and economic development on the increasing levels of waste production. The figure highlights a positive trend in waste recycling efforts, with an overall increase in the amount of waste recycled in Singapore. This could indicate progress in promoting recycling and developing the necessary infrastructure for waste processing and recycling, and a positive effect of Singapore's waste management plans.

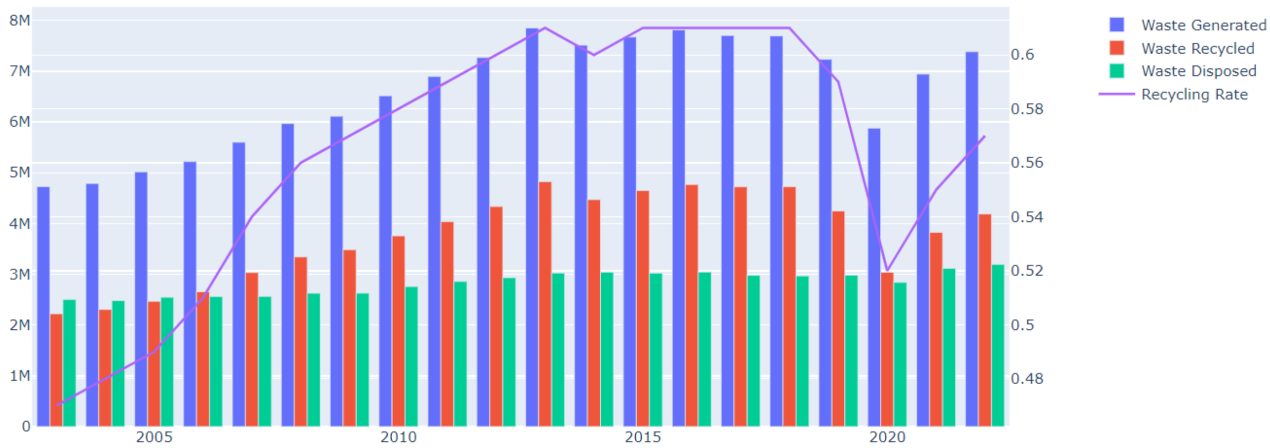

Figure 1: Bar graphic over waste generated, recycled and disposed, with recycling rate from 2003-2022

The trend in in the early years of figure 1 reflects successful initiatives and policies introduced with the Singapore Green Plan 2012, reducing the overall percentage of waste sent to landfills, and diverting materials back into the production cycle. The recycling rate, a crucial metric for measuring the effectiveness of waste management, shows consistent improvement. The goal drawn up in the Green Plan was to reach a 60% recycling rate by 2012, which was accomplished.[34] The observed upward trend suggests that a larger proportion of waste generated in Singapore is being recycled instead of ending up in landfills or being sent to waste-to-energy centers.

In the following decade in the 2010's the rates seem to plateau with some and fluctuations between years. Towards the end of the decade, around the time of the COVID-19 pandemic, there is a clear drop in waste generation and recycling. Especially during the Circuit Breaker period of April to May in 2020, in which the Singaporean government issued a stay-at-home order, saw the recycling rates drop, as recycling activities were reduced[35][36]. Overall Singapore did not manage to reach the goal of a 65% recycling rate in 2020 as set out in the Singapore Blueprint plan from 2009[34]. And while the pandemic certainly hampered Singapore's effort to reach their goal, the analysis suggest that even without the pandemic Singapore would have need a paradigm shift to increase its recycling efforts to reach its goal, as in the years leading up to the pandemic the recycling rate stagnated and remained at the same level.

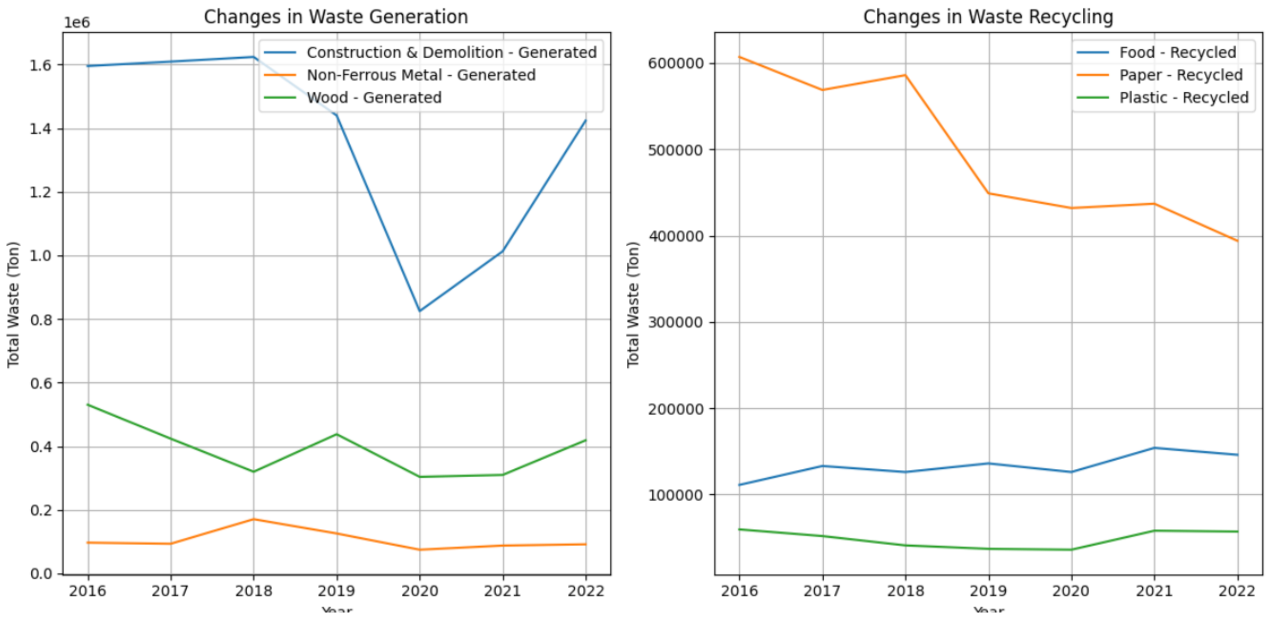

Figure 2: Changes in waste generated and recycled for materials in period 2016-2022

Table 1: Total percentage change of waste generation and recycling year by year

Year	Waste generation	Recycling
2016	1.833583	2.565757
2017	-1.406414	-0.937303
2018	-0.120712	0.035984
2019	-5.990903	-10.135421
2020	18.717169	-28.420061
2021	18.095238	25.855263
2022	6.350806	9.461579

Table 2: Percentage diffrence pre- and post-pandeminc

	Percentage difference
Waste Generation	-4.01
Waste Recycling	-9.91
Waste Disposal	4.49

As economic and social activities resumed in 2021, there was a notable recovery with a 18 percent increase in waste generation and a significant 25.8 percent rise in waste recycling, as seen in Table 1. Table 2 shows that when compared to the pre-pandemic period of 2019, waste generation in 2021 decreased by 5 percent, while waste disposal increased by 5 percent, and waste recycling experienced an 9.9 percent decline. The decline in waste recycling can be attributed to factors such as reduced construction activity and decreased demand for recyclables in the export market. Notably, waste materials like construction and demolition, wood, and non-ferrous metal shows a particular reduction in waste generation. Despite this the overall recycling rate improved from 52 percent in 2020 to 55 percent in 2021, as seen in figure 1. Most waste materials, including plastic and food waste showed higher recycling rates compared to 2019. However, the recycling rate for paper and cardboard, which is a significant waste stream, remained lower than the level observed in 2019, as seen in Figure 2.

While waste generation has gradually returned to pre-pandemic levels, it is important to note that the recycling rate has not yet caught up to its previous standing. Waste generation may have reached similar levels, but the recycling rate lags behind by a few percentage points. This highlights the need for concerted efforts to not only restore recycling rates to pre-COVID levels but also surpass them. Singapore's commitment to achieving a Zero Waste Nation, as outlined in its masterplan, emphasizes the importance of increasing recycling rates. According to the masterplan Singapore aims to have a recycling rate of 70% by 2030 [34]. To accomplish this, it is essential to bring about changes from the patterns observed in the previous decade. During the 2010s, the recycling rate remained relatively stable, which is not necessarily unfavorable. However, to meet the goals of the Zero Waste Nation masterplan, it is imperative to elevate the recycling rate beyond these steady levels. Notably, between 2003 and 2013, there was a consistent year-by-year increase in recycling rates. Building on this positive trend, renewed efforts are required to revitalize and surpass the recycling rates observed in recent years. By implementing effective strategies and fostering a culture of recycling, Singapore can make significant strides toward achieving its zero waste objectives.

2.3 Enviormental Impact

2.3.1 Waste-to-Energy

While for 2022 57% of generated waste was recycled, the remaining 43% does not get directly dumped into a landfill. Landfills play a significant role in waste management, and Singapore faces unique challenges in this regard due to its limited land area. The primary landfill in Singapore is known as the Semakau Landfill, located offshore from the mainland. However, the country's landfill situation is not without its issues. One of the main concerns is the limited availability of land for landfill expansion. Singapore's land scarcity necessitates careful planning and utilization of available space. As a result, the Semakau Landfill was created by enclosing a small island with an impermeable membrane, which allows for waste containment and prevents leachate from contaminating surrounding waters[37].

This innovative solution does however its limitations, as the landfill's capacity is finite. The second major issue is the sheer volume of waste generated by Singapore despite its small size. With limited landfill space, managing and accommodating this waste becomes a significant challenge. It highlights the importance of waste reduction and recycling efforts to minimize the strain on landfills. Additionally, there is a concern regarding the long-term sustainability of landfills in Singapore. As land scarcity continues to be a pressing issue, alternative solutions for waste management need to be explored. Becasue of this, Singapore has also included reduction of the amount of waste that gets disposed to prolonge the lifetime of the Semakau Landfill beoynd the year 2035 in their Zero Waste Nation plan[34].

Landfills have the potential for creating pollution. Landfills produce methane, a potent greenhouse gas, as organic waste decomposes. To deal with its limited landfill and its pollution consciences Singapore implemented Waste-To-Energy (WTE) initiatives as a key component of its waste management strategy. These initiatives aim to maximize the value and energy potential of waste while minimizing environmental impact. Singapore's approach to WTE is notable for its advanced technology and comprehensive waste management system[38].

According to the National Environment Agency (NEA), incineration plays a significant role in waste reduction, with the potential to decrease waste volume by up to 90 percent. This not only helps conserve landfill space but also allows for the recovery of heat, which is utilized to generate electricity. However, it is essential to evaluate the long-term sustainability of waste-to-energy initiatives. One concern is that when people believe their electricity comes from 'green sources' like waste-to-energy, they may be less motivated to conserve energy. This lack of incentive to reduce energy consumption can hinder overall sustainability efforts. Additionally, waste-to-energy currently only accounts for 3 percent of Singapore's electricity needs. This relatively small contribution indicates the necessity of alternative energy sources and conservation efforts for a sustainable energy mix[37].

Waste-to-energy initiatives do not provide direct incentives for waste reduction or responsible recycling.

Singapore faces challenges as it generates significant waste volumes despite being a small city-state. Relying solely on waste-to-energy may perpetuate unsustainable waste management practices without addressing these underlying issues. The waste-to-energy processes primarily focus on electricity generation, potentially overlooking opportunities for waste upcycling into higher-value products or the transition to more renewable energy sources. Incineration itself typically leads to increased carbon emissions and air pollution. Although according to NEA, a flue gas cleaning system removes dust and pollutants, improving air quality. The incineration reduces waste volume by about 90%.Ferrous scrap metal in the ash is recovered and recycled, reducing environmental impact. Ash residue is appropriately disposed of at the offshore Semakau Landfill[39].

WtE can utilize otherwise wasted resources, reduces the need for landfilling, and allows for the recovery of valuable materials. It is often positioned as a cleaner alternative to traditional incineration practices, harnessing energy that would otherwise go to waste. However, this argument assumes that incineration is the only option, whereas more responsible waste management plans focus on circular solutions that contribute less to climate change. The drawbacks of WtE must also be considered. The mass-burn process commonly used in WtE can destroy recoverable resources, such as minerals, wood, and plastics[38].

2.3.2 Environmental Savings Analysis

While WTE has provided certain benefits and solutions to waste management, it is crucial to consider alternative approaches that can further mitigate the environmental impact of waste. One such approach is recycling waste materials, which offers promising solutions to address the growing concerns associated with waste management. As of 2022 57% of all waste generated gets recycled, which helps reduce the consumption of raw materials, conserve natural resources, and decrease energy consumption and greenhouse gas emissions associated with the production of new materials. Data related to the conservation of energy and greenhouse gas pollution through recycling can help paint better picture of the environmental impact recycling has.

Table 3: Energy and greenhouse gasses saved from recycling waste material

Waste material	Energy saved (GwH)	Greenhouse Gases Saved (ton)
Ferrous Metal	13870.9236	45372180
Non-Ferrous Metal	26089	19753100
Paper	47163	4601280
Plastic	7390.1426	1023920
Glass	9.8616	93920
Total	94523.0478	70844400

Table 3 shows the result from the environmental impact analysis of the recycling efforts from 2003 to 2022 for certain waste materials. It shows the energy in gigawatt and tons of greenhouse gases saved through recycling. The data shows that ferrous metal recycling has resulted in substantial energy savings of 13,870.9236 GWh. This translates into a noteworthy reduction of 45,372,180 tons in greenhouse gas emissions. Glass recycling has also made a positive impact, with an energy saving of 9.8616 GWh. Additionally, this corresponds to a reduction of 93,920 tons in greenhouse gas emissions. The recycling of Non-Ferrous Metal has demonstrated its importance through significant energy savings of 26,089 GWh, resulting in a notable reduction of 19,753,100 tons in greenhouse gas emissions. Paper recycling has contributed to substantial energy savings of 47,163.12 GWh. Furthermore, this has led to a reduction of 4,601,280 tons in greenhouse gas emissions. Plastic recycling has also made a positive difference, with an energy saving of 7,390.1426 GWh. Additionally, this has resulted in a reduction of 1,023,920 tons in greenhouse gas emissions.

According to the NEA the TuasOnem, Singapore's newset WTE center, can create 120 megawatts of energy per 3600 tons of waste material incinerated[40]. In 2022, 3 197 000 ton of waste was disposed, which when incinerated equals to 106,566 mega watt of energy. While the energy saved from recycling glass, plastic, paper and metals in 2022 saved an estimated total of 4,073,482 mega watt. So while WTE centers are efficient in reducing the amount of space that disposed waste take up in a landfill, they are not as efficient at generating energy as recycling is at saving through recycling the waste material.

The cumulative results from recycling efforts between 2003 and 2022 highlight an impressive achievement, with a total energy saving of 94,523.0478 GWh and a reduction of 70,844,400 tons in greenhouse gas emissions.

To put that into perspective, the energy conserved from recycling is equivalent to the annual energy consumption of approximately 6,266,444 households in Singapore, which surpasses the country's population itself[41]. Furthermore, the greenhouse gas emissions saved through recycling can be compared to the emissions generated by cars in Singapore over a span of approximately 11 years, based on 2021 data[42]. These figures shows the significant environmental impact and sustainability benefits of recycling initiatives.

2.4 Top Waste Generation and Disposal Materials

Figure 3 gives us an overview of waste generation and disposal in 2022. Notably, three of the top disposal materials — food, paper, and plastic — emerge as the primary contributors to both waste generation and disposal, collectively accounting for 39.01% of the total waste generated and 71.32% of the disposed waste. These materials are commonly found in everyday items such as containers, junk mail, bags, bottles, plastic packaging, used paper, disposable cutlery, and leftover food. On the other hand, construction debris and ferrous metal, despite being among the top five waste output materials, constitute only 3% of the total waste disposed as they have high recycling rates, with approximately 65.94% of the total waste generation stemming from these materials. The recycling rate for paper/cardboard stands at 37%, indicating room for improvement as a significant portion is still being disposed of. Plastics and food waste, comprising the remaining two waste types in the top five, represent a mere 4.8% of the total waste recycled, despite making up 24.6% of the overall waste generation.

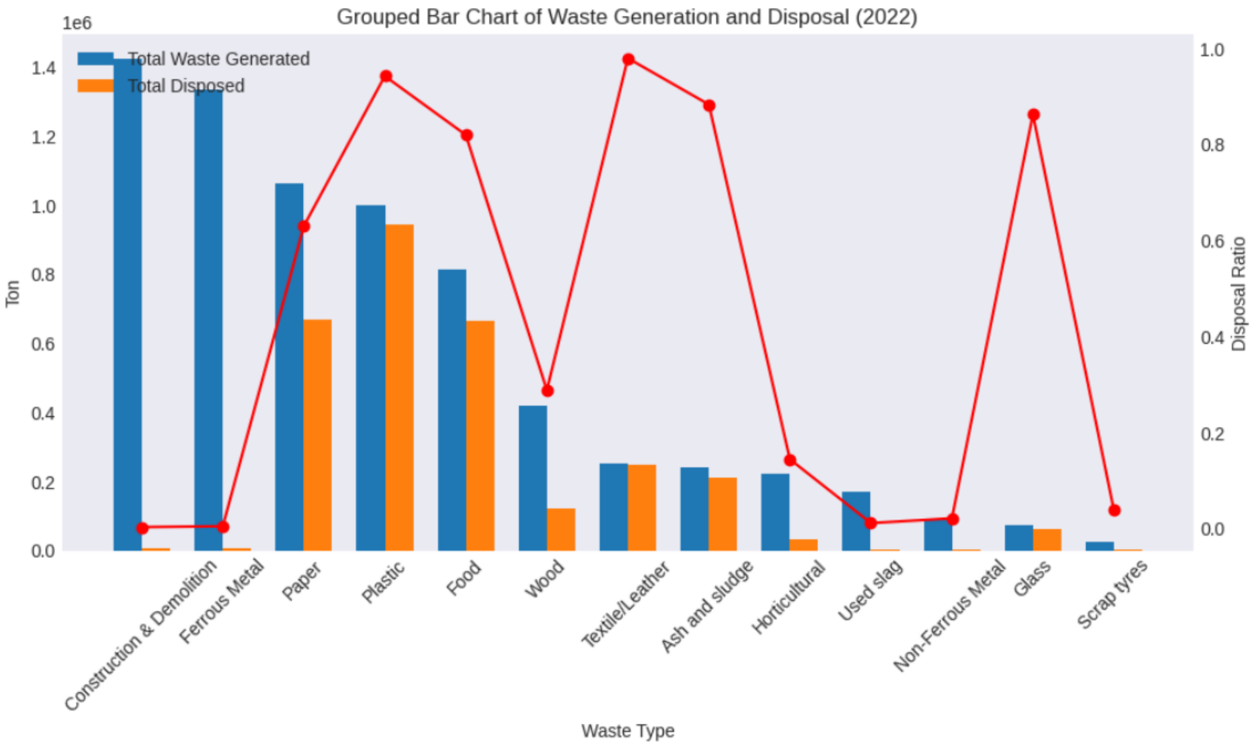

Figure 3: Total waste generation, disopasl and recycling rates for waste materials in 2022

Figure 4 illustrates the frequency at which different waste materials fell into the top five categories of waste generation between 2003 and 2022. Notably, the consistent waste materials responsible for the majority of waste generation throughout the entire dataset are paper, plastic, food, construction & demolition, and ferrous metals. Figure 5 shows the percentage of all waste generation that has come from these 5 waste materials. The combined data from these graph show the trend that these 5 materials consistently are responsible for 70-75% of total waste generation throughout the last 20 years.

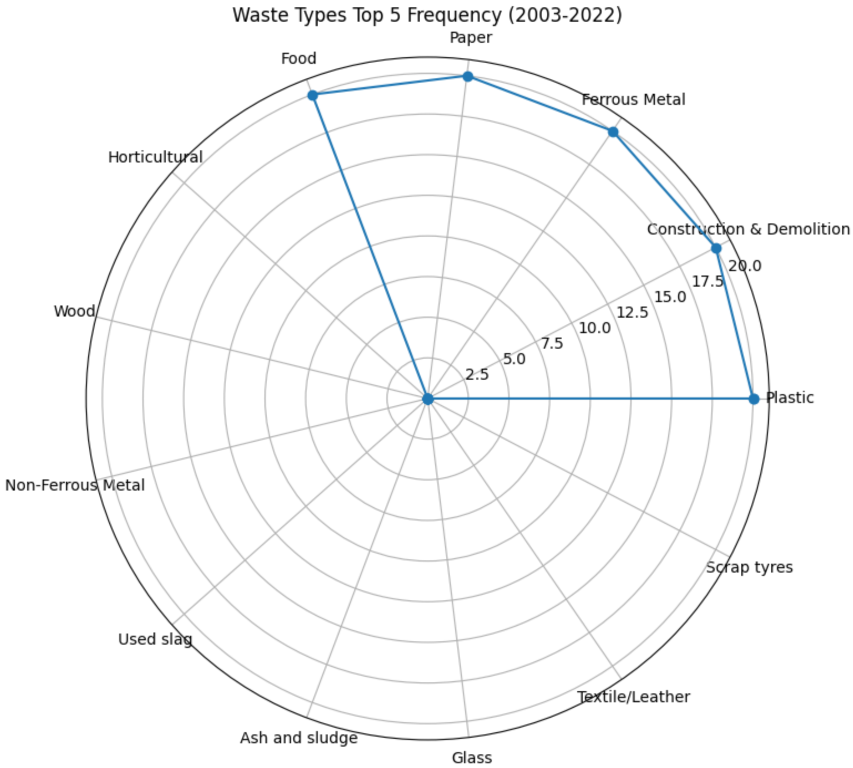

Figure 4: Top 5 waste materials count per year

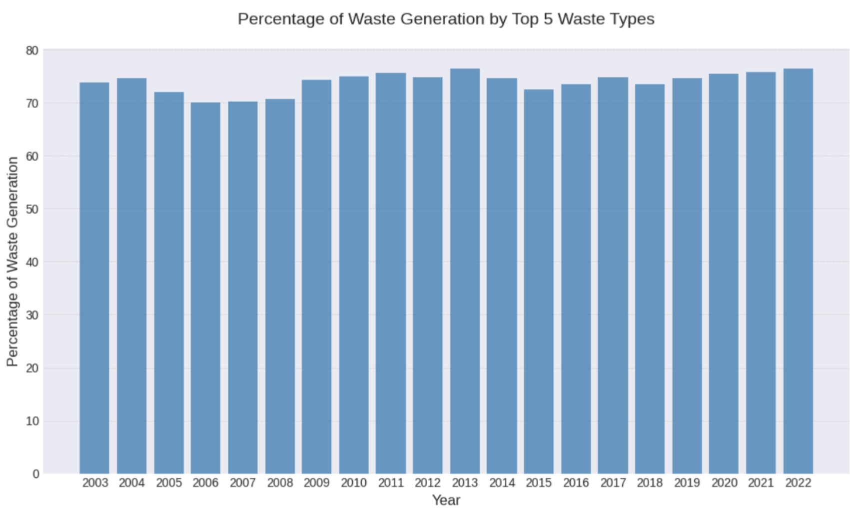

Figure 5: How much of the total waste generated per year the top 5 waste materials were responsible for

Examining the historical trend of recycling rates for these 5 materials, as depicted in Figure 6, highlights the impact of recycling efforts implemented under the Singapore Green Plan 2012. Notably, ferrous metals and construction & demolition started of with recycling rates around the 90%s and then it increased to be around 99%, which it has been more or less consistent since 2015. This indicates successful and sustained recycling practices in these sectors. Food waste, albeit slowly, shows an upward trend in recycling rates over the course of almost 20 years. While progress may be gradual, the positive direction suggests a growing focus on addressing food waste through improved recycling initiatives. However, concerning paper and plastic waste, the recycling landscape has not exhibited positive developments. In fact, both materials have experienced a decline in recycling rates in 2022 compared to previous years, reaching historically low values. This highlights the pressing need for targeted interventions to address the challenges associated with paper and plastic recycling.

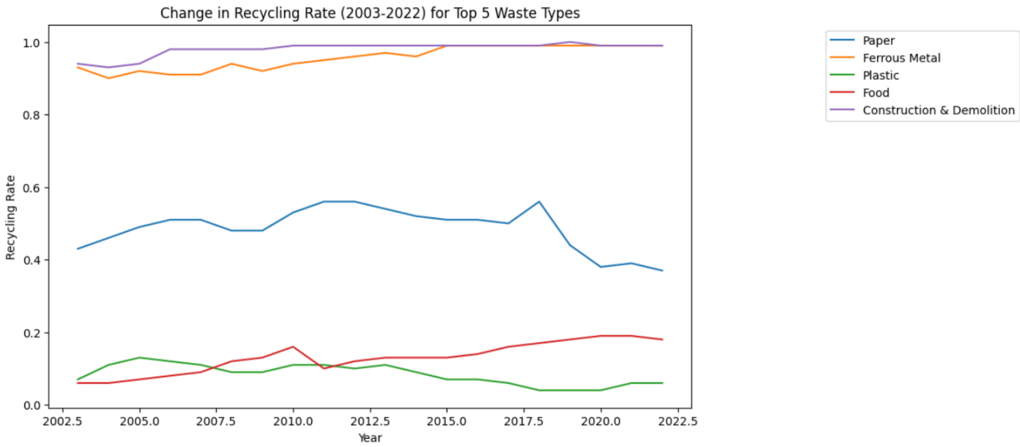

Figure 6: Total waste generation, disposal and recycling rates for waste materials in 2022

To enhance waste reduction efforts, the focus should primarily be on the top five waste types that contribute the most to Singapore's waste output. However, it is important to note that reducing construction debris and ferrous metal waste may present challenges due to their close ties to economic activities. Their generation is influenced by fluctuations in construction and business sectors, which are in turn linked to the overall economy. Moreover, the high recycling rates already achieved for these waste types further support their favorable status. A more targeted approach should be adopted to achieve greater waste reduction in paper/cardboard, plastics, and food waste, given their prevalence in households and offices. Opportunities exist for projects and campaigns aimed at reducing the output of these waste materials. Particularly, efforts should be intensified to reduce food waste, paper/cardboard waste, and plastic waste at their source. Subsequently, a strong emphasis should be placed on effective recycling practices to ensure these materials are properly managed when they do become waste.

Plastic recycling faces complexity due to the expense and difficulty of collecting and sorting various types of plastic. Plastic degradation, lack of markets for recycled plastic, and public confusion contribute to limited progress in recycling rates. Challenges include different types of plastics, contamination issues, and the competitive nature of new plastic production. Fragmented markets and inadequate infrastructure also pose obstacles. Systemic changes are needed, including legislation, alternative materials, and circular economy principles, to reduce plastic waste and improve recycling. Addressing misconceptions, improving infrastructure, and promoting responsible consumer behavior are key to achieving an effective and sustainable plastic waste management system[43].

In Singapore, plastic recycling faces complexity due to the expense and difficulty of collecting and sorting various types of plastic. With thousands of plastic variations, they cannot be melted down together, and plastic degrades after just a few uses. The lack of markets for recycled plastic limits its recycling potential. The recycling rates for paper and plastic in Singapore have shown limited progress over the past two decades, with plastic recycling rates even reaching historically low levels in 2022. Public confusion and misconceptions about recycling contribute to the problem, as individuals include non-recyclable plastics in their recycling bins. The challenges surrounding plastic recycling in Singapore are multifaceted, including issues with different types of plastics and contamination. Recycling alone cannot fully address the plastic pollution crisis. Systemic changes are required, such as implementing legislation to ban single-use plastics, promoting reuse and refill systems, and adopting circular economy principles. Improving infrastructure, addressing misconceptions, and promoting responsible consumer behavior are crucial for progress towards an effective and sustainable plastic waste management system in Singapore.[44].

2.5 Time Series Forecasting

In order to look into future trends of waste generation, we employed time series forecasting techniques. Our analysis aimed to predict waste generation patterns based on historical data and the identified factors that impact waste generation. According to the World Bank Groups' "What A Waste 2.0" report population growth, urbanization, economy, and consumer spending contribute are factors that significantly effect waste generation. Through a correlation analysis (see Table 4), we found strong positive correlations between waste generation and the factors GDP, population, and consumer spending. Singapore has already for many years had an urbanization rate of 100%, so it was not considered. Notably in the correlation analysis total GDP and GDP per capita exhibited similar high scores for their correlation with waste generation data. However, these two economic indicators also demonstrated a very high correlation with each other at 0.99, which is expected as they represent similar aspects of GDP. Using both these variables in the forecasting model may introduce redundant data or potentially yield adverse effects due to their strong interrelationship.

Table 4: Correlation analysis

Waste material	Tot-gdp	Gdp-per-capita	Population	Tot-consumer	Consumer-per-capita	Total-waste-generated
Tot-gdp	1	0.9965	0.9871	0.9855	0.8831	0.856338
Gdp-per-capita	0.9965	1	0.9755	0.9765	0.8732	0.8490
Population	0.9871	0.9755	1	0.9789	0.8483	0.8574
Tot-consumer	0.9855	0.9765	0.9789	1	0.8614	0.9159
Consumer-per-capita	0.8831	0.8732	0.8483	0.8614	1	0.7276
Total-waste-generated	0.8563	0.8490	0.8574	0.9159	0.7276	1

2.5.1 Limitation of forecasting - Dataset

For time series forecasting we are reliant on having future data for extra features that we want to use while prediction future values of a value like waste generation. With the datasets at our disposal we faced a limitation with that only population has future values, provided by the UN. To address the limitations we focused solely on utilizing the forecasted population values in our waste generation predictions. Population serves as a critical factor in waste generation, particularly in relation to urbanization and changes in consumption habits. It is however important to acknowledge the influence of other factors like GDP and consumer spending on waste generation. The admission of economical data comes as a result of that we simply do not have forecasted values for the economic factors like GDP and consumer spending. Forecasting economic variables is a complex task, as the economy is influenced by a wide range of factors and can be subject to significant fluctuations. Simply extrapolating economic data based on historical trends may not accurately capture the real-world scenario. Therefore, we chose not to incorporate GDP and consumer spending in our waste generation predictions, as we do not have reliable forecasted values for these variables.

By focusing on the forecasted population values, which we have available, we can still however gain insights into waste generation trends and their relationship with population dynamics. Utilizing the forecasted population values, we applied time series forecasting techniques to predict future waste generation trends. By analyzing historical waste generation data and considering the future population values, we developed forecasting models capable of estimating waste generation patterns for upcoming years. While we cannot directly incorporate the economic variables in our predictions due to the lack of forecasted values, it is important to consider their role when interpreting the results of our waste generation forecasts. The economy, along with population dynamics, should be taken into account to gain a comprehensive understanding of future waste generation trends.

2.5.2 Limitation of Forecasting - Covid Anomaly Years

For the analysis the years affected by the pandemic were excluded . The anomalous nature of the pandemic years prompted their removal from the analysis. The pandemic had a significant impact on waste generation, and the forecasted data did not accurately capture the rapid rebound in waste generation observed after the pandemic. This omission was necessary to ensure the integrity and accuracy of the analysis, as the forecasted data did not align with the post-pandemic trends observed in real-life data.

Examining the waste generation in the years following 2020, it is noteworthy that waste generation quickly picked up after the pandemic surpassing the forecasted projections. This trend underscores the importance of considering real-world events and anomalies when analyzing and forecasting waste generation patterns. The pandemic's influence on waste generation and subsequent recovery highlights the limitations of the forecasting model, as it did not account for the specific dynamics of the pandemic's impact on waste generation, as it is solely reliant on population data and previous waste generation data. The model did not understand the complex nature of waste generation in relation to an anomaly event like the Covid-19 pandemic.

2.5.3 Forecasting Analysis

For the time series forecasting, we utilized the ARIMA (AutoRegressive Integrated Moving Average) model from the statsmodels.tsa.arima.model module. This model allows us to capture the patterns and relationships in the historical waste generation data and make predictions for future waste generation trends based on the available population values. By analyzing historical waste generation data and considering the forecasted population values, we developed forecasting models capable of estimating waste generation patterns for upcoming years[45].

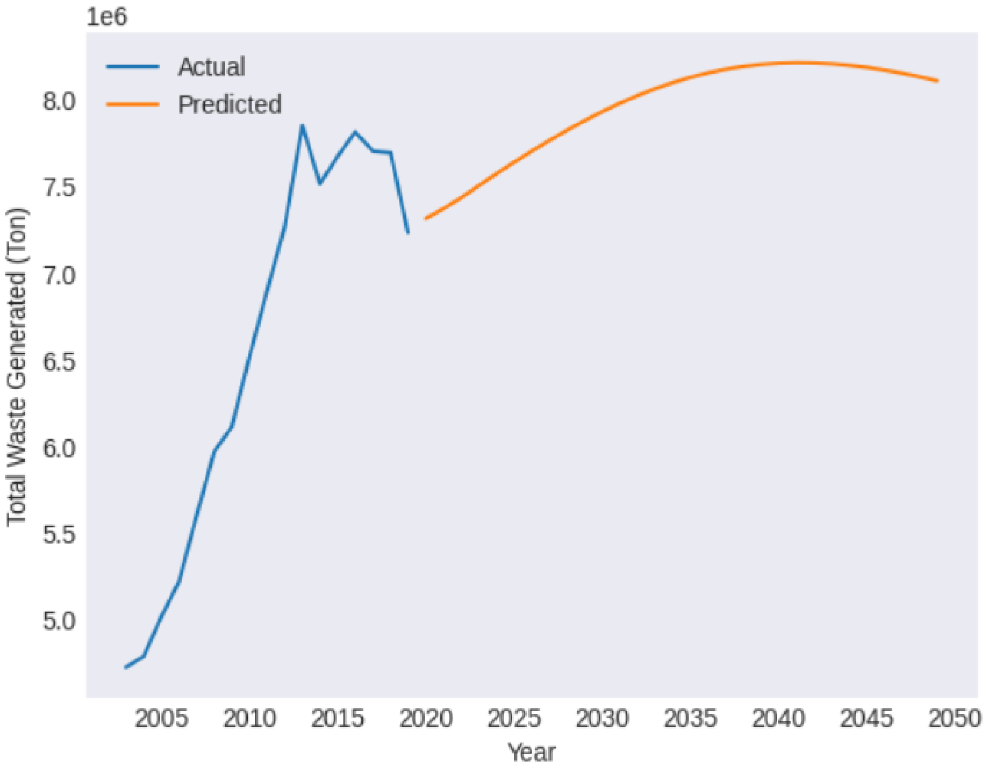

Figure 7: Forecasted values for waste generation in the coming decades based on population growth

From figure 7 we can see that waste generation initially showed an upward trend from the early 2000s until around 2013, which closely correlated with significant population growth during that period, as seen in figure 8. Singapore experienced rapid population growth, reaching its peak in 2007 with an annual increase of nearly 4%. This substantial population growth directly influenced the amount of waste generated. However, a notable shift in the pattern emerged after 2013. The rate of population growth began to decelerate, resulting in a significant change for Singapore. By the end of the 2010s, the population growth rate had decreased by approximately 75% compared to the beginning of the decade and experienced an 81.22% decrease from its peak in 2007, just 13 years prior. This slowdown in population growth, coupled with other factors such as the economy (which falls outside the scope of this forecast analysis), contributed to a deceleration in the increase of waste generation. It is worth noting that the global financial crisis in 2008 may have played a role in both the stagnation in waste generation and the decrease in birth rates, as waste generation is often tied to economy, and many countries saw lower birth rate then expected in the years following the financial crisis[46]. Additionally, improvements in waste management practices likely contributed to the observed changes in waste generation trends. This combination of factors, including population dynamics and external factors such as the economy and changing waste management strategies, contributed to the shift in waste generation patterns over time, as discussed earlier in this rapport.

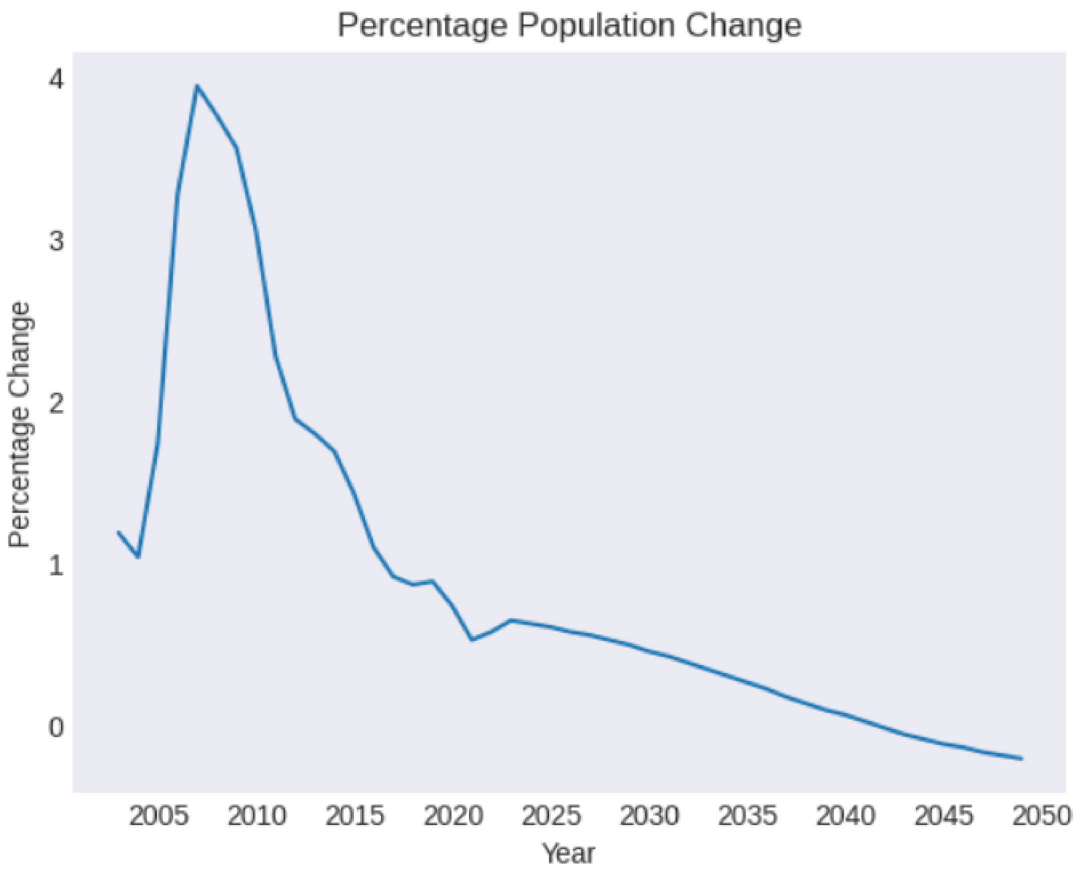

Figure 8: Percentage change in population over time

The analysis of waste generation trends in the years following 2020 reveals a increase in waste generation, albeit at a relatively moderate rate compared to earlier years. Although the percentage increase in population is not as substantial as in previous years, the absolute growth in population still has an impact on waste generation. As the population continues to grow, there will be probably be a corresponding rise in consumption patterns, resulting in increased waste production. Looking towards the future in figure 8, the graph highlights an shift in the population dynamics. Projections for the 2040s indicate a potential decrease in the population of Singapore, with the percentage change turning negative. This anticipated decline in population is mirrored by a corresponding decrease in waste generation in Figure 7, suggesting that a shrinking population may contribute to a reduction in waste production.

However, it is crucial to recognize that this forecast only takes into account historical waste generation data and population projections, and it does not provide a complete picture of future waste generation. Waste generation is a complex issue influenced by various factors besides population, including the economy, social norms and attitudes, laws and regulations and much more. The forecast does not explicitly consider economic fluctuations, policy interventions, or other societal dynamics that may affect waste generation trends. The disparity between the historical and predicted data further emphasizes the limitations of the forecast. The historical data, reflecting real-world observations, may exhibit more rapid changes in waste generation due to the interplay of economic factors and other complex dynamics. In contrast, the predicted data, driven primarily by population projections, follows a smoother curve that may not capture sudden shifts or short-term fluctuations.

To gain a more comprehensive understanding of future waste generation, it is important to consider additional variables such as economic indicators, consumer behavior, industry dynamics, and policy interventions. Integrating these factors into forecasting models can provide a more robust and accurate representation of waste generation patterns. But these kinds of predictions for the future are complex tasks in themselves, and go outside of the scope of this rapport. Therefor we are reliant on public data available to us. Understanding the intricate relationship between population dynamics, real-world events, and waste generation is vital for policy-makers and waste management stakeholders. And while this forecasting can not provide a definitive prediction of future waste generation it can give us an idea of how certain aspects like population will effect Singapore's waste generation in the coming decades.

2.6 The Future of Singapore's Waste Management

The Singapore government has taken significant steps towards achieving a zero-waste nation through its "Zero Waste Masterplan". This comprehensive plan includes a diverse set of initiatives aimed at enhancing waste management practices and promoting sustainability across the country. These initiatives have been strategically developed to tackle key challenges and drive positive change in waste management systems throughout Singapore [47].

Specifically, the 3Rs - Reduce, Reuse, and Recycle - form the foundation of Singapore's waste management approach. By emphasizing waste minimization, the city-state aims to address the issue at its source. Through public education campaigns and the promotion of responsible consumption, Singapore encourages individuals and businesses to make conscious choices that reduce waste generation. By consuming mindfully, Singaporeans can curtail unnecessary waste, conserve resources, and minimize the environmental impact associated with excessive consumption [48].

2.6.1 Policy Suggestions

To effectively **reduce** waste production, one crucial aspect that can be addressed is unnecessary packaging. Measures can be taken to ban or restrict the use of excessive and non-essential packaging, such as peeled and individually wrapped fruits [49]. By implementing regulations that discourage or prohibit such practices, significant reductions in waste generation can be achieved. These regulations can be accompanied by comprehensive sensitization campaigns aimed at raising awareness among consumers, retailers, and manufacturers about the environmental impact of excessive packaging. The campaign can emphasize the importance of sustainable packaging alternatives, encourage responsible consumer choices, and promote the concept of "less is more" when it comes to packaging. By combining regulatory measures and educational initiatives, it is possible to foster a culture of waste reduction and promote more sustainable practices in the production and consumption of goods [50].

A key strategy in waste reduction is the promotion of item **reuse** through repurposing or second-hand marketplaces, both physical and online. Encouraging individuals and businesses to find new purposes for items they no longer need helps extend their lifespan and reduces the demand for new products. Repurposing allows for creative and innovative ways to give items a new lease on life, minimizing the need for disposal [51]. Additionally, second-hand marketplaces provide platforms for individuals to sell or donate their used items, enabling others to benefit from them. This approach holds great potential for tackling the issue of waste generated by items such as textiles, which currently face low recycling rates. Shockingly, only 2% of second-hand textiles were recycled in 2022 in Singapore, with the majority ending up in disposal, often being burned [52]. To address this challenge, it is imperative to promote the reuse of textiles and other products through second-hand marketplaces, where individuals can sell or donate their used clothing, accessories, and household objects. Simultaneously, efforts should be made to enhance textile recycling technologies and infrastructure to increase the recycling rates and divert more textiles from disposal. Combining the promotion of second-hand markets with improvements in textile recycling can significantly contribute to waste reduction and the transition towards a more circular and sustainable economy [53].

Alongside these efforts, implementing laws to prevent tech companies from purposefully slowing down their products to drive new sales is crucial for reducing e-waste production. Such laws would address planned obsolescence, a practice where companies intentionally design products with a limited lifespan. By promoting product durability and ensuring fair consumer practices, these laws can contribute to reducing waste and fostering a more sustainable approach to consumption [54].

Moreover, artificial Intelligence (AI) holds immense potential for revolutionizing the **recycling** industry. By leveraging AI technologies, recycling processes can be enhanced, leading to increased efficiency and accuracy. AI can be employed in waste sorting facilities to automate the identification and separation of different materials, including plastics, based on their composition, color, or shape. This helps streamline the recycling process and improve the quality of recycled materials [55]. Furthermore, AI algorithms can analyze large datasets to identify patterns and trends in recycling behaviors, allowing for more targeted recycling campaigns and educational initiatives [56]. Additionally, a fundamental shift in the composition of plastic production is crucial.

By transitioning from conventional plastics to more environmentally friendly alternatives, such as biodegradable or compostable materials, the recycling rates for plastics can be significantly improved. Such a change would enable more effective sorting and processing of plastic waste, leading to higher rates of plastic recycling and reducing the burden on landfills and the environment [57]. Combining AI advancements with sustainable plastic production can pave the way for a more efficient and sustainable recycling ecosystem.

2.6.2 Ethical Implications

The previously suggested policies, such as banning unnecessary packaging, implementing laws against planned obsolescence, promoting item reuse through second-hand marketplaces, and leveraging AI in recycling, have significant ethical and social implications. From an ethical perspective, these policies align with the responsibility to protect the environment, address intergenerational justice concerns, promote transparency and accountability in business practices, and foster equitable access to sustainable goods. They contribute to environmental awareness, job creation in the green and circular economy sectors, social inclusion by providing affordable options, and technological advancements through AI integration [58]. However, it is crucial to address challenges, including stakeholder interests, fair labor practices in second-hand markets, and potential environmental impacts of alternative materials [59]. By adopting a comprehensive and inclusive approach guided by ethical principles and stakeholder engagement, these policies can maximize positive social and ethical outcomes in waste management.

3 Conclusion

Waste management and recycling are essential for achieving sustainable environmental practices in urban settings. The adoption of effective waste management strategies, guided by indicators such as waste generation, recycling rates, landfill diversion, and waste-to-energy conversion, is crucial for evaluating progress and addressing the challenges in smart cities.

The analysis of historical data over the past two decades has provided valuable insights into waste management trends in Singapore. It has highlighted the effectiveness of different waste management plans and identified areas that require improvement to achieve the goals set out in the Zero Waste Nation Plan. The impact of the COVID-19 pandemic on waste management was also observed, with waste generation rebounding after the pandemic but recycling rates lagging behind pre-pandemic levels.

To achieve Singapore's waste management targets, a paradigm shift is necessary, focusing on increasing recycling rates and reducing waste generation. The analysis identified the top five waste materials contributing to a significant proportion of waste generation: paper, plastic, food, ferrous metals, and construction demolition waste. While the recycling rates for ferrous metals and construction demolition waste are commendable, there is room for improvement in the recycling rates of paper, plastic, and food waste.

The use of time series forecasting provided insights into future waste generation trends, although limited by the availability of data on population as the sole feature. Economic factors, such as GDP and consumer spending, play a significant role in waste generation, but their absence in the forecasting analysis compromised its accuracy. The forecast suggests a slight increase in waste generation in the coming decades, aligning with population growth, and a corresponding decrease when Singapore's population is projected to decline in the 2040s. However, it is important to acknowledge the complexity of waste generation and the limitations of using population as the sole feature in forecasting models.

By implementing policies that prioritize waste reduction, such as banning unnecessary packaging and preventing planned obsolescence, cities can minimize waste production and promote responsible consumption. Additionally, promoting item reuse through second-hand marketplaces and leveraging AI technologies in recycling can contribute to resource conservation and the development of a circular economy. However, it is important to consider the ethical and social implications of these policies, ensuring fairness, inclusivity, and environmental responsibility. Stakeholder engagement, transparency, and ongoing monitoring and evaluation are key in implementing comprehensive and sustainable waste management practices. By embracing a holistic approach to waste management, cities can pave the way for a cleaner, healthier, and more sustainable future for both present and future generations.

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