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Assessment of Municipal Plastic Waste and Recycling Systems in Pokhara, Nepal: Current Status, Challenges, and Sustainable Management Approaches

Dikpal K.C., Rishav Khanal, Saugat Tiwari, Sanjay Baral*

School of Engineering, Faculty of Science and Technology, Pokhara University, Nepal

* Author to whom correspondence should be addressed; E-Mail: *sanjaybaral@pu.edu.np*

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Abstract

Plastic waste, largely composed of non-biodegradable petroleum-based polymers, has become a growing environmental and public health challenge in Pokhara Metropolitan City (PMC), Nepal. This study assesses plastic waste generation and recycling practices using four estimation approaches: household waste sampling, landfill volume density assessment, data from private waste contractors, and population based per-capita calculations. Findings from a survey of 400 households indicate that PMC generates nearly 11227.847 metric tons of plastic waste annually, with plastic comprising 16.86% of total municipal solid waste and Low-Density Polyethylene (LDPE) contributing the highest share due to its widespread use in packaging. At present, only 10.86% of this waste is recycled by existing private facilities. Economic and technical analysis shows that a well-equipped recycling center operated by at least three workers with one machine could recycle about 218.4 metric tons of plastic per year, reduce 582.4 metric tons of Greenhouse Gas (GHG) emissions, save 1,517 m³ of landfill space, and create meaningful revenue opportunities. Overall, the results emphasize the need for integrated waste management, improved source-level segregation, and increased investment in recycling infrastructure. Strengthening these systems can enhance environmental protection, reduce landfill pressure, support local employment, and contribute to long-term sustainability in PMC.

Keywords

Greenhouse Gas, Plastic, Plastic wastes, Recycling, Revenue

1. Introduction

1.1 Background

Plastic has become a part of nearly everything we use each day because it is cheap, durable, easy to shape, and works well for packaging, household items, medical tools, and countless everyday products [1],[2]. Because of their durability, affordability, and light weight, plastics are favored over materials like glass, metal, and paper [3]. However, this same ease has contributed to a substantial and quickly expanding waste stream that has an impact on human health, natural ecosystems, and waste management system worldwide [4],[5],[6],[7]. Recent studies highlight the importance of integrated waste characterization and life cycle assessment in evaluating sustainable waste management options. For instance, Sarquah et al.[8] demonstrate the potential of refuse derived fuel (RDF) valorization, while Voss et al.[9] provided a framework for assessing the environmental economic performance of waste treatment pathways, including pyrolysis and gasification. Haupt et al. [10] further offer modular life cycle assessment tools for evaluating emissions and energy recovery from municipal solid waste, which can inform the technical and environmental feasibility of plastic waste management strategies in urban contexts like Pokhara.

Increased plastic use has led to significant amounts being discarded, damaged, or worn out, contributing to environmental pollution and human health risks [11]. Both macroplastics and microplastics accumulate in aquatic and terrestrial ecosystems, contaminating lakes, oceans, soils, and wildlife habitats [11],[12]. Dioxins, furans, mercury, and polychlorinated biphenyls are among the hazardous substances released by improper disposal, which includes open burning and uncontrolled landfilling [13].

Globally, plastic production and consumption continue to grow. Per capita plastic use is projected to more than double from 46 kg in 2019 to 100 kg by 2060, with Asia consuming above the global average and showing particularly rapid growth [14]. China and India, for instant, are expected to increase plastic consumption dramatically as incomes rise and industrial output expands [14]. As per Geyer, et. al. (2017), by 2015 the world had generated about 6,300 metric tons of plastic waste, of which only about 9% was recycled, 12% was incinerated, and the remaining 79% accumulated in landfills or leaked into the natural environment [15]. Global plastic trash is predicted to exceed 12 billion metric tons by 2050, of which 8.3 billion metric tons are expected to end up in landfills or the environment [16]. According to Blazso [17] estimates, the amount of plastic garbage produced worldwide could surpass 27 billion metric tons by 2050, with about a third coming from Asia. Plastics with one time uses that are thrown away right away after usage account for a large amount of this trash [18]. Improper disposal increases GHG emissions and pollutes the environment. The 3R strategy (Reduce, Reuse, Recycle), which combines recycling and waste reduction techniques, can greatly lessen the load on landfills, preserve resources, and lessen their negative effects on the environment [19],[20]. In this regard, improper management of one metric tons of plastic garbage can result in 1000 – 3000 kg of GHG emissions; by 2050, worldwide emissions from the plastic life cycle could surpass 56 gigatonnes [21].

Considering Nepal's comparatively less contribution to the world's plastic garbage, the nation faces significant issues because of its growing urbanization and inadequate recycling infrastructure [22],[23]. In underdeveloped countries, where inadequate infrastructure, low public knowledge, and poor regulatory enforcement obstruct efficient waste management, these issues are considerably more severe [24]. However, existing data on plastic waste generation in Nepal is often derived from secondary sources which shows considerable variation, necessitating critical evaluation and primary data collection to ensure accuracy and relevance for local policymaking. Nepal's per capita plastic consumption was predicted to be 7.3 kg in 2017 [25], but according to world bank data, it may have reached 17.52 kg, with each person producing 0.3 kg of solid garbage every day [26].

Plastic imports dominate Nepal's domestic consumption, primarily sourced from India and China, with minor contributions from other countries. In the fiscal year 2021/22, Nepal imported 380,000 metric tons of plastic while producing 165,000 metric tons domestically [27]. Urbanization, tourism, and changing lifestyles have accelerated plastic waste generation, straining the limited municipal waste management systems [28]. Landfills, collection systems, and recycling practices are insufficiently developed, with much of the waste remaining unsegregated and unmanaged [29].

PMC exemplifies the challenges faced by rapidly growing urban areas in Nepal. With a rising population, expanding economy, and flourishing tourism sector, the city produces significant amounts of plastic waste [29],[30],[31]. Plastic constitutes a substantial portion of the municipal waste stream, even though the methods used for collection and management practices are inadequate. Private waste collectors transport mixed waste, including biodegradable and non-biodegradable materials, to temporary landfill sites located at Ward No. 32, Lame Aahal. Although a new landfill has been proposed in Ward No. 33, source segregation, recycling, and reuse systems remain largely unimplemented.

Tourism exacerbates the problem by increasing demand for packaged goods and single-use plastics. Without a dedicated plastic waste management system, plastics are often openly dumped or burned, leading to environmental pollution, public health risks, and lost economic opportunities. The city also misses chances to reduce GHG emissions, conserve landfill space, and generate revenue through recycling and innovative approaches such as plastic credit systems [28].

Despite growing plastic waste volumes in Pokhara, few studies have quantified its exact composition, recovery potential, or current recycling practices. Limited data exist regarding the operational efficiency of recycling systems, manpower needs, and the economic feasibility of interventions. Similarly, environmental impacts such as potential reductions in GHG emissions or landfill savings remain poorly documented. This lack of comprehensive information underscores the need for detailed research to guide sustainable plastic waste management strategies in the PMC.

The main objective of this research is to evaluate the quantity, composition, and recycling practices of plastic waste in Pokhara Metropolitan City, along with their economic and environmental impacts. Specifically, the study aims to measure the total plastic waste generated using various assessment methods, analyze the environmental benefits such as GHG reduction and landfill space conservation, and assess the economic viability of plastic recycling.

This study examines the current plastic waste management and recycling practices in PMC and explores ways to improve them. At present, most plastic waste is dumped in landfills along with other waste, while only a small portion is recycled into pellets, aggregates, raw materials, coal, and clinkers. By adopting more efficient plastic waste management systems, the city could reduce overall plastic waste, minimize contamination, control disease, and improve public health. It could also cut down on plastic imports, reduce resource extraction, and create both economic and environmental benefits. Ultimately, the research aims to support PMC in transitioning toward more sustainable, economically viable, and environmentally responsible waste management practices.

2. Methodology

2.1 Study area

The study and data collection were conducted inside the PMC which is located at central part of the map of Nepal, between 28˚04' to 28˚23' north latitude and 83˚48' to 84˚11' east longitude, with an area of 464.24 sq. Km at Kaski district. The boundaries of PMC are at east region Rupa Rural Municipality (RM), north-east: Madi RM, North: Machhapuchchre RM, west: Annapurna RM and Parbat district and at south to south-east: Syangja and Tanahun districts as depicted in Figure 1 [32]. PMC is the Nepal's largest metropolitan city by area and second largest one by population. National Statistics Office (NSO) reported 513,504 population of Pokhara Metropolitan City in Census 2021 with 140,459 households [33].

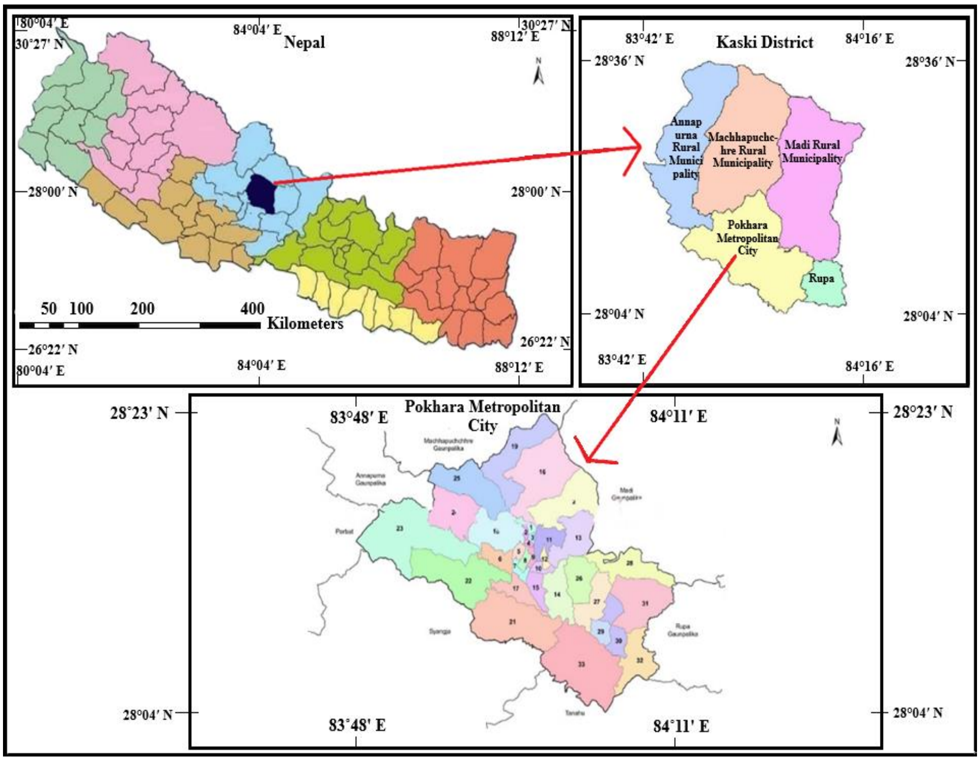


Figure 1: Location map of study area, PMC, Nepal

Due to the increase in mass flow of people inside Pokhra Metropolitan City each year, the waste generation in the city has also increased. Solid waste management in the city is poor because of previous landfill site located at PMC-14, Bachchebuduwa remained close due to Pokhara International Airport. Temporary landfill site at PMC ward no. 32, Lame Aahal was managed for 2 years since 2021 AD but still due to unavailability of new landfill site (proposed at PMC ward 33), there is still in use of current landfill site [30]. Because of national and international tourists visit Pokhara every year in significant numbers, dependency on plastic products is also higher as compared to other cities of Nepal. That's why PMC was selected as the study location for this study. This study was conducted by collecting data from sample household survey, from Himalayan Life Plastic industry located at ward no. 10, from Green Road Waste Management (GRWM) Private limited located at ward no. 17, from Plastic Information Center (PIC) at ward no. 12, from PMC Sanitation Section located at ward no. 8 and from different Waste Collection Parties of Pokhara.

2.2 Sample and sample size

PMC has total of 140,459 households and millions of people live temporarily [33]. Data collection for this study was carried out by calculating sample number by the sample size formula with 95% level of confidence and considering 5% margin of error can be occurred during study [34],[35],[36].

$$n = \frac{(Z)^2 . p(1-p) / e^2}{1 + \frac{Z^2 . p(1-p)}{e^2 . N}} \qquad (1)$$

Where n is the required sample size, e is the margin of error expressed as a decimal (±5% or ±0.05), p is the estimated population (0.5 for maximum sample size), N is the total population *(N=140459)*, and Z is the score (1.96 for a 95% confidence level).

Initial household number (n=353) as a sample size number is determine using the equation 1 for household survey. Total of 400 households inside PMC were randomly selected in this data sampling to estimate the total plastic wastes generation in 15 days. They were pre-informed to segregate or separate the plastics wastes they consumed during 15 days in 16-30 November 2024 A.D. A scheduled routine was applied to collect the data from each household. The total collected plastics were weighed with the help of GRWM staff and driver as shown in Figure 2.

Figure 2: Segregation and Weighing of plastic wastes in a household

2.3 Data collection

Data for this study were collected using both primary and secondary sources. Primary data were obtained through field visits to key waste management institutions in PMC, including the metropolitan waste management section, municipal waste contractors, household level surveys, the temporary landfill site, and existing plastic recycling centers. Direct observations were carried out to understand the types of waste generated, particularly plastics, along with collection, transportation, segregation, recycling, and disposal practices as shown in Figure 3. In addition, records from municipal solid waste contractors were monitored for one month to estimate daily, weekly, and annual waste and plastic waste generation, considering vehicle numbers, capacities, and collection frequency as illustrated in Table 1. Secondary data were collected through a comprehensive review of relevant literature, including journal articles, reports, publications, books, and related documents, which supported and complemented the primary findings. The study adopted a well-organized workflow to ensure a systematic research work for plastic waste and recycling systems in PMC as depicted in Figure 4. Figure 4 illustrates the sequential workflow of data collection, validation, and analysis, highlighting the integration of primary household surveys with secondary municipal and industrial datasets used for cross-verification.


a)

b)

c)

Figure 3: a) Weighing mixed plastics after segregation and shredding, b) landfill site at PMC-32, Lame Aahal, c) Collection, sorting, and segregation of plastic waste at the recycling center

Table 1: PMC waste collection parties, vehicles capacity and total trips during the month of September 2024

S.N	Name of Company	Service area (PMC wards)	Vehicle Counts		Capacity (kg)		Trips/Month	
			Large	Small	Large	Small	Large	Small
1	Bhadrakali Waste Management Pvt. Ltd.	6,11,12,13,20	4	5	3000	1500	221	400
2	Nepal Public Health Environment for Development Pvt. Ltd	1,2,5,18,23,24,25	2	3	2000	1500	125	150
3	Pokhara Phoharmaila Bybasthapan Private Limited	7,17,21,22	0	6	-	1300	-	206
4	Waste Management Recycling Private Limited	10,14,15	3	3	3000	1500	156	162
5	Batabaran Sunder Nepal Private Limited	3,4,8,9	3	4	3000	1500	275	300
6	Pragati Sansar Nepal Private Limited	16,19,26,27,28,29,30,31,32,33	2	4	3000	1500	122	380
Total			14	25				

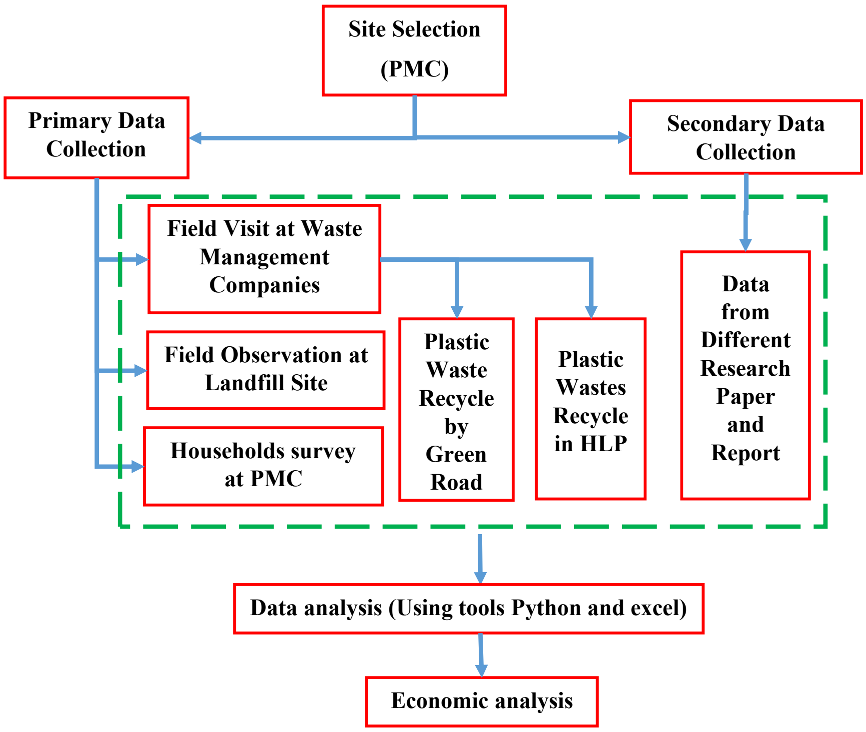


Figure 4: Schematic diagram showing the flow of this research paper

2.4 Reconciliation of Plastic Waste Estimation Methods

Four independent methods were used to estimate plastic waste generation in PMC: (1) household waste sampling, (2) landfill volume-density assessment, (3) data from private waste contractors, and (4) per-capita calculations based on population data. Discrepancies among these estimates were critically evaluated. The household survey was selected as the primary basis for subsequent analysis due to its direct measurement, independence from municipal reporting biases, and alignment with established waste characterization methodologies [8]. A comparative summary of the four methods is provided in Table 1, 2 and 3. While each estimation method has inherent limitations, the household survey approach was selected as the primary basis for analysis because it provides direct measurement of plastic waste generation at the source, minimizes dependence on municipal reporting assumptions, and aligns with established waste characterization methodologies reported in recent literature [8, 10]. Landfill-based and contractor-reported estimates were used for triangulation and validation rather than direct substitution, as these methods are influenced by waste mixing, density assumptions, and incomplete collection coverage.

During the field visit to the landfill site, it was observed that both biodegradable and non-biodegradable waste are openly dumped without segregation, recycling, or treatment. Two dozers are used to cover the waste with soil. The site operates more as an open dumping area than a proper landfill, as it does not follow standard management guidelines. Chemical sprays are occasionally used to speed up the decay of organic waste and control odor. The landfill is located, hollow area formed after a landslide near the proposed bus park, close to the Seti River. Table 2 outlined the average trips of large and small trucks for waste collected and disposed of in landfill site in different days of a week.

Table 2: Weekly average vehicle trips and waste disposal at landfill site

SN	Days	Large Truck Trips	Small trucks Trip	Total Trips
1	Sunday	20	60	80
2	Monday	20	60	80
3	Tuesday	20	60	80
4	Wednesday	20	60	80
5	Thursday	20	60	80
6	Friday	20	60	80
7	Saturday	14	25	39

It was found that GRWM Pvt. Ltd., located in Ward 12 of PMC, collects about 1.648 metric tons of plastic each month only from ward 12. Total plastic wastes collection and recycled by GRWM was found to be 19.776 metric tons per year. The collected plastics are recycled at its center and are used to produce roads, bricks and blocks, helping save around 16% of raw materials and aggregates. After visiting Himalayan Life Plastic (HLP) industry in PMC-10, it was found that annual collection and recycled PET plastics waste was found to be 1200 metric tons.

From the household (HH) survey conducted in PMC in 16-30 November 2024 recorded a total of 1.314 metric tons of plastic waste was generated in the 15 days from 400 sample households. Using equation 2, the annual plastic waste generation was estimated to be 11.227.85 metric tons as outlined in Table 3.

$$\text{Total plastic waste generation} = \frac{\text{Total plastics waste of sample households} * \text{Total households}}{\text{Sample Households}} \quad (2)$$

Table 3: Total plastic wastes based on 400 households in PMC (15 days)

Description	**Quantity**
Total Plastic waste generation in 400 HH in 15 days	1314.030 kg
Total Plastic waste generation in 400 HH per day	87.602 kg
Total Plastic waste generation in per HH per day	0.219 kg
Total Plastic waste generation in PMC per day	30761.223 kg
Total Plastic waste generation in PMC	11227.847 metric tons/year
Per Capita Plastic waste generation in PMC	0.059 kg/capita/day
Per Capita Plastic waste generation in PMC	21.865 kg/capita/year

3. Result and discussion

Data were collected through surveys, field visits, and interviews. The raw data were then cleaned and processed to obtained key results. Data analysis were carried out using tools such as excel and python, with the findings presented through bar charts, pie charts, and line graphs.

3.1 Total plastic waste reached to landfill site

Based on the field data observed and calculated, PMC generates about 2920443.3 m^3 of solid waste per year, with an average waste density of 211 kg/m^3 [37]. This equals about 61,621.347 metric tons of municipal solid waste (MSW) annually. Among this, about 19% (around 11,708.056 metric tons) consists of plastic waste [26]. Total plastic waste generated in PMC is found to be 12293.458 metric tons per year, combining 11708.056 metric tons per year with 5% leakage to environment [37].

3.2 Plastic waste by statistical method of waste parties

Table 4 presents the waste collection data from six different contractors of PMC recorded during the first 30 days September 2024. Mean daily waste collection of PMC is 152,834 kg (Equation 3). So the yearly waste generation is 54,256.07 metric tons and considering that 19% [26], [38] of waste consists of plastic, the annual plastic waste generation is 10,308.653 metric tons (Equation 4). So the total plastic waste collection by waste management parties is 10824.085 metric tons per year (Equation 4) considering 5% environment leakage [37]. Total plastic waste generation of PMC is 12606.910 metric tons per year considering the per capita waste generation of PMC [26] and total population of PMC [33]. Total plastic waste generation in PMC considering 400 sample HH for 15 days is 11227.847 metric tons per year.

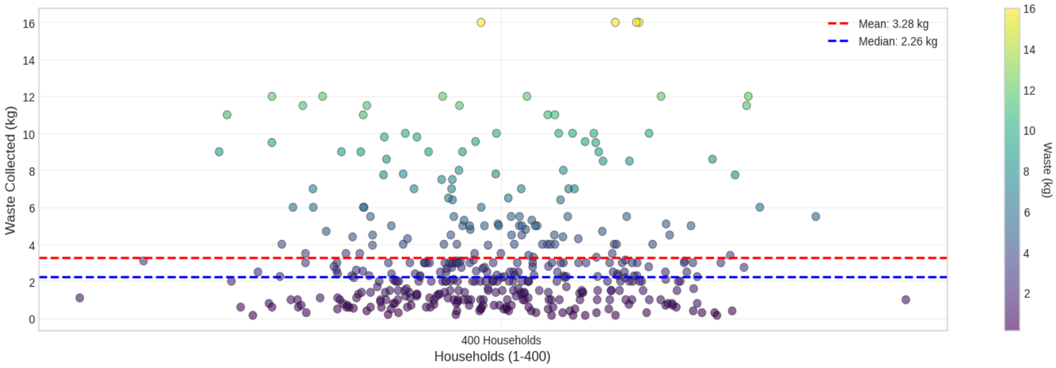
Table 4: Total MSW quantity calculation based on waste collection parties

Party	Vehicle Trips		Capacity (Kg)		Total	Vol.	Total
	Large(f_1)	Small(f_2)	Large(x_1)	Small(x_2)	(f_1x_1+f_2x_2)	ratio	Capacity(Kg)
1	221	400	3000	1500	1263000	0.9	1136700
2	125	150	3000	1500	600000	0.9	577500
3	0	206	-	1300	267800	0.9	241020
4	156	162	3000	1500	711000	0.9	639900
5	275	300	3000	1500	1275000	0.9	1147500
6	122	380	3000	1500	936000	0.9	842400
Total							4585020

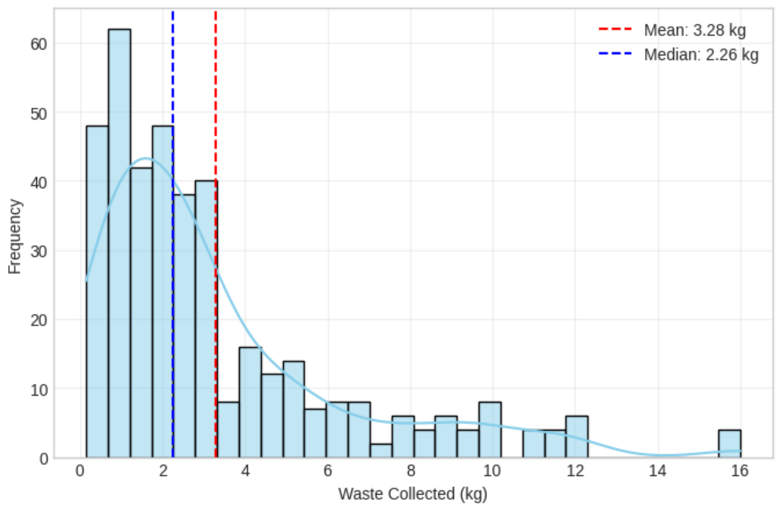
$$\text{Mean Daily Waste Collection } \bar{x} = \frac{\sum fx}{N} = \frac{4585020}{30} = 152{,}834 \text{ Kg} \quad (3)$$

$$\text{Plastic waste} = 19\% \text{ X } 54{,}256{,}070 = 10{,}308{,}653.3 \text{ Kg} \quad (4)$$

The validity of the discussion is supported by the strong consistency observed across all three visualizations, each showing the same right-skewed pattern and the same relationship between the mean (3.28 kg), median (2.26 kg), and outliers. With a large sample of 400 households, the data is statistically reliable and representative, reducing the likelihood of random variation. The beeswarm, histogram, and box plot independently confirm the concentration of most households in the low-waste range and the presence of a smaller number of high-waste generators, demonstrating internal coherence and verifying that the collected data accurately reflects real waste-generation behaviour in PMC as highlighted in Figure 5.



a)



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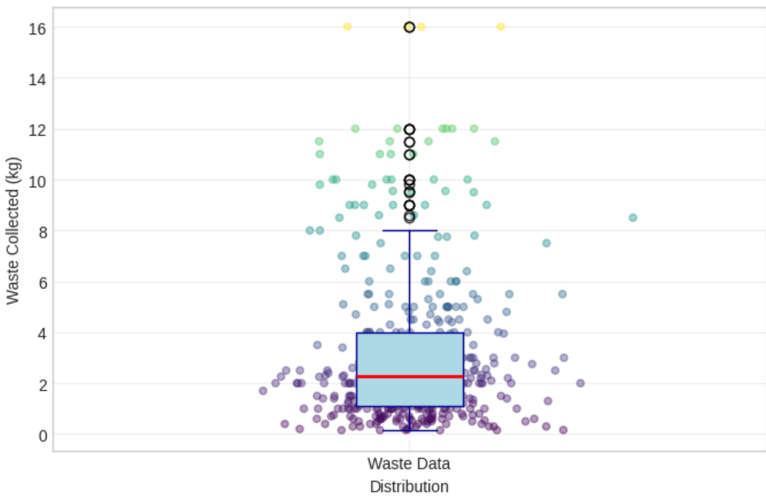

c)

Figure 5: Plastic waste collection from 16-30 November, 2024 a. Beeswarm plot b. histogram c. box plot

3.3 Plastic recycling rate and recycle value

Total plastic recycled by GRWM and HLP was found to be 1219.776 metric tons per year in PMC. Thus the total percentage of plastic recycled is equal to the 10.86 % (Equation 7 and 8) which is equal to NPR 2,438,688.368 per year (Equation 9).

$$\%\ \text{Plastic Recycle} = \frac{\text{Net recycled plastic in PMC}}{\text{Total Annual Plastic generation in PMC}} \quad (7)$$

$$\%\ \text{Plastic Recycle} = \frac{1219.776}{11227.847} * 100\ \% = 10.86\% \quad (8)$$

$$\text{Total current Recycle value} = \frac{10.86}{100} * \text{NPR } 22455694 = \text{NPR } 2{,}438{,}688.368/\text{year} \quad (9)$$

Plastic credit systems offer a market-based mechanism to incentivize recycling, but their implementation in PMC requires careful design. Credits for easily recyclable plastic (NPR 334/ton) and hard-to-recycle plastic (NPR 20,041/ton) were reported, yet no formal system exists. Successful implementation would require: (1) a transparent registry to track plastic recovery, (2) third-party verification to prevent greenwashing, (3) integration with extended producer responsibility (EPR) policies, and (4) financing mechanisms such as green bonds .or international climate funds. Lessons can be drawn from emerging systems in Southeast Asia, where digital platforms are used to monitor and trade plastic credits. For PMC, implementation would require municipal oversight in coordination with licensed recyclers, integration with national extended producer responsibility (EPR) frameworks, and third-party verification to ensure transparency and prevent credit inflation or greenwashing. From interview and research study by other, 1Kg of the plastic waste segregation or sorting was found to be NPR 14-16 price range (Table 5). From the table 5, the cost comparison between primary data from this study and secondary data from Sarbottam and Ghorahi Cement Industries shows that segregation and bailing costs are similar, while shredding and logistics costs vary. The absence of a margin in this study results in a slightly lower total sorting cost (14 NPR/kg) compared to the industrial values (15.5–16 NPR/kg). This highlights that while secondary data provide benchmarks, primary data better reflect local operational conditions and actual costs.

Table 5: Plastic segregation/Sorting cost in different companies [39]

Industry/Recycle	**Sarbottam Cement Industries Limited**	**Ghorahi Cement Industries**	**This study**
Segregation cost (NPR/Kg)	4	4	4
Bailing Processing cost (NPR/Kg)	3	3	3
Shredding Cost (NPR/Kg)	1.5	0	2
Logistics (Loading / unloading / Transportation) (NPR/Kg)	3	5	4
Local Government Taxes (NPR/Kg)	1	1	1
Margin (NPR/Kg)	3	3	0

Total Cost of sorting (NPR/Kg)	15.5	16	14

3.4 Plastic waste generation in PMC

Figure 6 shows that plastic waste generation in PMC was estimated at 12,606.91 metric tons/year using per-capita data [38], 12,293.46 metric tons/year from landfill records, and 10,824.09 metric tons/year based on waste management parties' reports. The sample household survey produced a comparable estimate of 11,227.85 metric tons/year. Because the household survey was independent of previous datasets, its value was used for subsequent analyses.

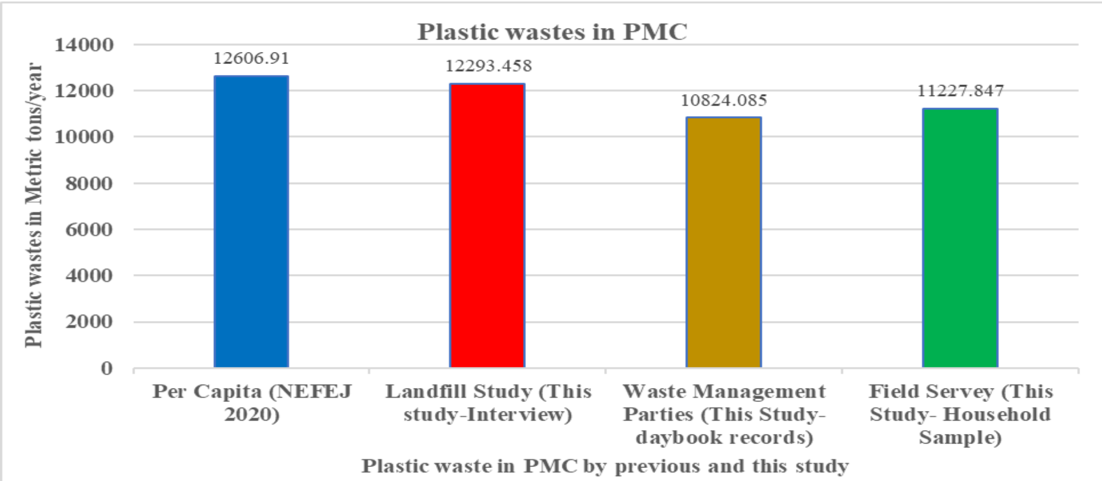

Figure 6: Total plastic wastes generation in PMC based on 4 different ways

Figure 7 compares the share of plastic in MSW across global and regional contexts. Previous studies show that plastics make up about 12% of global MSW [40], 8% in Asia [40], and around 10% in India [41]. In Nepal, reported values range from 13–16%, while Kathmandu studies show 15.94–19%. For Pokhara, earlier assessments ranged from 8.80% [37] to 19% [26], [38]. In this study, three different datasets estimated plastic constituents in PMC's MSW at 18.46%, 16.25%, and 16.86%, with the household survey specifically indicating 16.86%.

The Green Road recycled 19.78 metric tons/year of plastic, while HLP recycled 1,200 metric tons/year, giving a total of 1,219.776 metric tons/year. Based on the household survey, PMC generates 11,227.847 metric tons/year of plastic waste, meaning only 10.86% is currently recycled. This recycling rate is comparable to the global average of about 9% [15], indicating that PMC's existing recycling efforts are similar to global trends but still limited.

LDPE accounted for the highest share at 23%**,** followed by MLP and HDPE. PVC had the lowest proportion at 9%**.** The high amount of LDPE is likely due to its widespread use in packaging and carry bags (Figure 8). The study found that PMC has not yet developed an effective plastic waste management system. Although door-to-door collection exists, all waste is collected together without source segregation, and there is no transfer or sorting facility near the landfill. As a result, mixed waste is directly transported and dumped, which can increase environmental and health risks. In contrast, Green Road and HLP have encouraged households to separate plastics and collect these materials through their own collection systems.

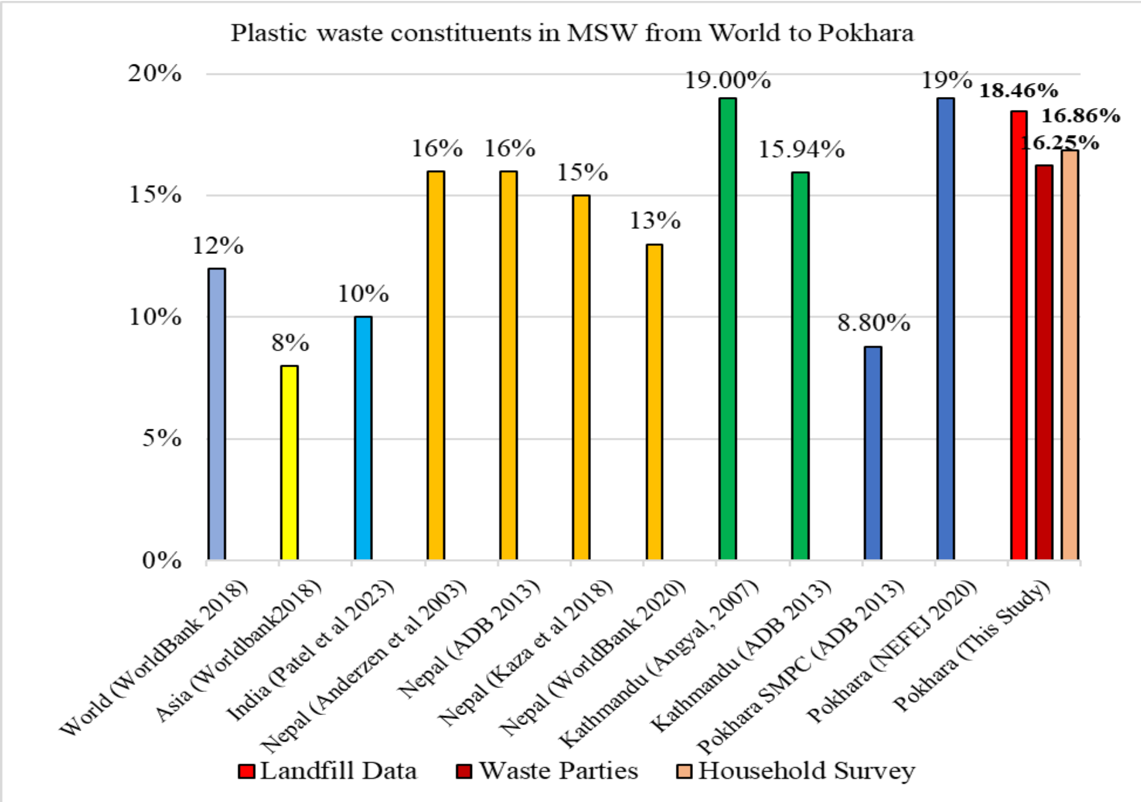

Figure 7: Total plastic waste constituents in MSW in World, Asia, India, Nepal, Kathmandu, and Pokhara.

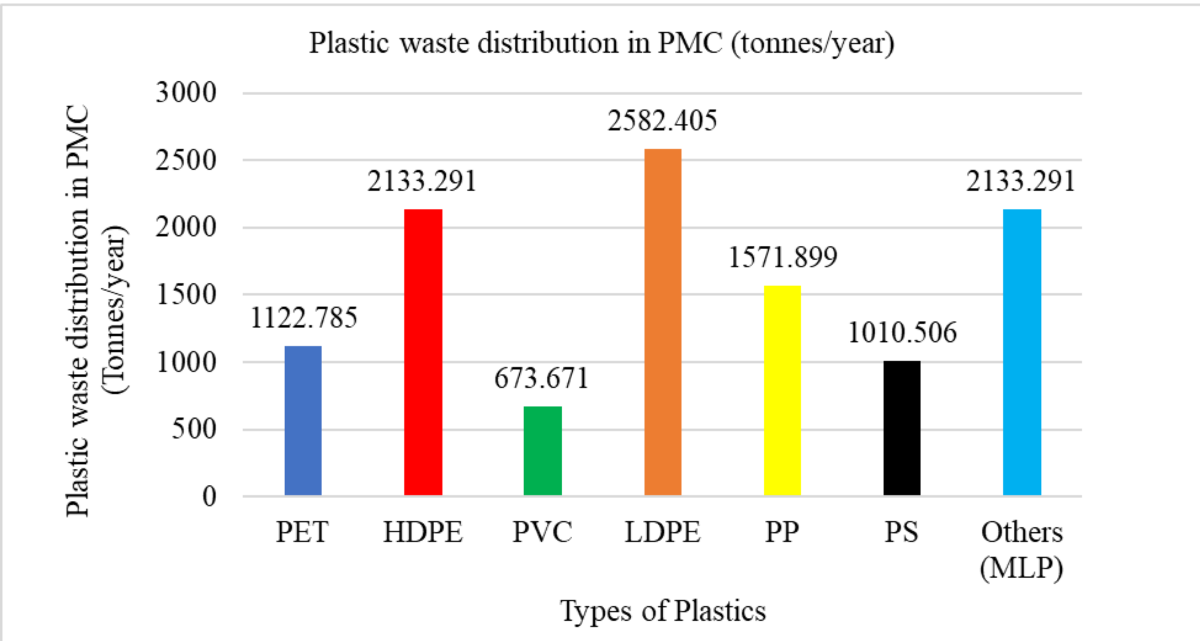

Figure 8: Different type of plastic wastes in PMC and its weight in tonnes/year

3.5 Market rate and plastic waste potential of Pokhara Metropolitan City

From the market price of recyclable material (Table 6), the average benefit in selling plastic was found to be NRP 2 per KG. the average gross revenue potential of plastic materials is about NPR 22,455,649 per year (NPR 2*11227.847*1000 = NPR 22,455,694/year).

PMC could earn about NPR 22.46 million per year if all plastic waste were fully recycled. After accounting for 5–20% losses, the revenue potential ranges from NPR 21.33 million to NPR 17.07 million. At present, only 10.86% of plastic waste is recycled, generating about NPR 2.44 million per year for private recyclers. This income could grow significantly if PMC adopts stronger recycling and circular economy practices [8], [9].

Table 6: Recyclable market value in PMC with cost and sell price [38]

Items	Buying Price (NPR/Kg)	Selling Price (NPR/Kg)
Plastics (Mixed)	11	13
Beer Bottles	1	1.5
Books/Papers	8	12
Iron	13	15
Other metals	70	90

3.6 Economic analysis of plastic waste recycles

For a 1-km road segment (25 mm thick, 3.75 m wide), the bitumen requirement is about 11,250 kg. When plastic waste is blended with bitumen at rates up to 20%, the cost comparison for VG10 and VG30 (Figures 9 and 10) shows maximum savings of NPR 225,000 and NPR 232,425, assuming a plastic price of NPR 5/kg. Even when plastic prices vary, the graphs indicate that incorporating plastic consistently lowers bitumen costs. Using a 20% plastic bitumen mix also provides environmental benefits, including an estimated 6 metric tonnes of CO_2 reduction and decreased landfill use.

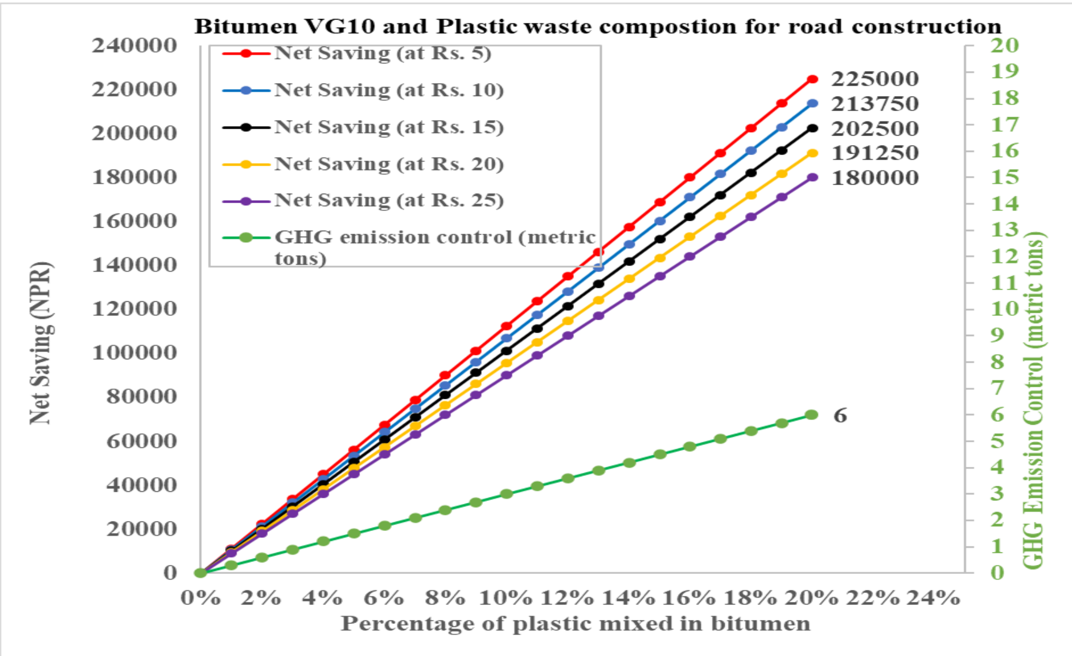

Figure 9: Net saving amount in NPR and GHG emission in Metric Ton of CO_2 by using Plastic-Bitumen VG10 road

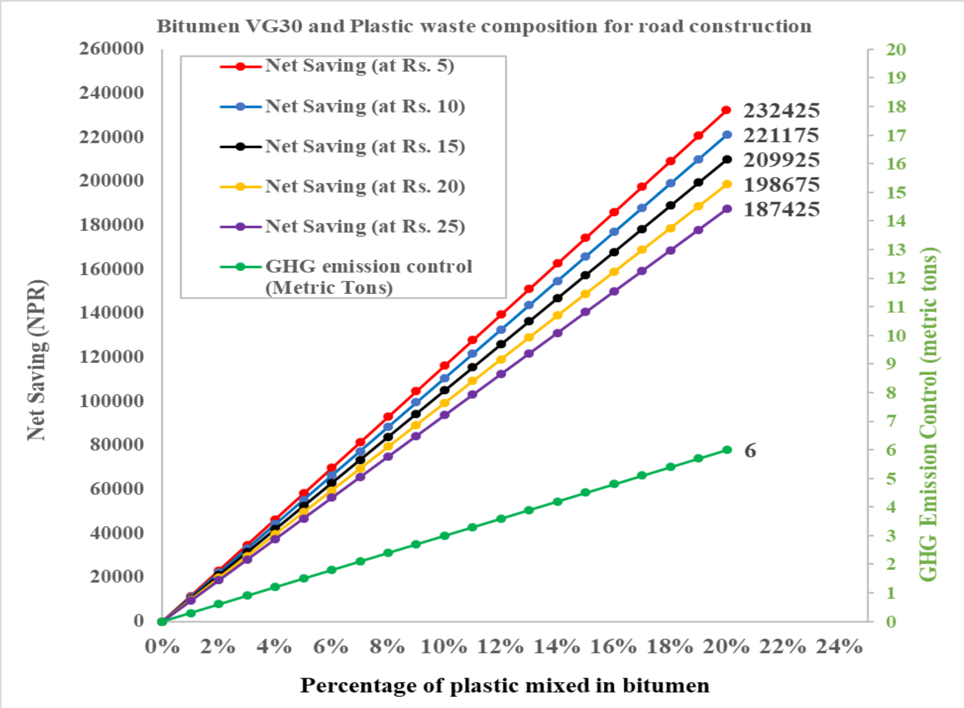

Figure 10: Net saving amount in NPR and GHG emission in Metric Ton of CO_2 by using Plastic-Bitumen VG30 road

The Green Road Waste Management facility in Pokhara (Ward 17) was established with an initial UNDP investment of USD 105,000, equivalent to NPR 14.18 million at present value. The combined cost of infrastructure, one complete machine set, and one vehicle amounts to NPR 12.9 million. The center operates on rented land at NPR 30,000 per month (NPR 360,000 annually). Two staff members (driver and helper) are employed for waste collection with a monthly salary of NPR 34,600, while the wages for three segregation workers are accounted for within the plastic processing cost.

Green Road is not getting enough plastic because people do not separate waste at home and the collection system is limited. This has led to a negative IRR of –36%, meaning the project is not financially viable right now. It is still running only because UNDP covered the initial costs. Currently, the center recycles about 1.5 tonnes of plastic per month, but it hopes to reach 20 metric tons per month if plastic segregation and collection in PMC improve.

Table 8: IRR of plastic recycling project (existing and future project)

SN	Project	MARR	IRR	Result	Decision
1.	Green Road (Current condition)	16.16%	-36%	IRR is negative	Reject the project
2.	3 Men and hand segregation	16.16%	11%	IRR<MARR	Reject the project
3.	3 Men and machines segregation	16.16%	21%	IRR>MARR	Accept the project
4.	6 Men and hand segregation	16.16%	19%	IRR>MARR	Accept the project

5.	6 Men + 2*machines segregation	16.16%	30%	IRR>MARR	Accept the project

Based on a nominal MARR of 16.16% for Nepal, the IRR analysis (Table 8) shows that the current Green Road setup is not viable, with an IRR of –36%. When evaluating alternative scenarios under the assumption of smooth segregation, collection, and operation processes, the results indicate that a plastic recycling project becomes feasible only when it meets a minimum operational threshold of at least three workers, one complete set of recycling machines, and one collection vehicle with two staff members. Scenarios involving machine-based segregation or an increased workforce (six workers) both achieve IRRs higher than the MARR, making them financially acceptable. In contrast, the hand-segregation model with only three workers yields an IRR below the MARR and remains infeasible. This analysis highlights the importance of adequate labor and mechanization for the economic viability of plastic recycling centers [8].

A sensitivity analysis using the Present Worth (PW) method was carried out for the proposed “3-Men + Machine” plastic-recycling project over a 10-year period with a MARR of 16.16%. The evaluation included all major costs which are initial investment of NPR 5,000,000, a Bolero vehicle, one machine set, salaries for three processing workers and two collection staff and annual net revenue after deducting all operating expenses. Plastic credit values were also included in the annual annuity. By varying costs and revenues from –30% to +30%, the baseline Net Present Value (NPV) at 0% was found to be NPR 2,191,280.29. The project remains profitable under moderate changes, with NPV rising to NPR 6,718,664.38 at +30% revenue and NPR 6,061,280.29 at –30% cost. However, under adverse conditions such as a 30% cost increase, the NPV drops to –NPR 1,678,719.71, indicating a potential loss. Overall, the project is financially viable but sensitive to large cost escalations or revenue reductions (Figure 9).

The analysis of plastic-recycling scenarios shows a clear increase in environmental benefits as processing capacity expands (Figure 12). The current Green Road project recycles about 19.78 metric tons of plastic per year, reducing about 52.74 metric tons of CO_2 emissions and saving 137.33 m^3 of landfill space. In comparison, a simple upgrade to a “3-Men” model raises recycling capacity to 109.2 metric tons per year, with corresponding reductions of 291.20 metric tons of CO_2 and 758.33 m^3 of landfill volume. Adding a machine further doubles the impact, enabling 218.4 metric tons of recycling and delivering 582.40 metric tons of GHG reduction along with 1516.67 m^3 of landfill saving. The “6-men + 2 machines” model scales this even higher, achieving 436.8 metric tons of recycling and providing over 1164.80 metric tons of CO_2 reduction. Among current operations, HLP PET recycling stands out with the highest individual contribution where 800 metric tons of PET processed annually, resulting in 2133.33 metric tons of GHG reduction and 5555.56 m^3 of landfill space saved. Overall, the results indicate that expanding manpower and mechanization significantly enhances plastic recovery and offers substantial environmental gains across all indicators. This results suggest that increasing plastic-recycling capacity and mechanization greatly magnifies environmental benefits as output rises, avoided CO_2 emissions and landfill savings also rise substantially [10], [42].

While the modeled scenarios show positive returns, real-world implementation faces several barriers. These include inconsistent waste segregation at source, fluctuating market prices for recycled plastics, high transportation costs, limited municipal enforcement, and lack of financial incentives. The sensitivity analysis as presented in Figure 11 indicates that a 30% increase in costs could render the project unprofitable, highlighting the need for risk mitigation strategies such as long-term offtake agreements, government subsidies, and community engagement programs. These results should be interpreted cautiously, as real-world constraints such as inconsistent source segregation, fluctuating recycled plastic prices, limited municipal enforcement capacity, and rising transportation costs may reduce achievable revenues and increase operational risks beyond those captured in the modeled scenarios.

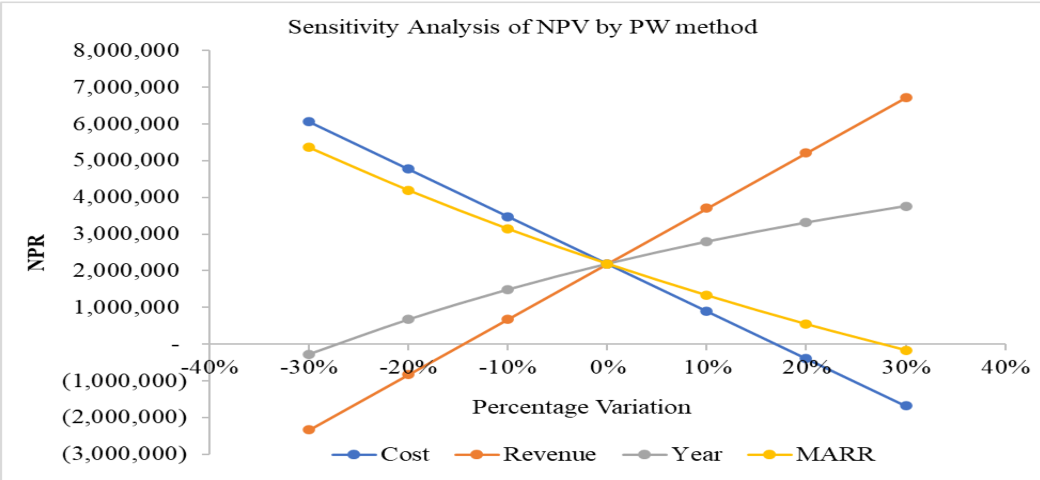

Figure 11: Sensitivity analysis of 3 men and machines project

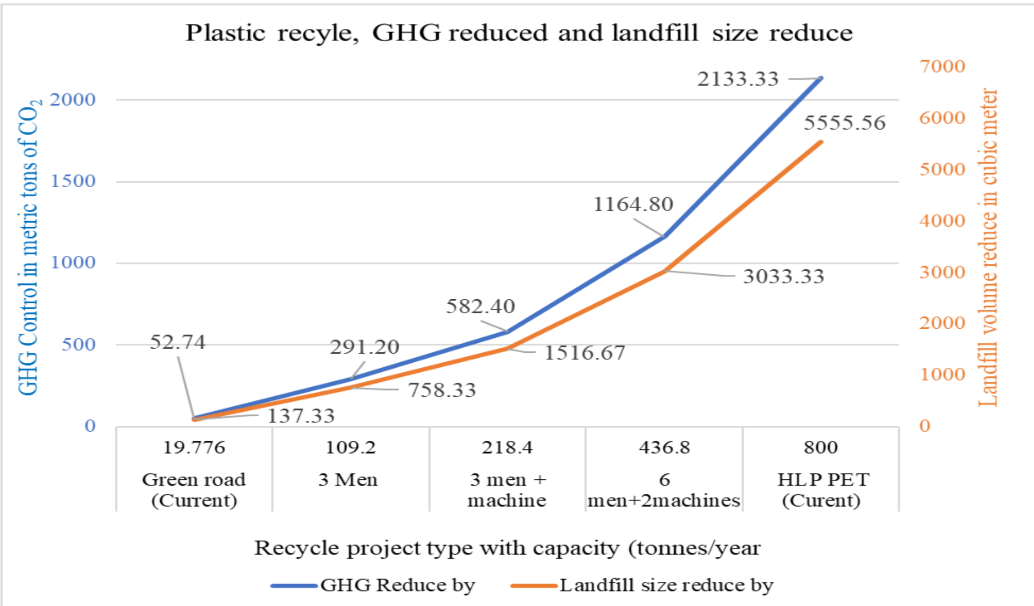

Figure 12: Plastic recycle leading to GHG emission and landfill size reduction

4. Conclusions

This study found that plastic waste makes up 16.86% of the total MSW generated in PMC, which is slightly lower than the value reported by the NEFEJ study based on World Bank data. Household surveys estimated that PMC generates around 11,227.86 metric tons of plastic waste annually, with LDPE being the most used type and PVC the least. At present, only Green Road and HLP recycle plastic in PMC, and together they process just 10.86% of the total plastic waste, generating about NPR 2.4 million per year at traditional market rates. The theoretical gross revenue potential is much higher around NPR 21.33 million and this revenue can be increased by improving segregation, upcycling, and the sale of plastic credits.

The evaluation of different recycling models showed that facilities employing at least three workers for sorting, one set of machines, and one vehicle with two operating staff are financially and technically feasible, provided that proper source segregation is practiced. Recycling one metric tons of plastic can save about 6.94 cubic meters of landfill space and prevent 2.67 metric tons of CO_2 emissions. With a "3-men + machine" setup, it's possible to recycle around 218.4 metric tons of plastic each year. This can earn roughly NPR 3.9 million in net revenue, while also cutting 582.4 metric tons of CO_2 and saving more than 1,516 cubic meters of landfill space. Plastic waste in Pokhara Metropolitan City also has potential for energy recovery through waste-to-energy pathways such as pyrolysis; however, a detailed techno-economic and environmental feasibility assessment, including feedstock characterization, conversion efficiency, reactor scale, emission control, and cost analysis, is required before any quantitative energy estimates can be established.

If expanded properly, plastic recycling can create jobs, reduce imports, and deliver substantial environmental and health benefits. However, current recycling efforts are limited mainly due to poor source-level segregation and inadequate municipal support. The findings suggest that a well-managed recycling center can significantly increase revenue, reduce GHG emissions, and conserve landfill space, while contributing to cleaner air and improved urban sustainability. Using plastic waste in road construction can further reduce costs and lessen the environmental burden, and advanced methods such as mechanical recycling, gasification, and waste-to-energy offer additional opportunities.

Recommendations and Future Work

To enhance plastic recycling in PMC, mandatory source segregation should be enforced through municipal bylaws, supported by color-coded bins and reliable collection systems. Capacity building of municipal staff and informal waste pickers through training in efficient sorting and baling techniques is essential and can be strengthened through partnerships with NGOs and private recyclers. Financial incentives, including green procurement policies, tax benefits, and transparent plastic credit mechanisms, are recommended to improve economic viability. Infrastructure development should prioritize material recovery facilities and carefully evaluated public private partnerships. Finally, establishing a multi-stakeholder coordination platform involving PMC, recyclers, communities, and academia would support effective implementation, monitoring, and future system optimization.

Future work will assess the feasibility of converting plastic waste into energy through pyrolysis by analyzing feedstock quality, energy content, and conversion efficiency. The study will also examine suitable reactor types, costs, and operational challenges. Environmental impacts and emission control measures will be evaluated to determine the practicality of pyrolysis in Nepal's waste-to-energy system.

Conflicts of Interest Statement

The authors declare no conflicts of interest for this study.

Data Availability Statement

The data supporting the findings of this study are presented in the manuscript. Additional data will be provided upon request.

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