Classification of Recyclable Plastic Waste by Near-Infrared Spectrometer

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Abstract. This study addresses the pressing issue of plastic waste management in Khulna City, Bangladesh, highlighting its direct impact on health and the environment. The conventional methods of sorting plastic waste in the existing Recycling Shops (RSs) in Khulna City are time-consuming and rely on visual inspection. The research proposes the application of handheld Near-InfraRed (NIR) spectrometers in RSs for efficient plastic waste identification. This spectrometer provides cloud-based computing and a centralised database for material classification based on their chemical composition. A survey conducted in three selected RSs over six months reveals an average monthly input of 15 tons of plastic waste per RS, with a 75% recycling rate. The NIR analysis classifies plastics into eight distinct types, including Polyamide (PA), Polyethylene (PE), Polyethylene terephthalate (PET), Polymethylmethacrylate (PMMA), Polypropylene (PP), Polystyrene (PS), Polyvinyl chloride (PVC), and Styrene Acrylonitrile Resin (SAN). Notably, PP and PET emerge as the most abundant materials, consisting of 65% of the total plastic handled. The study detailed the monthly input and output data, indicating the percentages of various plastics handled in the RS. The performance evaluation of the handheld NIR spectrometer for five known plastic types demonstrated an overall accuracy rate of 87.6%. The existing manual sorting process of plastic waste in RS of Khulna was found to be convenient and accurate. However, incorporating the NIR spectrometer into Khulna City's plastic waste management system for automatically sorting plastic waste can further improve the efficiency of recycling practices. The proposed solution holds the potential to address environmental concerns, promote sustainability, and contribute to a healthier future in waste management practices in Bangladesh.

Keywords: Solid Waste Management (SWM), Municipal Solid Waste (MSW), Recyclable Plastics, Near-Infrared (NIR) Spectroscopy, Recycling Shops (RS).

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1 Introduction

Plastic, a non-biodegradable organic substance, persists in the environment for extended periods, emerging as a pressing global challenge with growing concerns for health and the environment. Consequently, there is a need for creative and effective solid waste management solutions. Plastics are widely used in both manufacturing and daily life. From 2008 to 2018, there was a notable increase in global plastic production, rising from 254 million tons to 359 million tons, with a projected tripling by 2050 (Othman et al., 2021). Plastic waste management has become a critical challenge in Bangladesh, especially in Khulna city (Moniruzzaman et.al.2012). Khulna, the third-largest city in Bangladesh, produces approximately 520 tons of municipal solid waste (MSW) daily. Plastics account for 3.1% of this waste stream, equating to a daily plastic waste generation of 16.1 tons (Alamgir, 2005). Recycling plastic waste is of utmost importance. In Khulna City, 7.2% to 7.65% of the total generated solid wastes are recycled daily (Moniruzzaman, 2011; Bari et. al. 2012a) which are comprised of plastic (Ahmed et. al 2023), paper (Raj et. al. 2017), garments (Tabassum et.al. 2017), bones (Siddique et. al. 2015) etc. Most of these wastes are decomposable organics (Atauzzaman & Bari 2023) other than plastics. Due to disintegration plastic becomes micro-plastics and cause soil, water and marine pollution (Roksana, et. al, 2023). Therefore, Recycling plastic waste is vital because it protects the environment and wildlife, conserves resources, reduces energy use, lowers greenhouse gas emissions, minimises landfill waste, extends its lifespan, creates jobs and economic opportunities, raises public awareness of responsible consumption, removes rainwater clogging in drains, and promotes sustainable practices.

Plastic recycling offers environmental benefits by reducing greenhouse gas emissions from landfills. According to a report from the Federal Environment Ministry of Germany, plastics recycling in Turkey results in a net mitigated emission factor of 926 CO_2-equivalents per tonne of waste (Vogt et al., 2015). In contrast, the energy consumption in the recycling process leads to 271 kg of CO_2 emissions per ton (Gradus et al., 2017). Additionally, plastic recycling can lower management costs by decreasing the amount of solid waste sent to landfills. Plastic recycling can yield a net profit of US$0.15 per kilogram (Genc et al., 2019). Improved plastic waste recovery can reduce recycling costs, and profits may even result from using recycled plastic granules. However, achieving higher plastic recovery rates necessitates better communication and collaboration among government, local authorities, the public, and the private sector. Individual waste collectors, dealers, and small recycling industries are involved in waste recycling within Khulna City (Moniruzzaman, 2011). Tokai and Feriwalas are considered as waste collectors, serving as the first link, while recycle dealers are seen as the second link in the recycling chain (Bari et. al. 2012b).

Sorting of plastic waste samples based on its chemical composition is the primary function of plastic recycling. In Khulna City, conventional plastic waste sorting, which relies on visual inspection of their physical appearance, is employed for large scale separation. Reusing plastics presents a challenge due to the hundreds of distinct types, often indistinguishable to the human eye. This challenge is a significant factor contributing to the current recycling rate of less than 20% for globally produced Plastic

(Geyer et al., 2017). The type of Plastic samples can be instantly identified when scanned with a handheld NIR spectroscopy device. To better identification of plastics samples, it is necessary to consider more than just their appearance and also examine their physical and chemical properties and characteristics. In this regard, optical spectroscopy can play a vital role in identifying plastic types based on their absorption spectrum. NIR spectroscopy utilises cloud-based computing and centralised databases, offering nearly limitless computational capacity for classification algorithms and vast spectral databases (Schmidt et al., 2020).

NIR spectrometers have evolved beyond controlled lab settings, becoming more compact, lighter, and robust. The spectrometer is part of a unique cloud-based system designed for capturing, retrieving, and analysing NIR data. The process involves measuring spectra, transmitting them to the cloud via a mobile app, real-time cloud analysis, and sending the results back to the user. NIR spectroscopy examines the interaction of molecules with light in a specific range of wavelengths, from 750 to 2,500 nanometres (Schmidt et al., 2020). Within this range, it focuses on how molecules vibrate and combine, providing valuable insights into their composition and properties. Due to relatively lower absorption coefficients, the light can penetrate the sample to a greater depth, often several millimetres, which is deeper than the mid-infrared range. NIR spectra typically do not provide a straightforward representation of the sample being tested. To create predictive models, statistical methods which can be computationally intensive, such as Principal Component Analysis (PCA) or Linear Regressions, are essential (Schmidt et al., 2020). The classification of black plastics is not possible by NIR spectroscopy due to the low reflectance of black plastics. However, a Convolutional Neural Network (CNN)-based algorithm can detect feature information, where the CNN-based algorithm deploys a high-resolution camera to capture waste images and sensors to detect feature information (Xia et al., 2021). The performance of NIR spectroscopy can be assessed using confusion matrices, which can be obtained from Partial Least Square Discriminant Analysis (PLS-DA) involving both fitting and cross-validation (Rani et al., 2019). In addition to categorising materials like plastics, NIR spectroscopy is widely used for quality assurance and monitoring processes in the food, pharmaceutical, and medical sectors. It is also employed to analyse nutrients and moisture content in food and feed (Schmidt et al., 2020).

The broad objective of this study is to classify recyclable plastic waste according to its chemical composition. This is the very first time that NIR spectroscopy has been used in Bangladesh to classify plastic waste based on its chemical composition. This study involves conducting a comprehensive survey to quantify and analyse the monthly mass flow of plastic waste in Khulna RSs, classifying recyclable plastic waste based on its specific chemical compositions using NIR spectroscopy categorisation, and assessing the accuracy of NIR spectroscopy through the utilisation of a confusion matrix.

2 Research Methodology

2.1 Selection of Recycling Shops and Survey Procedure

Khulna, the third-largest city in Bangladesh, covers an area of 45.65 square kilometres and is divided into 31 wards, with a population of 1.5 million (KCC, 2005). This study selected three specific plastics RSs—M/S Madina Plastics, M/S Dia Enterprise, and M/S JN Pet Flakes located in Sonadanga, Khulna. Their locations are illustrated in Fig. 1. These RSs primarily collect Plastic from plastic recycling dealers, as well as from informal collectors known as "Tokai" and "Feriwala," along with waste traders (Moniruzzaman, 2011).

Upon selecting these RSs, data regarding plastic input was recorded from April 2023 to September 2023. Similarly, output data, including plastic flakes, plastic grain, and recycled plastic products, was recorded over the same period. To accomplish this, plastic waste data was collected for seven consecutive days in April 2023, and data collection continued at regular monthly intervals until September 2023. Plastic waste is collected into two main types at these RSs: Mixed Plastic and PET plastic. Plastic recycling involves several key stages, including collection, sorting, and cutting, washing, drying, and producing plastic grain or new products.

2.2 Step by Step Recycling Process in RS

Sorting of Plastic Waste. After receiving plastic waste from wholesalers, Tokai, and Feriwala, the workers at RS undertake the process of sorting. This step involves visually separating recyclable plastic waste from non-plastic materials, metals, wood, and non-recyclable plastics. This sorting process relies on human judgment based on the physical characteristics of the Plastic, as depicted in Fig. 2b. It is important to note that this sorting process is highly time-consuming.

Cutting of Plastic Waste. Before cutting the plastic waste, any portions that are considered non-recyclable are separated. The remaining plastic waste is then transformed into plastic flakes through a plastic shredding machine. These plastic flakes are depicted in Fig. 2d.

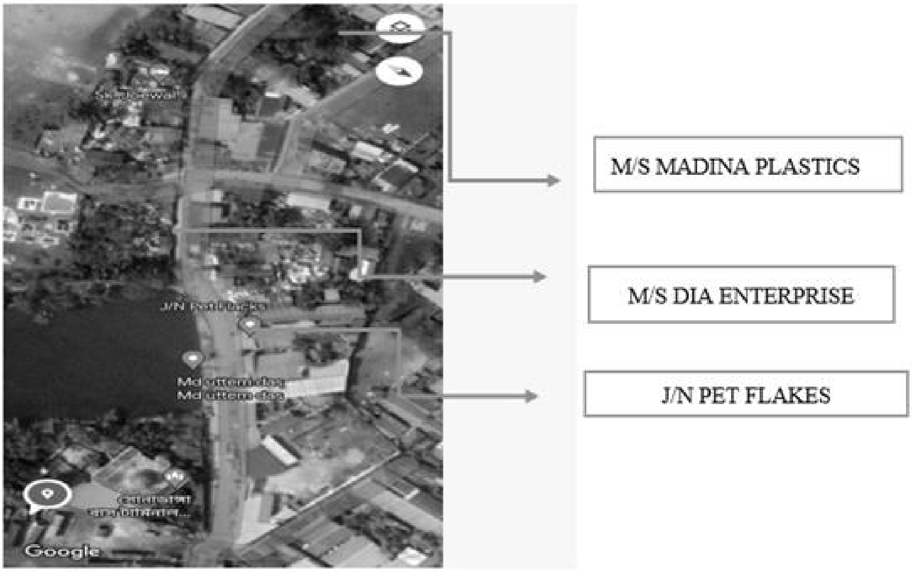

Fig. 1. Location of Recycling Shops Surveyed in This Study

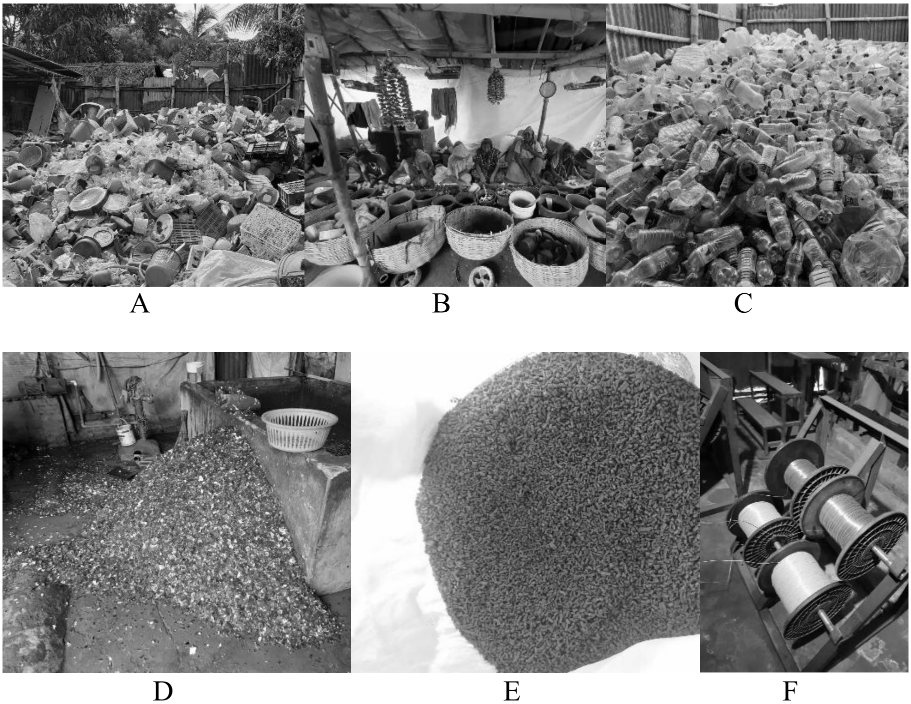

Fig. 2. Conventional Recycling Process: a. Plastic Waste Stored at RS, b. Conventional Sorting Process, c. Sorted Plastic, d. Plastic Flakes, e. Plastic Grain, f. New Product from Plastic Waste

Washing and Drying. The shredded plastics then undergo a washing and drying process to prepare the plastic flakes for recycling. This involves removing dust, mud, and other impurities from the plastic flakes through a water-based washing process while ensuring they are separated from debris. Subsequently, the plastic flakes are dried using sunlight.

These dried flakes may be further processed to produce plastic grain, as shown in Fig. 2e. These products are sold to the recycling industry or used to create new products like plastic threads, as depicted in Fig. 2f, which are subsequently marketed in the local area.

2.3 Estimating the Plastic Recycling Rate in Khulna

The input and output data from various RSs were analysed to determine the plastic recycling rate in Khulna. This involved calculating the recycling rate for each RS and subsequently determining the average recycling rate for the entire city.

The process of categorising recyclable plastic waste begins with the collection of small-sized plastic samples, such as plastic flakes or granules. These samples were then transported to the "Waste and Resource Recovery Laboratory" at KUET. Here, advanced technology known as Near-Infrared Spectroscopy (NIR), shown in Fig. 3a, is employed to classify the plastic samples. Each plastic sample undergoes multiple scans to ensure accurate results.

NIR spectroscopy is a cloud-based device that connects to a mobile phone. When plastic samples are scanned using NIR spectroscopy, the plastic type is displayed on the mobile phone screen, as depicted in Figs. 3b and 3c. Additionally, NIR spectroscopy provides data in the form of a graph, showing reflectance versus wavelength for each plastic sample. However, these graphs cannot be directly extracted from the mobile app. Instead, the reflectance and wavelengths of each plastic type are compiled into an MS Excel file, which is then used to generate graphs for each type of plastic.

Within the RSs, Plastic is typically collected as PET and mixed Plastic. These mixed plastics are further sorted into more than 45 distinct types based on their chemical composition. Overall, these various types cover only eight types of chemical composition of the Plastic. As determined by NIR spectroscopy. Combined with input and output data from plastic waste, this information allows us to ascertain the percentage of each plastic type within the recycling process.

2.4 Establishing a Confusion Matrix for Evaluating the Performance of NIR

In the creation of a confusion matrix, a set of 40 no's white PET samples, 30 no's colour PET samples, 46 no's PE samples, 40 no's PP samples, and 30 no's PVC plastic samples were employed. These samples served as the basis for generating the confusion matrix, aiding in accurately classifying plastic types.

A B C

Fig. 3. Testing with NIR Spectroscopy: a. NIR Spectroscopy, b. Scanning of Plastic Sample by NIR Spectroscopy, c. Data Acquired from Mobile App

3 Results And Discussion

3.1 Plastic Waste Recycling Frequency at RS of Khulna

The field survey conducted between April 2023 and September 2023 found that each RS in Khulna City received or collected an average of 15.0 tons of plastic waste per month and successfully recycled 11.2 tons of plastics in that period, as per Table 1. On average, 75% of this plastic waste was successfully recycled at RSs. The details of plastic input and output data at these RSs, along with the corresponding percentage rates, are presented in Fig. 4.

Table 1. Plastic Input and Output Data at RS Shop and Their Corresponding Ratio

Shop Name	Month	Input (Kg)	Output (Kg)	Input–Output Ratio
M/S DIA ENTERPRISE	April	2748	1926	0.7009
	May	21032	17153	0.8156
	June	14810	10242	0.6916
	July	11307.5	6578.3	0.5818
	August	9051.7	10171.6	1.1237
	September	15728.2	17401.9	1.1064
	Average	12446	10579	0.8500
M/S MADINA PLASTICS	April	15662	11983	0.7651
	May	10671	8201	0.7685
	June	25674	17448	0.6796
	July	33226	15349.7	0.4620
	August	29519	20357.5	0.6896
	September	30625	23069.8	0.7533
	Average	24230	16068	0.6632

Shop Name	Month	Input (Kg)	Output (Kg)	Input–Output Ratio
M/S J/N PET FLAKES	April	16951	12283	0.7246
	May	6047	4688	0.7753
	June	5523	4281	0.7751
	July	9569.5	6888.5	0.7198
	August	6043.8	8111.1	1.3421
	September	5398.4	5417.8	1.0036
	Average	8255	6945	0.8901
Total		269587.1	201551.2	0.7476
Total Average		14977	11197	0.7476

In August and September, M/S Dia Enterprise and M/S JN PET Flakes shops achieved an input-output ratio of Plastic that surpassed 1. This anomaly occurred because they had stored Plastic from the previous month and sold it in August and September, leading to an input-output ratio exceeding 1 for these specific months.

3.2 Classification of Plastic According to Chemical Composition

At RS, plastic materials are collected in two main categories: PET plastic and mixed Plastic. These plastics are then separated according to some local categories. For example, PET plastic is further sorted into different subcategories, including PET White, PET Green, PET Tiger, and PET Kotka White. The mixed Plastic is sorted based on visual inspection. Once plastic samples were obtained, they were brought to the laboratory, where they underwent scanning using Near-Infrared Spectroscopy and were subsequently classified based on their chemical composition. The plastic samples were classified into eight distinct plastic types, including PP, PET, PE, PVC, PA, SAN, PS, and PMMA. Any plastic material that doesn't fall into these categories is grouped as non-plastics and other materials. For example, CD hard black, shoe average bata, lota, and sandals were classified as other types of Plastic. Although initially considered non-recyclable, bottle labels are made from PP plastic. The RS owner sells the non-recyclable Plastic, such as bottle labels, to the local brick kilns, which is used as fuel for burning bricks. The classification of plastic samples by NIR spectroscopy is shown in Table 2.

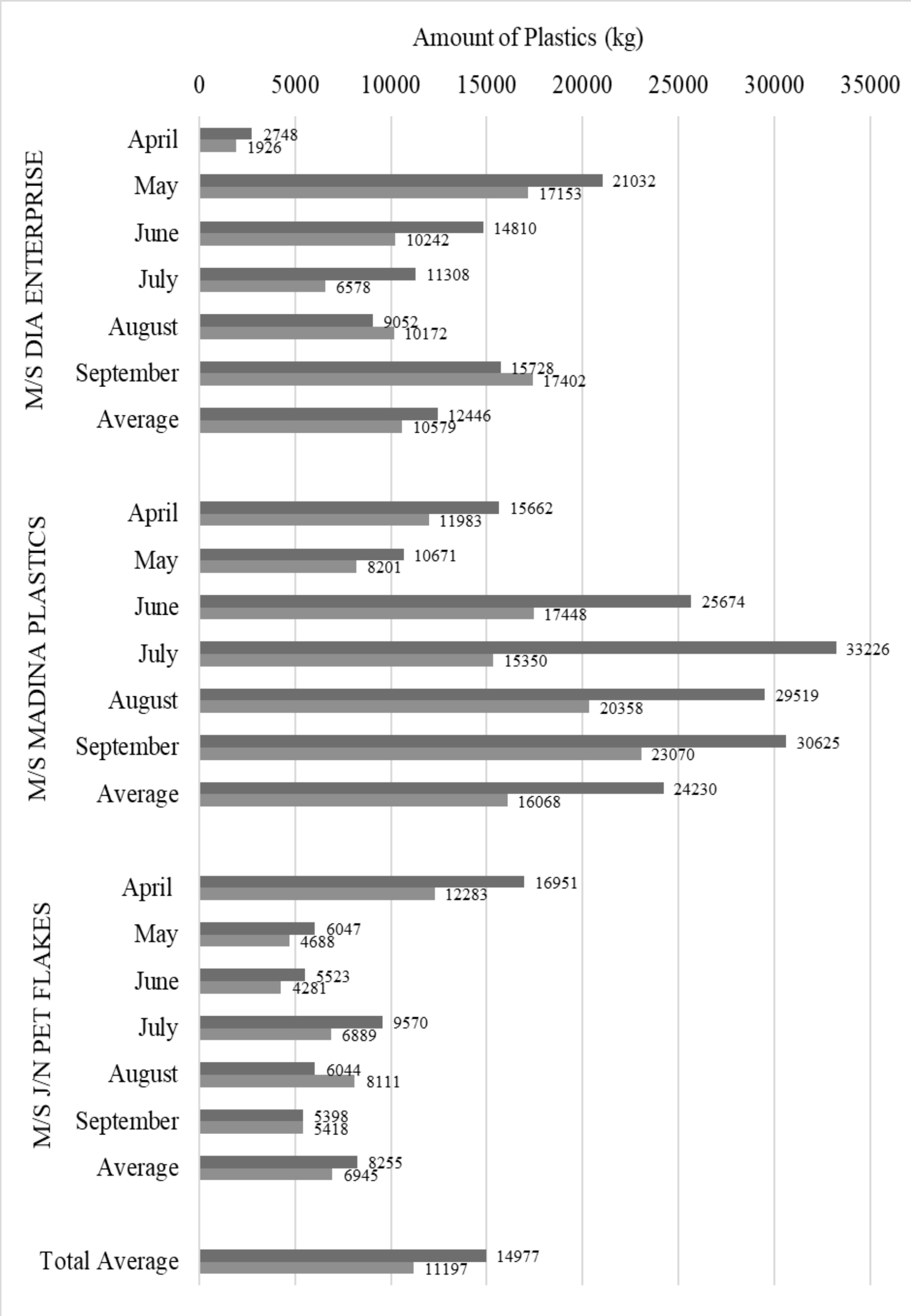

Fig. 4. Graphical Representation of Plastic Input and Output in the Surveyed Recycling Shops

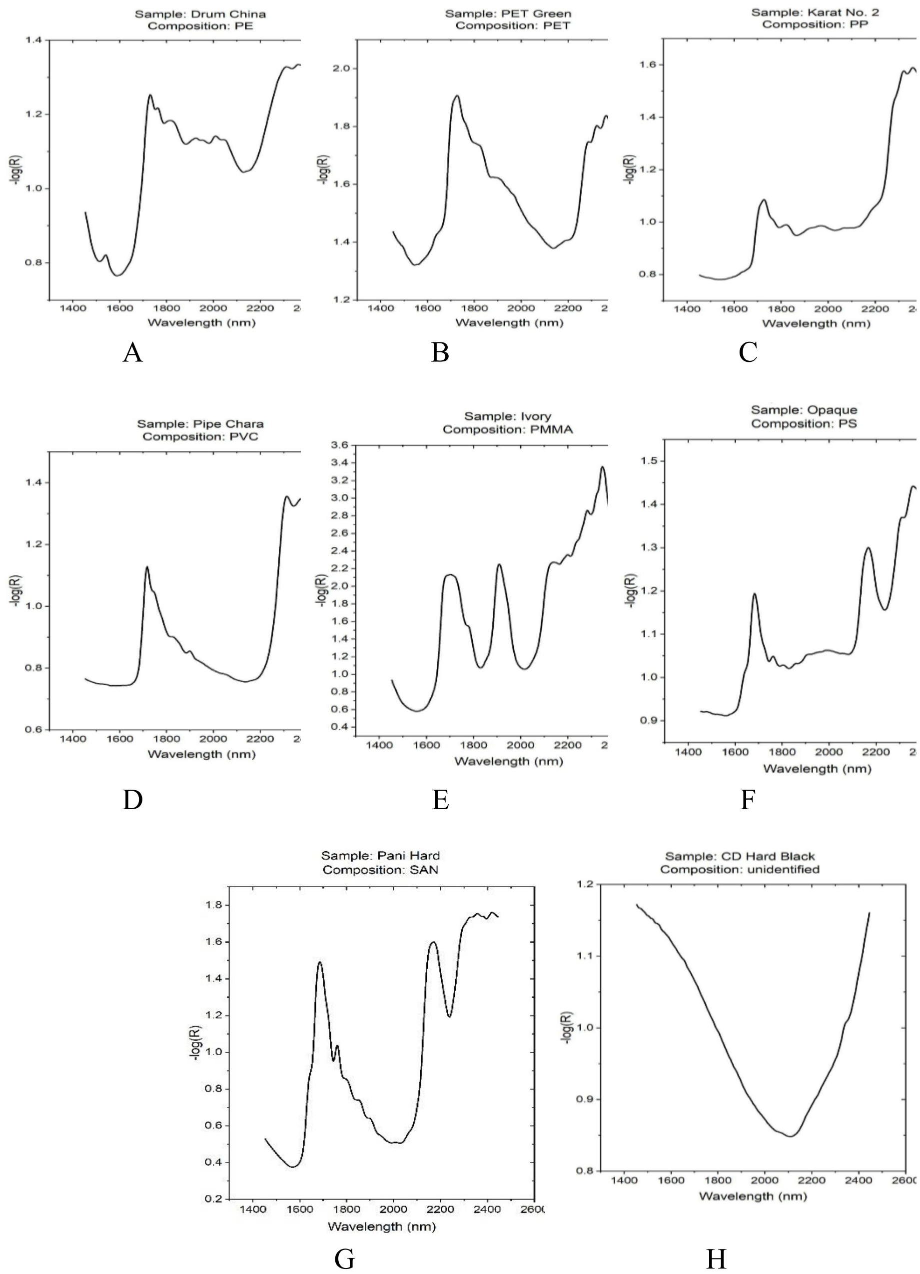

Fig. 5. Graphs Obtained from NIR Spectroscopy: A. Graph of PE Plastic, B. Graph of PET Plastic, C. Graph of PP Plastic, D. Graph of PVC Plastic, E. Graph of PMMA Plastic, F. Graph of PS Plastic, G. Graph of SAN Plastic, H. Graph of Unidentified Materials

NIR spectroscopy investigates how molecules interact with light in a designated wavelength range, typically extending from 1,400 to 2,500 nanometres, as shown in Fig. 5. The graph above is generated by scanning plastic samples using NIR spectroscopy. Each plastic sample exhibits a distinct graph with specific wavelengths and reflectance values. These individualised graphs enable the differentiation of various plastic types from one another.

Table 2: Classification of Plastic Waste through NIR

Plastic Types	No. of Sampl es	Local Name of Samples
PA	2	Polyamide (Nylon), Abs Hard Black
PE	14	Drum China, Drum No. 2, Gastric, Hawa Red, High Brush Blue/Harpic/Parachute, High Brush Plastic, Karat No 1, Medical, Pepsodent, Mukh Mojo Orange, Pipe Alu, Mukh Chapa Blue, Pran, Technique/Churi
PET	4	PET Green, PET Kotka White, PET Tiger, PET White
PMMA	1	Ivory
PP	14	Chair Cutting Green, Gastric Doba, Grain Blue, Karat Fruit, Karat No. 2, Pen, PET Bottle Label, PP Blue, PP Doba, PP Doba No. 2, PP Milk (Dudh), PP No. 1, PP Water (Pani), RFL Blue
PS	2	Opaque, Transport Hard
PVC	3	Pipe Chara, Pipe Hard PVC, Pipe Water (Pani)
SAN	1	Pani Hard
Others	4	CD Hard Black, Lota, Sandal, Shoe Average Bata
Total	45	

3.3 Percentage of recyclable Plastic at RS

After the classification of Plastic by NIR spectroscopy, the percentage of each type was calculated from the output data of Plastic from RS. The percentage of each is shown in Fig. 6.

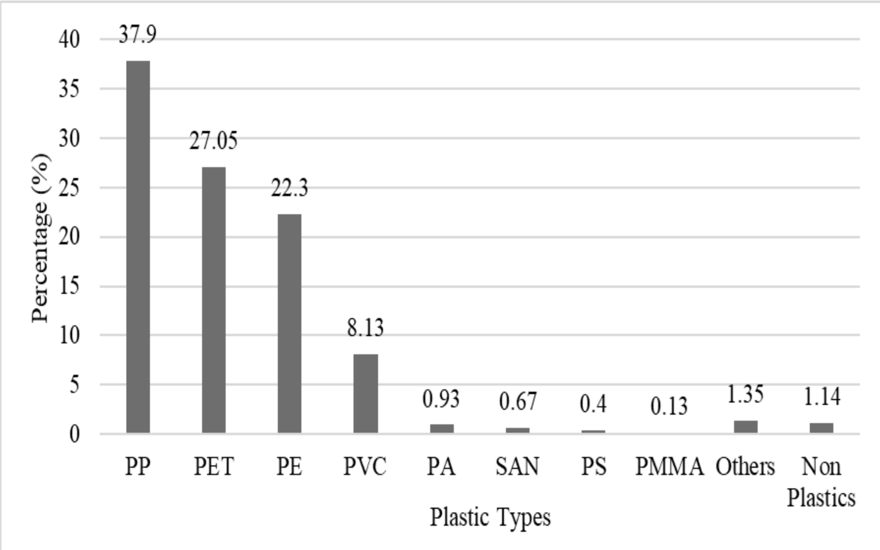

Fig. 6. Percentage of Recyclable Plastic Waste

From Fig. 6, it is evident that PP (Polypropylene), PET (Polyethylene Terephthalate), PE (Polyethylene), and PVC (Polyvinyl Chloride) plastics are the most common, while other types are relatively less common. PP and PET are the most abundant materials, constituting 37.9% and 27% of the recycling plastic waste, respectively. The percentages of recycling for PE, PVC, PA, SAN, PS, and PMMA are 22.3%, 8.13%, 0.93%, 0.67%, 0.4%, and 0.13%, respectively. PET and PP are the second and third most abundant plastic materials in the recycling process, and their recycling percentages are quite similar. On the other hand, PMMA, SAN, PA, and PS are not very common types of Plastic in the recycling stream.

3.4 Effect of Seasonal Variation on the Recycling Rate

For the survey conducted between April 2023 and September 2023, six months were chosen and categorised into three seasons: pre-monsoon (April and May), monsoon (June, July, and August), and post-monsoon (September). Fig. 7 illustrates the variations in plastic waste collection and recycling rates during these seasons. During the pre-monsoon period, an average of 12.2 tons of plastic waste was collected in each RSs. This figure increased to approximately 16.1 tons in the monsoon season, and in the post-monsoon season, it further rose to around 17.3 tons. The collection rate in the monsoon season surpassed that of the pre-monsoon, but the highest rates were observed in the post-monsoon period. This can be attributed to the ease of collecting plastic waste during the post-monsoon season compared to the monsoon season. Each season's input and output ratio values were 0.77, 0.69, and 0.89 for pre-monsoon, monsoon, and post-monsoon, respectively.

This suggests that the output of Plastic from the RSs is significantly smaller during the monsoon season compared to the other seasons. This discrepancy is attributed to the difficulty in drying plastic flakes during the monsoon season, making the recycling process less efficient. During the monsoon season, the drying of plastic waste poses significant challenges in the RSs, primarily attributed to the low sunlight levels. The heavy rainfall and overcast skies characteristic of this season result in a notable reduction in sunlight, a critical element for the drying process, particularly for plastic materials. This limited exposure to sunlight hampers the natural drying of plastic flakes. The monsoon season, marked by elevated humidity levels, poses challenges for plastic waste recycling. High humidity interferes with effective drying, extending the drying time due to reduced sunlight. This leads to material backlogs in RSs, affecting the output rate. The prolonged moisture exposure results in quality issues, including degradation and contamination of recycled plastics. Damp conditions foster mould growth, hindering recycling and posing health concerns. Operational disruptions, such as delays and longer turnaround times, further impact the efficiency of recycling facilities.

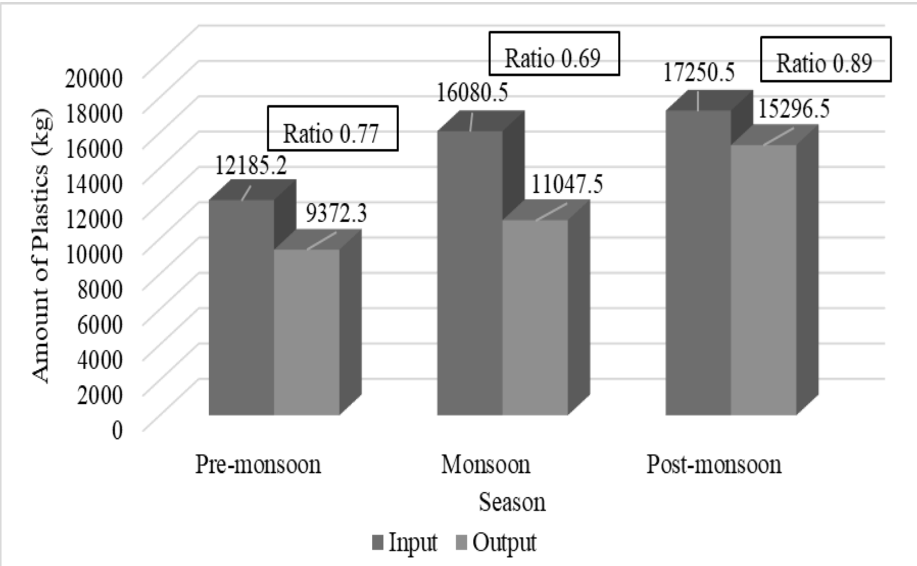

Fig. 7. Plastic Waste Input-Output Ratio in Pre-monsoon, Monsoon and Post-monsoon at RSs

3.5 Performance Evaluation of NIR Spectroscopy

The performance of NIR spectroscopy was evaluated by producing a confusion matrix, as shown in Table 3. For producing a confusion matrix, 40 no's PET white samples, 30 no's PET Coloured samples, 46 no's PE samples, and 30 no's PVC known plastic samples were used. Each plastic sample was scanned by NIR spectroscopy two or three times. The "Unsuccessful Trial" column contains samples not assigned to any of the considered classes.

NIR spectroscopy demonstrated high effectiveness in accurately classifying all types of PP samples. However, when distinguishing between different plastic categories, its accuracy rates varied. It performed well in identifying PVC with an impressive accuracy rate of 90%. For white PET, the accuracy stood at 87.5%, while for coloured PET and PE, the rates were 76.7% and 82.6%, respectively.

During the trial, a total of 186 plastic samples were utilised. Among these, 163 were accurately detected, while 23 were not identified correctly. The overall accuracy level achieved in the trial is 87.63%.

Table 3. Confusion Matrix for checking the performance of NIR spectroscopy

Experimental Class	PET White	PET Coloured	PE	PP	PVC	Unsuccessful Trial	% of Accuracy
PET White	35	0	0	0	0	5	87.50
PET Coloured	0	23	0	0	0	7	76.67
PE	0	0	38	0	0	8	82.61
PP	0	0	0	40	0	0	100.00
PVC	0	0	0	0	27	3	90.00

4 Conclusions

The issue of solid waste management can be significantly alleviated through the recycling of plastic waste. Considerable plastic waste is generated daily, contributing to various problems such as environmental pollution and health concerns. Recycling plastic waste offers a solution that results in reduced greenhouse gas emissions, decreased landfill usage, and the prevention of drainage blockages. Additionally, recycling serves as a source of income for many individuals involved in waste collection, trade, and the informal sector.

The findings of this study can be summarised as follows:

- The plastic samples were categorised into eight distinct types, including PP, PET, PE, PVC, PA, SAN, PS, and PMMA. Among these types, the recycling percentages for PE, PVC, PA, SAN, PS, and PMMA are 22.3%, 8.13%, 0.93%, 0.67%, 0.4%, and 0.13%, respectively.
- Manual sorting of plastics using visual and tactile methods was found to be highly effective, achieving an accuracy rate of 87.6%, a result confirmed when tested with NIR Spectroscopy technology.
- While RSs are essential in combating plastic pollution within the city, their operations can sometimes negatively impact their surroundings. It is crucial to treat the water used for cleaning before discharging it into rainwater drains.
- Handheld NIR spectroscopy acts as a 'lab in hand' technology that can accurately detect plastic types based on their chemical composition in a short time, making it a powerful tool for the reliable and fast analysis of plastic materials. Thus, this study recommends that the application of NIR spectroscopy devices in the RS could increase their operating performance.

- Working conditions in RSs are often underprivileged, and workers must be provided with necessary safety gear such as hand gloves, boots, and other protective equipment. Moreover, first aid services should be readily available in these shops and provided to workers free of charge.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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