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Using Spectral and Laser Techniques in Plastic Detection and Recycling

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Abstract

Plastic pollution is currently a global challenge, with plastic waste increasingly accumulating due to weak enforcement and the absence of safe disposal practices. This research aims to explore innovative solutions for effective waste management using advanced infrared technology. The study uses a Bruker attenuated total reflection spectrometer (400-4000) cm^{-1} and an infrared laser (805) nm to analyze six random samples of plastic waste (juice and milk cartons). The results demonstrate that infrared analysis of strong absorption peaks (400-1800) cm^{-1}, specifically infrared spectroscopy and laser, is able to accurately identify plastic types based on their unique spectral signatures, speeding up the sorting process and improving purity. Laser results also indicate the appearance of strong plastic peaks at 12.500 cm^{-1}. The study highlights the advantages of infrared technology compared to conventional sorting methods and discusses the technical challenges that may face its implementation in recycling facilities. The research relies on a methodology that combines theoretical study and practical application, analyzing data from academic sources, and applying the technology to real-world models. This study identified effective formulations for several types of polymers (polyethylene, polypropylene, polystyrene, and polyvinyl chloride (PVC)), with only PE and PP being recyclable. This study aims to provide practical and effective solutions for plastic waste management and contribute to the development of a sustainable circular economy.

Keywords: Spectroscopic methods, plastic waste management, recycling, lasers

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استخدام التقنيات الطيفية والليزرية في الكشف عن البلاستيك وإعادة تدويره

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الخلاصة

يُمثل تلوث البلاستيك حاليا تحديًا عالميًا، حيث تتراكم النفايات البلاستيكية بشكل متزايد نتيجة ضعف تنفيذ القوانين وغياب ممارسات التخلص الآمن. يهدف هذا البحث إلى استكشاف حلول مبتكرة لإدارة النفايات بفعالية باستخدام تقنية الأشعة تحت الحمراء المتقدمة. تستخدم الدراسة مطياف بروكر للانعكاس الكلي المُخفف (400-4000) سم$^{-1}$ وليزر الأشعة تحت الحمراء (805) نانو متر لتحليل ست عينات عشوائية من النفايات البلاستيكية (علب العصير والحليب). تُظهر النتائج أن تحليل الأشعة تحت الحمراء لقمم الامتصاص القوية (400-1800) سم$^{-1}$، وتحديدًا مطياف الأشعة تحت الحمراء والليزر، قادر على تحديد أنواع البلاستيك بدقة بناءً على بصماتها الطيفية الفريدة، مما يُسرّع عملية الفرز ويُحسّن نقاءها. كما أشارت نتائج الليزر إلى ظهور قمم بلاستيكية قوية عند (12.500 سم$^{-1}$). تُسلط الدراسة الضوء على مزايا تقنية الأشعة تحت الحمراء مقارنةً بطرق الفرز التقليدية، وتناقش التحديات التقنية التي قد تواجه تطبيقها في مرافق إعادة التدوير. يعتمد البحث على منهجية تجمع بين الدراسة النظرية والتطبيق العملي، وتحليل البيانات من المصادر الأكاديمية، وتطبيق التكنولوجيا على نماذج واقعية. حددت هذه الدراسة تركيبات فعالة لعدة أنواع من البوليمرات (البولي إيثيلين، والبولي بروبيلين، والبوليسترين، وبولي فينيل كلوريد (PVC))، علمًا بأن البولي إيثيلين والبولي بروبيلين هما النوعان الوحيدان القابلان لإعادة التدوير. تهدف هذه الدراسة إلى تقديم حلول عملية وفعالة لإدارة النفايات البلاستيكية والمساهمة في تطوير اقتصاد دائري مستدام.

الكلمات المفتاحية: الطرق الطيفية، إدارة النفايات البلاستيكية، إعادة التدوير، الليزر

Introduction:

Plastic has revolutionized many industries thanks to its durability, low cost, and versatility. However, the widespread use of plastic, particularly single-use plastics, has led to a global environmental crisis. According to a report by the United Nations Environment Programmed (2018), more than 300 million tons of plastic are produced annually, much of which ends up in landfills, oceans, and natural ecosystems. Most plastics are non-biodegradable, meaning they remain in the environment for hundreds of years, harming wildlife, polluting water sources, and contributing to the accumulation of micro plastics in the food chain. [1]. The concept of recycling is an important strategy for managing plastic waste sustainably and continuously. Not only does it reduce the volume of waste in landfills, but it also plays a role in conserving natural resources, reducing the impact of greenhouse gas emissions, and making it economically viable to convert it into new products instead of disposing of it.[2]

Modern technologies play a key role in waste management, offering smart, efficient, and scalable solutions to contemporary environmental challenges. These include artificial intelligence, robotics, and infrared spectroscopy to improve material sorting, composition determination, and processing. [3]

The pyrolysis fluids were analyzed using FTIR spectroscopy to characterize their composition and identify the active components. The results indicate that pyrolysis is a promising method for recovering energy and useful chemicals from low-density polyethylene (LDPE) and high-density polyethylene (HDPE) waste. [4]

Near-infrared (NIR) spectrometry was used to identify polylactic acid (PLA), a bioplastic, in waste management. The study highlights the growing importance of proper bioplastic waste management as its use and demand increase, near-infrared (NIR) offers advantages in identifying and quantifying other components in plastics, such as fillers and softeners, and can be used to identify plastics containing carbon black.[5],[6].

The use of laser-induced plasma ablation technology in commercial plastics recycling for classification, sorting, identification, and elemental analysis is inaccurate because it lacks an understanding of molecular dynamics, thermodynamic interactions, bond cleavage, and the effects of process parameters, which are essential for plastics recycling. The study emphasizes the importance of addressing plastic contamination through improved recycling procedures.[7]

The researchers used laboratory-based Fourier transform infrared (FTIR) spectroscopy in attenuated total reflection (ATR) mode to analyze various polyolefin samples and developed a systematic study of automated discrimination between NIR spectroscopies. The study emphasizes the importance of fine sorting in mechanical recycling to achieve properties comparable to virgin polymers and aims to provide a theoretical basis for industrial applications of near-infrared (NIR) spectroscopy in plastic waste sorting.[8]

Given the global interest in recycling plastic waste for utilization, the combination of spectroscopy and machine learning techniques is expected to contribute to solving the problem of efficiently identifying and classifying plastic waste in the early stages of high-value recycling. The spectroscopic techniques currently used for plastic waste classification include near-infrared (NIR) spectroscopy, mid-infrared (MIR) spectroscopy, Raman spectroscopy, laser-induced breakdown spectroscopy (LIBS), X-ray fluorescence (XRF), terahertz (THz) spectroscopy, and others.

Combined machine methods include both traditional machine methods and deep learning methods.[9]

Plastic waste has become a major environmental concern worldwide, prompting researcher to improve recycling efficiency. Improving the purity of recycled plastics facilitates the selection of appropriate processing methods for different materials. This study proposed a multi-wavelength laser Raman detection method and system to enable rapid and accurate identification of plastic waste. By analyzing the Raman spectra of various plastics under different laser wavelengths and introducing a fluorescent coefficient to measure the wavelength effect, the identification of characteristic Raman peaks of different plastics was demonstrated. The integrated area of Raman spectra across seven bands was identified as key criteria for identifying plastic types [10].

Recycling plastics from small household appliances has become of great importance in improving the environment and addressing resource scarcity, and has received attention in various countries. First, spectra were collected from samples with different colors, oxidation levels, and flame retardants. It was found that samples with different colors and oxidation levels exhibited different reflectance's, while those with flame retardants exhibited smaller absorption peaks. The spectra were then preprocessed and analyzed, and the results showed that samples collected under different conditions had little effect on plastic classification. Finally, the plastic spectra were classified using algorithms such as the support vector machine (SVM), backpropagation neural network (BP), k-nearest neighbor algorithm (k-NN), partial least squares discriminant analysis (PLS-DA), and linear discriminant analysis (LDA).[11]

Overview of Plastic Waste and Recycling

1.1 Definition and Types of Plastics

Plastic is a synthetic or semi-synthetic material primarily composed of long chains of polymers, typically derived from petrochemical sources. These polymers are engineered to exhibit properties such as durability, flexibility, and chemical resistance, making plastics suitable for a wide range of applications.[12]

Plastics are broadly classified into two main categories:

- Thermoplastics, which can be melted and reshaped multiple times without significant degradation. Common types include:
  - Polyethylene (PE): used in bags and bottles
  - Polypropylene (PP): used in containers and packaging
  - Polyethylene terephthalate (PET): used in beverage bottles
  - Polyvinyl chloride (PVC): used in construction and medical supplies
- Thermosetting plastics, which harden permanently after heating and cannot be remolded. Thermoplastics are generally easier to recycle than thermosets due to their ability to melt and reform without significant chemical alteration [13]

1.2 Sources and Scale of Plastic Pollution

Plastic pollution stems from a variety of sources, including industrial production, consumer usage, and improper disposal. One of the primary contributors is single-use plastics, such as packaging materials, bags, and utensils, which are often discarded after a single use [14].

Globally, more than 300 million tons of plastic are produced annually, and a significant portion of this waste ends up in the environment. Marine ecosystems are particularly vulnerable, with more than 8 million tons of plastic entering the oceans and seas annually, most of it from land-based sources. Over time, larger plastic waste degrades into micro plastics that are consumed. Polypropylene (PP): Similar to high-density polyethylene (HDPE), with additional peaks at 1170–1150 cm^{1} and 840–810 cm^{1}, it is ingested by marine organisms and may eventually reach humans via the food chain.[15]

The rapid growth in plastic production—from 2 million tons in 1950 to more than 367 million tons in 2020—is attributed to increased demand and consumer habits, particularly for packaging and single-use products. Inadequate recycling infrastructure, particularly in developing countries, further exacerbates the problem.[16]

Without effective intervention and rapid research, projections indicate that by 2050, the oceans could contain more plastic than fish.

Safety plastic types for juice and milk:

-High-density polyethylene (HDPE): Spectral properties: Strong absorption at 2900-2850 cm^{-1} (carbon-hydrogen vibrations), 1470-1460 cm^{-1}, 730-720 cm^{-1}. Uses: Milk jugs, detergent bottles, children's toys. Safe for food use.

- Containers, food cans, microwave-safe utensils and Safe for food use.

- Polyethylene terephthalate (PET) Spectral properties: Peaks around 1720 cm^{-1} (C=O), 1270 cm^{-1}, 1100 cm^{1} (C-O), 730 cm^{-1} (aromatic ring). Uses: Juice and soft drink bottles, food containers. Safe for single use. As shown in figure (1)

Fig. (1): plastic resin identification codes

Results and Discussion:

In this research, laser and infrared spectroscopy were used to detect and recycle plastics. An infrared laser with a wavelength of 805 nm and a fast Ocean detector were used to measure the beam intensity and energy. In this experiment, the infrared spectra of the spectral range (400-4000) cm^{-1} were studied using an infrared spectrometer. Six random samples of plastic were taken for testing, as follows:

1-Test samples: In this stage of the research, different samples (six samples) of plastic juice , milk containers and food delivery containers were collected. They were collected randomly without indicating the company or country of manufacture. They were washed, dried, cut and stored in closed containers.

2- Measurement System

An optical experiment was built to measure the intensity and energy of the laser beam using the following devices:

•A low-power semiconductor laser with a wavelength of (805 nm)

•A fast, sensitive spectrometer with a sensitivity of (1 nm) (Ocean Optics)

• single-mode optical fiber

•computer with detector software

•Various holders and holders

•optical table

As shown in figure (2)

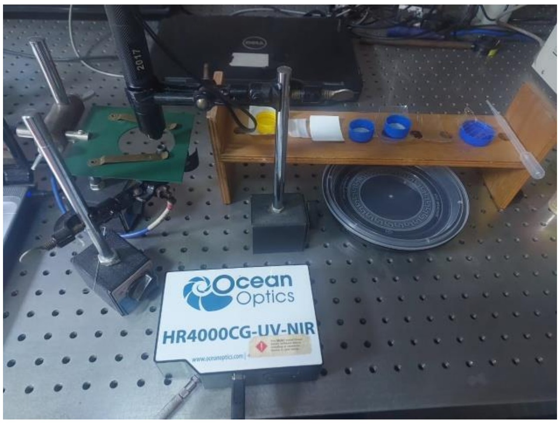

Fig. (2): Measurement System different plastic samples

3- Infrared Spectrometer

ATR-FTIR spectrometer was used to measure the vibrational spectra of the interaction of infrared radiation and the material to determine the energies of the active regions of plastic samples, as shown in Figure (3). The spectrometer specifications are attached in Table (1). Special Opus spectrometer software was also used.

Fig. (3): ATR-FTIR spectrometer (BRUKER ALPHA)

Table (1) Specifications for the Infrared Spectrometer

Properties	values	Components
Spectral range	375 – 7,500 cm-1	IR laser sources
KBr beam splitter	500 – 6,000 cm-1	Detectors
measurement time	1 min,	Fourier transform
spectral resolution	4 cm-1	

Experiment 1: Infrared Laser Spectrum and Intensity Study

In this experiment, an infrared laser with a wavelength of (805 nm) was used, along with a high-speed (HR 4000 Ocean) detector to measure the beam intensity and energy. Six plastic samples were tested as illustrated in the images below (1-6) figures (4-9).

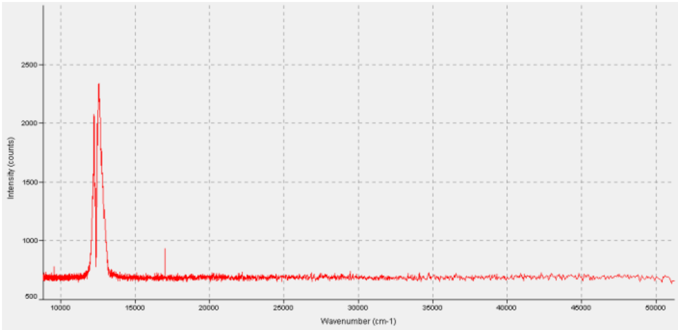

Fig. (4): Plastic Sample 1

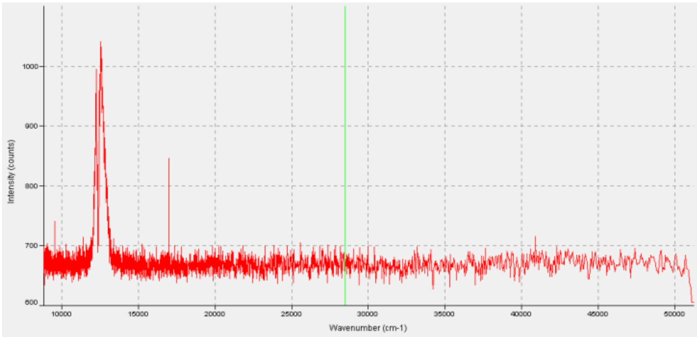

Fig. (5): Plastic Sample 2

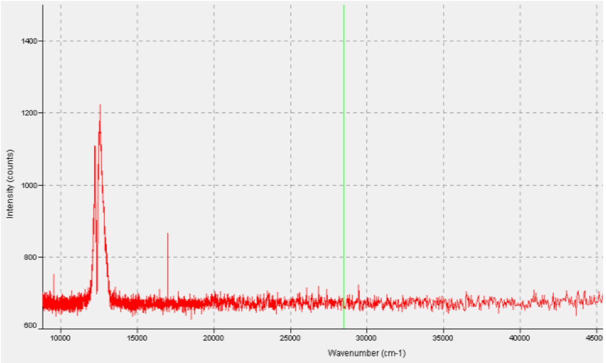

Fig. (6): Plastic Sample 3

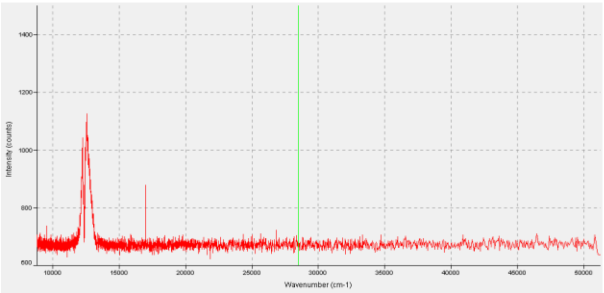

Fig. (7): Plastic Sample 4

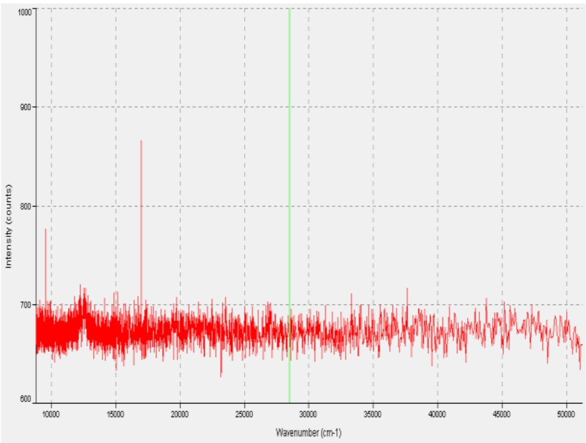

Fig. (8): Plastic Sample 5

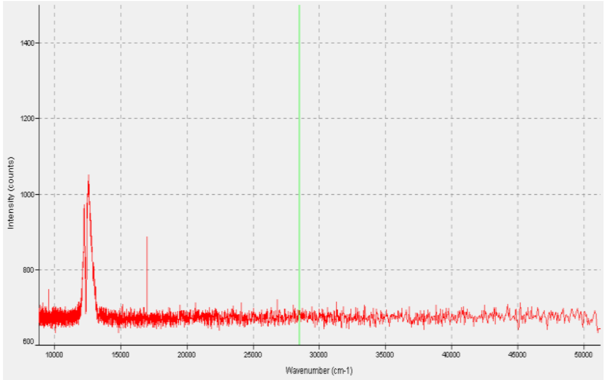

Fig. (9): Plastic Sample 6

Results of Experiment 1: Analysis of the Plastic Laser Spectrum

Figures (4-9) show the intensity spectrum of the laser beam interacting with the plastic samples. The peaks (12500) cm^{-1} in the spectrum indicate strong emission at specific frequencies, while the valleys indicate weak emission. Each type of plastic has a unique pattern of peaks and valleys, known as its

"spectral fingerprint." By comparing these spectral patterns to reference infrared spectra databases, the plastic type can be accurately identified.

Experiment 2: Fourier Transform Infrared (FTIR) Spectroscopy

This experiment analyzed the FTIR spectra over the spectral range of

(400–4000 cm⁻¹) using a Bruker ATR-FTIR spectrometer, as shown in figure (10). Six random plastic samples taken from juice and milk bottles were analyzed. The results showed distinct absorption peaks, particularly in the region of (400–1800 cm⁻¹).

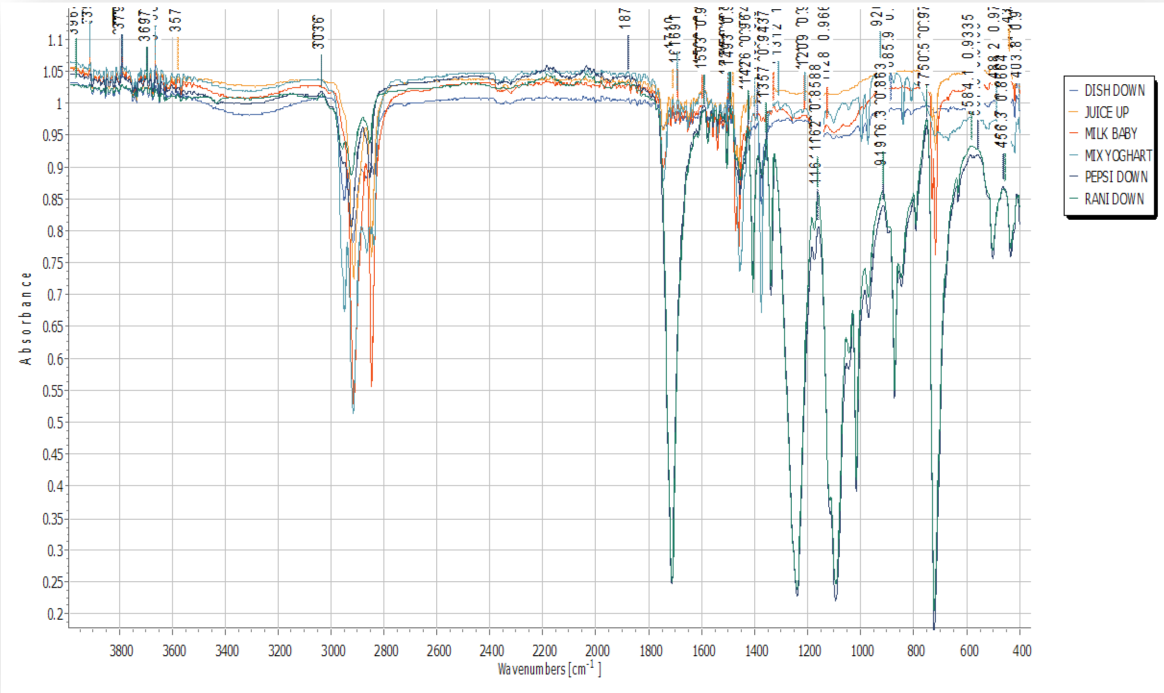

Fig. (10): FTIR spectra for plastic samples

Figure (10) shows the infrared absorption spectra for six plastic samples. It provides a detailed explanation of the analysis and how to identify the types of plastic. the Key regions to look for include:

1- 3300-2500 cm^{-1}: O-H and N-H stretching vibrations (often broad peaks).

2- 3000-2800 cm^{-1}: C-H stretching vibrations (aliphatic).

3- 1750-1700 cm^{-1}: C=O stretching vibrations (carbonyl groups).

4- 1650-1450 cm^{-1}: C=C stretching vibrations (aromatic and alkene).

5- 1465 and 1375 cm^{-1}: CH_2 and CH_3 bending vibrations.

6- 1300-1000 cm^{1}: C-O stretching vibrations (ethers, esters, alcohols).

7- 1000-600 cm^{-1}: A distinctive fingerprint region for each polymer.

To identify plastics, their main peaks were compared with databases: Use Fourier transform infrared spectra databases (online or software) like (NITS) to identify potential isomers based on their functional groups.as fallowing:

1- Polyethylene (PE): Look for strong peaks around 2920 and 2850 cm^{-1} (C-H stretching), and 1465 and 720 cm^{-1} (CH_2 bending).

2- Polypropylene (PP): Similar to PE, but with peaks around 2950, 2870, 1460, 1375, and 840 cm^{-1}. Polyethylene terephthalate (PET): Look for peaks around 1720 cm^{-1} (C=O ester), 1240 and 1090 cm^{-1} (C-O ester), and 725 cm^{-1} (aromatic ring).

3- Polystyrene (PS): Look for peaks around 3025, 2920, 1600, 1490, 750, and 700 cm^{-1} (aromatic ring).

4- Polyvinyl chloride (PVC): Look for peaks around 2900, 1425, 1250, and 610 cm^{-1} (C-Cl stretching).

The spectra show significant differences, indicating that the samples are likely different types of plastic. The spectra show multiple peaks, indicating complex polymer structures or mixtures of polymers.as in table (2)

Table (2) plastic type with their FTIR peaks and recyclability

Plastic Type	**Common Uses**	**FTIR Peaks (cm⁻¹)**	**Recyclability**	**Notes**
HDPE (High-Density)	Milk jugs, detergent bottles, rigid containers	2920 & 2850 (C-H stretch), 1465 & 720 (CH_2 bend)	Generally recyclable	Often recycled into pipes, lumber, new bottles.
LDPE (Low-Density)	Plastic bags, films, squeeze bottles	2920 & 2850 (C-H stretch), 1465 & 720 (CH_2 bend)	Varies significantly	Plastic bags can be problematic for recycling machinery.
Polypropylene (PP)	Yogurt containers, bottle caps, food packaging	2950, 2870, 1460, 1375, 840	Varies depending on region	Recycled into auto parts, fibers, containers.
Polyethylene Terephthalate (PET)	Plastic bottles (soda, water), food containers	1720 (C=O ester), 1240 & 1090 (C-O ester), 725 (aromatic)	Generally recyclable	Recycled into fibers for carpets, clothing, new bottles.
Polystyrene (PS)	Disposable cups, plates, packagi	3025, 2920, 1600, 1490, 750,	Often difficult to recycle	Bulky, breaks easily, many municip

	ng ("styrofoam")	700 (aromatic)		alities don't accept it.
Polyvinyl Chloride (PVC)	Pipes, window frames, some packaging	2900, 1425, 1250, 610 (C-Cl stretch)	Rarely recycled	Contains chlorine, which can release harmful substances.

Conclusions

1. In this research, a plastic type was accurately identified using ATR-FTIR technology.

2. The active groups were identified as a pre-recycling step.

3. This technique is simple, direct, inexpensive, and non-destructive method that can be used in various environments and deal with different samples.

4. The quality of recycled plastic can be assessed by detecting its chemical composition.

5. Through the interaction of an infrared laser beam with the plastic samples, structural information regarding its chemical and physical properties can be obtained.

6. with usingspectroscopic methods, further research can be conducted to develop new detection techniques.

7- Merging between two detection technique make High reliability for result.

Conflict of Interest:

The authors declared no conflict of interest.

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