

Review

Application of Laser-Induced Breakdown Spectroscopy (LIBS) in Identifying and Quantifying Heavy Metals in Industrial Plastic-Waste Streams in Asia

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Abstract

The growing volume of plastic waste produced has made the need for efficient identification and quantification strategies to detect and identify harmful contaminants, particularly heavy-metals, in industrial plastic-waste streams more urgent than ever. Traditional chemical digestion methods (acid digestion, ICP-MS, or AAS) provide accurate quantification and are time-consuming, costly, and not high-throughput-sorting. Laser-induced breakdown spectroscopy (LIBS) offers several advantages, including rapid real-time analysis, minimal sample preparation, multi-element detection, and efficient elemental characterization. The current review aims to investigate the possibility of using the LIBS technique to detect and quantify some heavy-metals like lead (Pb), cadmium (Cd), chromium (Cr), and arsenic (As) in heterogeneous industrial plastic wastes. The calibration strategies (reference standards) as well as optimization of the signal response and algorithms for data processing, including chemometric models, are evaluated to reduce the limit of detection and enhance analytical accuracy. The results indicate that LIBS can detect heavy-metal contamination at concentrations relevant to regulatory limits and can be scaled for online quality-control monitoring in plastic recycling facilities. In this review, the results have been summarized to support the use of LIBS for waste management towards environmental compliance, reduced use of hazardous materials in recycling products, and reduced health problems due to heavy-metal pollution.

Keywords: laser-induced breakdown spectroscopy (LIBS); heavy metals; industrial plastic waste; elemental analysis; rapid screening; recycling quality control; multi-element detection; environmental compliance; chemometric modeling



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1. Introduction

Industrial plastic-waste generation has surged in Asia over recent decades, in tandem with rapid urbanization and industrial growth [1]. Asia now produces a significant portion of the world's plastic waste, over 121 million tons in 2016, accounting for roughly one-third of global plastic waste. For example, China alone generated about 49 Mt of plastic waste in 2016, while India produced around 17 Mt. Much of this waste is mismanaged; the Asia-Pacific region is projected to contribute more than 70% of global mismanaged plastic waste by 2025 [2]. A considerable fraction of Asia's plastic waste comes from industrial sources, e.g., manufacturing scrap, e-waste plastics, and packaging from industrial goods, which often contain heavy-metal additives or contaminants [3]. These heavy metals include lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), arsenic (As), and others, which are frequently found in plastics as pigments, stabilizers, flame-retardant synergists, or impurities [4,5]. For instance, lead compounds have been widely used as PVC stabilizers and pigments, and cadmium salts as colorants, resulting in legacy plastic materials with high heavy-metal content. Studies have reported upper concentrations of Pb in waste electronic plastics on the order of 0.01–0.2% by weight [6,7]. Such heavy-metal-laden plastics pose serious environmental and health risks in Asia, especially when recycled or disposed of improperly. Heavy-metal contamination in plastics poses environmental risks, and recent research on copper contamination and industrial pollutant decontamination emphasizes the need for fast and precise analytical tools like LIBS for real-time monitoring in industrial processes [8–10].

Heavy metals in plastic waste can leach into soils and groundwater or generate toxic dust and fumes during informal recycling (e.g., open burning or rudimentary smelting). In regions of China that have served as major e-waste recycling hubs, such as Guiyu and Taizhou, soil and sediment samples have shown moderate to high contamination with heavy-metals, including Cd, Pb, and Hg [11,12]. The blood lead levels seen in children in these communities have been high, and they have demonstrated other indicators of heavy-metal exposure, making this a public health hazard. Tang et al. (2015) reported high Cd and Hg concentrations in the surface soils around a plastic recycling site in Wen'an, North China, with means of 0.36 mg/kg and 0.41 mg/kg, respectively, and higher concentrations in river sediments [13]. Heavy metals around the area had significant ecological risk and are not carcinogenic but can pose health risks to the local population, particularly children. The same applies to other developing countries in Asia, where informal plastic and e-waste recycling is practiced around the world. The informal recycling dumps in India have been reported to have high levels of lead (Pb) and Cadmium (Cd) in air and soil, which is hazardous to both the workers and the local population [14]. This review indicates that the heavy metals contained in waste plastic in Asia are a serious issue with respect to pollution and health hazards, and on-site rapid monitoring of heavy-metal contamination is possible using LIBS and other spectroscopic techniques [15–17]. Studies on the behavior of impurities in metals at high temperature during their industrial processing have confirmed the potential for on-site rapid monitoring of heavy-metal contamination, both by LIBS and other spectroscopic techniques [18,19].

This has prompted action from regulators, who have developed frameworks to limit hazardous substances in plastics. Along with the Restriction of Hazardous Substances (RoHS) directive in the European Union, many countries in Asia have enacted RoHS-like laws. For example, the China RoHS restricts the application of plastics that contain a certain amount of Pb, Hg, Cd, and Cr (VI) (and brominated flame retardants) in the electronics industry [20]. The E-Waste Management Rules of India also cap such heavy metals in electronic equipment and set up a phase-out [21]. Other measures involving lead and cadmium, which are aimed at the elimination of toxic additives in appliances and vehicles,

include the J-Moss of Japan and the Resource Recycling Act of Korea [22]. Some Southeast Asian countries (such as Singapore and Vietnam) have enacted laws that are similar to the original six EU RoHS substances. The policies specify certain threshold concentrations (usually 100 ppm for Cd and 1000 ppm for Pb, Hg, Cr (VI)) for the concentration of the restricted metals in plastics in electronics and some packaging products. Also, international conventions and agreements such as the Stockholm and Basel Conventions (amended in 2019) now include plastics with PFCs and heavy metals, which is creating pressure for Asian countries to improve their hazardous plastic-waste management [23].

With growing interest in intelligent contaminant sensing and environmental compliance, AI-assisted spectral and imaging methods are increasingly being investigated for elemental analysis. In the case of gold-mine tailing, SWIR hyperspectral imaging is used to estimate the concentration of chromium, which is found in these tailings, and has proved to be suitable for spatially resolved analyses of heavy metals in complex waste materials [24]. Convolutional neural networks have also been applied on top of LIBS alone for the purpose of multi-component elemental quantification [25], and model-interpretation techniques have been used to demonstrate that CNNs trained with the LIBS spectra can learn chemically meaningful elemental features [26]. While these studies did not focus on plastic waste per se, the analytical approaches could be useful for the future development and application of AI-enabled LIBS methods for the detection of heavy metals in industrial plastic-waste streams.

With the growing volume of plastic waste, the need to efficiently and accurately detect and quantify other harmful substances, such as heavy metals, in industrial plastic waste is more important than ever. Traditional chemical digestion methods (acid digestion, ICP-MS or AAS) are highly accurate for quantification of the material, time-consuming and expensive, and are not high-throughput sorting methods. Rapid analysis in real time, little sample preparation, multiple elements detection, and elemental analysis are the advantages that can be achieved by using the laser-induced breakdown spectroscopy (LIBS) technique. In this review, the potential of the LIBS technique in the detection and quantification of some heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr) and arsenic (As) present in the heterogeneous industrial plastic wastes is explored. The calibration strategies (reference standards) and designing of signal response and algorithms for signal processing and chemometric models are explored to decrease the limit of detection and improve the analytical accuracy. In this review, the potential of LIBS has been shown for the rapid preliminary screening of unusually high concentrations of regulated metals in recycled plastics, but confirmatory techniques like ICP-MS or ETAAS are necessary for accurate quantitative determination. Moreover, the fact that the application of LIBS was successfully implemented in a quasi-real-time analysis of waste polymers containing chlorine on a conveyor belt suggests that it can be considered for in-line quality control and sorting applications in industrial plastic recyclers [27,28].

The traditional laboratory metal detection methods (e.g., acid digestion followed by ICP-MS or AAS) are accepted and accurate but not fast enough and practical enough to be applicable in the field for high throughput waste sorting applications. Portable X-ray fluorescence (XRF) analyzers have been used to spot check plastics for lead or cadmium, but XRF has limitations in detecting low atomic number elements and requires several seconds per measurement for low concentrations. Furthermore, its accuracy is dependent on sample geometry, and metals such as Be or Na cannot easily be detected. However, conventional analytical approaches like Gas Chromatography–Mass Spectrometry (GC-MS) suffer from long analysis times and complex sample preparation, making them unsuitable for rapid applications in industrial waste screening [29]. This restriction shows the practical

benefit of LIBS, as it allows real-time on-site elemental detection in industrial plastic-waste streams with high throughput, without the need for extensive sample preparation, to monitor hazardous metals.

However, the regulations are not easily implemented in Asia. Banned heavy metals are still present in enormous quantities in legacy plastics, and compliance with the regulations in the informal waste recycling industry is not widespread [30,31]. Much of plastic-waste recycling is in the informal sector in countries such as India and the Philippines, where people generally do not have the necessary equipment to identify and sort out hazardous materials [31]. Consequently, recycled plastics contaminated with heavy metals can be added to recycled products or incinerated, causing pollutants to be released [30]. There is a clearly expressed need for rapid, on-site analytical methods that can be used to screen plastics in real time to sort contaminated plastics and to ensure recycled plastics are safe [31].

Traditional lab-based metal analysis methods (e.g., acid digestion and ICP-MS or AAS) are very precise but too slow and impractical to use with high-throughput waste sorting in the field. Portable X-ray fluorescence (XRF) analyzers have been used to “spot check” plastics for lead or cadmium; however, XRF can only detect low atomic number elements and is only capable of measuring low concentrations for several seconds per measurement [32]. Furthermore, it is not very accurate if the sample geometry is not suitable for its use, and it will not easily detect metals such as Be or Na.

Laser-induced breakdown spectroscopy (LIBS) holds great promise to overcome these challenges. LIBS is an optical emission method that is rapid and essentially nondestructive and can simultaneously determine various elements in the material with little sample preparation [33–35]. LIBS can be used to provide the possibility of in situ heavy-metal screening, such as scanning plastic-waste pieces on a conveyor belt, and identifying those pieces that are high in lead or cadmium content. The use of LIBS for separating plastics with brominated flame retardants and heavy metals (HFRs and HMs) has been investigated over the last 20 years. The successful application of such a material in an industrial application could help to substantially reduce the contamination of plastic polymers entering feedstocks and ensure proper treatment of hazardous waste streams to achieve safe and efficient plastic recycling in Asia [36,37]. The review gives a detailed summary of the LIBS working principle and its application to the analysis of heavy metals in industrial plastic waste, particularly in the Asian region. We compare LIBS with conventional methods, summarize case studies of various Asian countries, and discuss challenges and future opportunities in the deployment of LIBS to scale. In this context, we showcase how LIBS can help reach the circular economy objectives in Asia by facilitating the identification and quantification of heavy metals in plastic wastes quickly and accurately, for environmental safety and regulatory compliance [38].

Literature Search Strategy

This review followed the PRISMA 2020 guidelines for the identification, screening, and selection of the relevant literature. A systematic search was conducted across six databases: Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. Database-specific search strings are provided in Table 1. The searches were carried out between 1 December 2025 and 30 June 2026 and were limited to records published from 1998 to 2026.

Eligible sources included English language, peer-reviewed original research articles, review articles, and conference proceedings, together with relevant official or technical reports issued by recognized governmental, regulatory, standards, industrial, or scientific organizations. Sources were considered eligible when they addressed the principles,

applications, or comparative performance of LIBS for elemental or heavy-metal analysis, particularly in relation to plastic waste, e-waste, or industrial recycling. No restriction was applied to the country of study origin or the nationality of the authors. The Asia-focused scope of this review was applied to the case-study and discussion sections rather than as a geographical restriction during the database search.

As summarized in the PRISMA 2020 flow diagram shown in Figure 1, the search identified 660 records: 250 from Scopus, 190 from Web of Science, 130 from ScienceDirect, 40 from SpringerLink, 25 from Wiley Online Library, and 25 from Google Scholar. After the removal of 65 duplicate records, 595 unique records were screened by title. Of these, 145 were excluded because they were clearly outside the scope of LIBS, heavy-metal analysis, or plastic and e-waste applications.

Table 1. Database-specific search strings and yield.

Database	Search Field	Exact Search Expression	Records Identified
Scopus	Article title, abstract, and keywords (TITLE-ABS-KEY)	TITLE-ABS-KEY(("laser-induced breakdown spectroscopy" OR "laser induced breakdown spectroscopy" OR LIBS) AND (plastic OR plastics OR polymer OR polymers OR "plastic waste" OR "plastic wastes" OR "industrial plastic waste" OR "industrial plastic wastes" OR "waste plastic" OR "waste plastics" OR "recycled plastic" OR "recycled plastics" OR "electronic waste" OR "e-waste" OR WEEE) AND ("heavy metal" OR "heavy metals" OR "hazardous metal" OR "hazardous metals" OR "toxic metal" OR "toxic metals" OR lead OR cadmium OR chromium OR mercury OR arsenic OR antimony OR nickel OR copper OR zinc))	250
Web of Science Core Collection	Topic search (TS): title, abstract, author keywords, and Keywords Plus	TS = (("laser-induced breakdown spectroscopy" OR "laser induced breakdown spectroscopy" OR LIBS) AND (plastic OR plastics OR polymer OR polymers OR "plastic waste" OR "plastic wastes" OR "industrial plastic waste" OR "industrial plastic wastes" OR "waste plastic" OR "waste plastics" OR "recycled plastic" OR "recycled plastics" OR "electronic waste" OR "e-waste" OR WEEE) AND ("heavy metal" OR "heavy metals" OR "hazardous metal" OR "hazardous metals" OR "toxic metal" OR "toxic metals" OR lead OR cadmium OR chromium OR mercury OR arsenic OR antimony OR nickel OR copper OR zinc))	190
ScienceDirect	Title, abstract, or author-specified keywords	("laser-induced breakdown spectroscopy" OR "laser induced breakdown spectroscopy" OR LIBS) AND (plastic OR plastics OR polymer OR polymers OR "plastic waste" OR "plastic wastes" OR "industrial plastic waste" OR "industrial plastic wastes" OR "waste plastic" OR "waste plastics" OR "recycled plastic" OR "recycled plastics" OR "electronic waste" OR "e-waste" OR WEEE) AND ("heavy metal" OR "heavy metals" OR "hazardous metal" OR "hazardous metals" OR "toxic metal" OR "toxic metals" OR lead OR cadmium OR chromium OR mercury OR arsenic OR antimony OR nickel OR copper OR zinc)	130
Springer Link	Keywords	("laser-induced breakdown spectroscopy" OR "laser induced breakdown spectroscopy" OR LIBS) AND (plastic OR plastics OR polymer OR polymers OR "plastic waste" OR "plastic wastes" OR "industrial plastic waste" OR "industrial plastic wastes" OR "waste plastic" OR "waste plastics" OR "recycled plastic" OR "recycled plastics" OR "electronic waste" OR "e-waste" OR WEEE) AND ("heavy metal" OR "heavy metals" OR "hazardous metal" OR "hazardous metals" OR "toxic metal" OR "toxic metals" OR lead OR cadmium OR chromium OR mercury OR arsenic OR antimony OR nickel OR copper OR zinc)	40

Table 1. Cont.

Database	Search Field	Exact Search Expression	Records Identified
Wiley Online Library	All fields	("laser-induced breakdown spectroscopy" OR "laser induced breakdown spectroscopy" OR LIBS) AND (plastic OR plastics OR polymer OR polymers OR "plastic waste" OR "plastic wastes" OR "industrial plastic waste" OR "industrial plastic wastes" OR "waste plastic" OR "waste plastics" OR "recycled plastic" OR "recycled plastics" OR "electronic waste" OR "e-waste" OR WEEE) AND ("heavy metal" OR "heavy metals" OR "hazardous metal" OR "hazardous metals" OR "toxic metal" OR "toxic metals" OR lead OR cadmium OR chromium OR mercury OR arsenic OR antimony OR nickel OR copper OR zinc)	25
Google Scholar ^a	General keyword search: three searches conducted separately	Query 1: "laser induced breakdown spectroscopy" plastic "heavy metal"; Query 2: LIBS plastic (lead OR cadmium OR chromium OR mercury OR arsenic OR antimony); Query 3: "laser induced breakdown spectroscopy" ("e-waste" OR WEEE) plastic	25
Total			660

^a Google Scholar does not support field-restricted Boolean searching. The three queries were conducted separately, and the results were reviewed in order of relevance. The retrieved results were combined, duplicate and clearly irrelevant records were removed, and 25 unique records were retained for formal title and abstract screening.

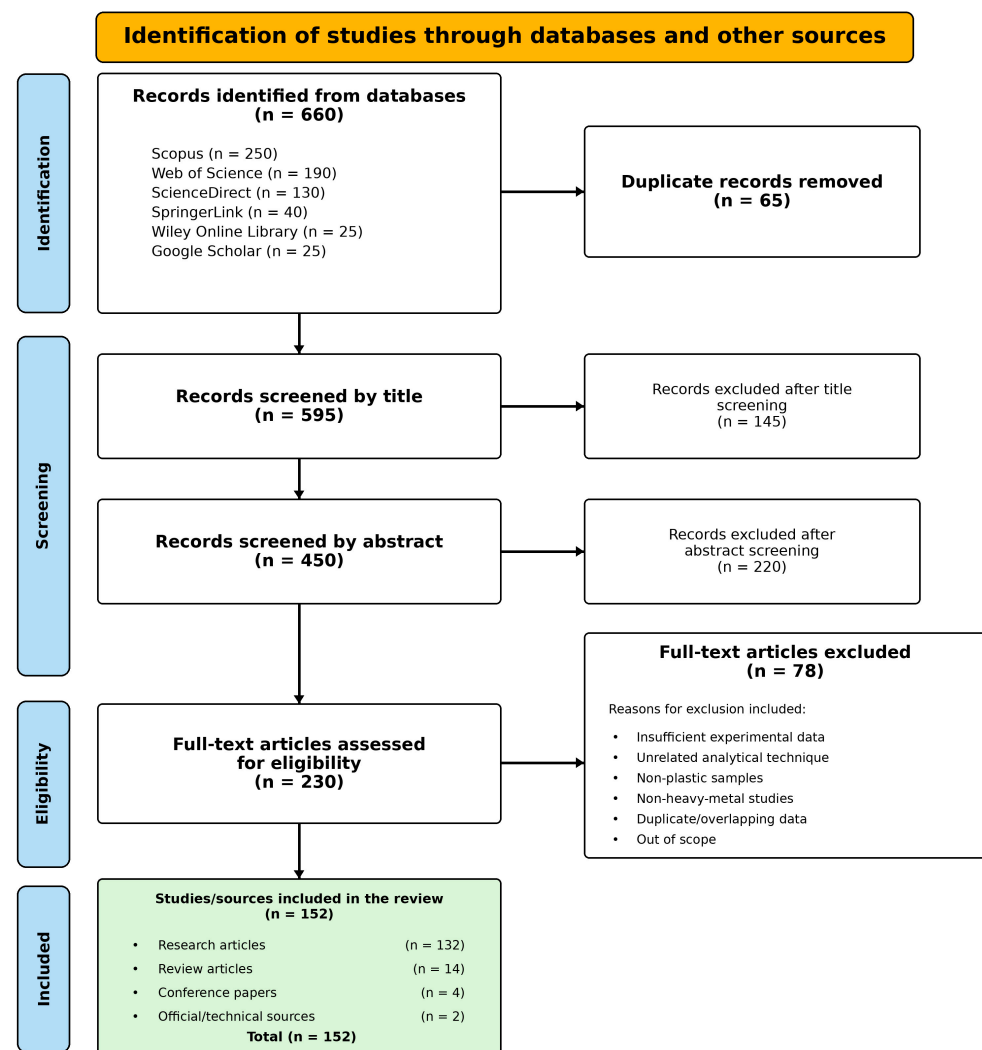


Figure 1. PRISMA 2020 flow diagram illustrating the study selection process for the systematic review on the application of laser-induced breakdown spectroscopy (LIBS) in identifying and quantifying heavy metals in industrial plastic-waste streams.

The remaining 450 records underwent abstract screening, after which 220 were excluded. The full texts of the remaining 230 records were then assessed for eligibility. A total of 83 records were excluded for the following reasons: insufficient experimental data ($n = 24$); use of an analytical technique unrelated to LIBS ($n = 18$); use of non-plastic sample matrices ($n = 14$); lack of focus on heavy-metal analysis ($n = 11$); duplicate or overlapping datasets ($n = 9$); and content outside the scope of the review ($n = 7$). The final review therefore included 152 sources, comprising 132 original research articles, 14 review articles, four conference papers, and two official or technical sources.

Title and abstract screening, followed by full-text eligibility assessment, was conducted independently by Muhammad Asad Khan and Asadullah Dawood. Disagreements at any stage were resolved through discussion between the two reviewers. When consensus could not be reached, M. Hisham Alnasir was consulted as a third reviewer and adjudicator. No automated screening tools were used.

2. Principles of Laser-Induced Breakdown Spectroscopy (LIBS)

LIBS is an atomic emission spectroscopy technique in which a highly energetic laser pulse is focused onto the surface of a sample to create a micro-plasma, and the light emitted by the cooling plasma is analyzed to determine elemental composition [39,40]. In a typical LIBS system, a pulsed laser (often a Q-switched Nd: YAG at 1064 nm or one of its harmonics) is directed and focused onto the plastic sample (Figure 2). The intense, short laser pulse ablates a tiny amount of material (in the order of nanograms) from the sample surface, a process known as laser ablation. The ablated material is instantly vaporized and forms a hot plasma plume ($\sim 10,000$ – $20,000$ K or more) containing excited atoms, ions, and electrons from the sample [39,41]. The excited atoms and ions rapidly release energy as light at wavelengths that are characteristic of the type of element (each element has its own set of colors or “fingerprint” spectral emission lines) [40]. This emitted light can be collected by a fiber optic or lens and dispersed on a spectrometer to produce an emission spectrum with peaks that represent the various types of elements within the sample. For example, lead produces prominent emission lines at ~ 405.8 nm and 220.3 nm (among others), while cadmium has lines near 228.8 nm [42]. The intensity of each spectral line is proportional to the concentration of that element in the ablated micro volume [39,40]. Thus, LIBS can be used for qualitative identification of elements by their wavelengths and for quantitative analysis by calibrating line intensities against known concentrations.

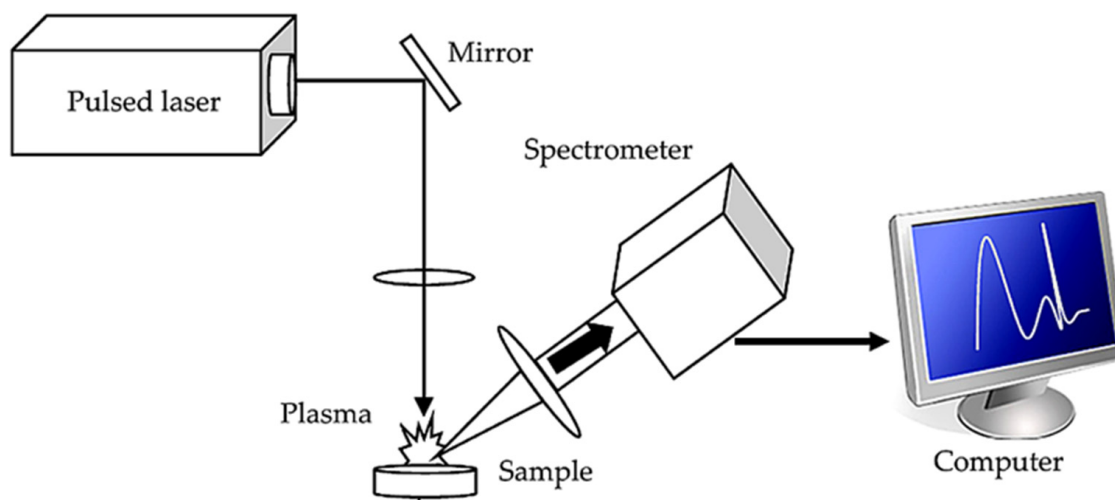


Figure 2. Schematic of a typical LIBS system.

There are several benefits to using LIBS when compared to traditional elemental analysis methods for this specific application. It is quite simple to analyze plastics without digestion with acid or other chemical treatment; first, virtually no sample preparation is required. This is especially critical for industrial waste streams, where many samples would need to be prepared, which would be time-consuming and labor-intensive [43,44].

Second, LIBS is very fast, with laser-induced shots and spectral acquisition only taking a few microseconds and effective measurement times of a few milliseconds to seconds per sample [44,45]. The processing of thousands of plastic parts could be achieved per hour, which would allow for real-time sorting. In contrast, laboratory ICP-MS/AAS methods have digestion and analysis times of hours or days, and cannot be used at conveyor-belt speeds. Third, LIBS is a multi-element technique; the broad wavelength range of the plasma emission (typically 200–900 nm is observed with modern spectrometers) means that all elements in the plastic (from light elements like C, H, N to heavy metals like Pb or Hg) can be detected simultaneously. This is a distinct advantage over AAS, which measures one element at a time, or even handheld XRF, which might miss low-Z elements and requires different filters or settings per element. LIBS can thus screen for a whole suite of heavy metals (and even chlorine or bromine for halogenated additives) in one measurement. Additionally, LIBS systems can be made portable and even handheld. Recent technological advances have led to handheld LIBS analyzers weighing ~1.5 kg that can be taken to field sites or used on factory floors. This portability, together with the capacity of LIBS to work with irregularly shaped samples (such as shredded plastic fragments) and to handle analysis through transparent containers or in air, makes it very suitable for on-site waste analysis. Lastly, the LIBS is quasi-nondestructive because only a microscopic ablation of the sample is involved, allowing what remains for use later on. The laser cut leaves a minute burn, but does not destroy the whole plastic object, unlike the way acid digestion methods work [44,46].

However, LIBS has its drawbacks and challenges in heavy-metal detection in plastics. An important limitation would be its detection sensitivity. The typical detection limits of LIBS for heavy metals in solid matrices are in the low parts-per-million range. This is satisfactory for regulatory levels (e.g., 100 ppm Cd or 1000 ppm Pb) but is not comparable to the sensitivity of ICP-MS < 1 ppm [40]. It is difficult to detect very low concentrations of metals (less than a few ppm) in a sample with LIBS, and it is difficult to distinguish below vs. above a closely set regulatory limit [39]. For instance, if Cd concentration in a plastic is ~5 ppm, then LIBS may not be able to reliably quantify that, but ICP-MS could.

In order to achieve good sensitivity, it is often necessary to enhance the LIBS signal using signal enhancement techniques, such as double-pulse lasers, longer integration times, and/or argon purge gas to boost the intensity of the lines. Another difficulty is matrix effects—the plasma formation and emission in LIBS are affected by the sample matrix (physical/chemical properties of the plastic), and this may affect the intensity of spectral lines independently of concentration [46]. The plasma temperature or density may differ between different polymer types (PVC vs. polyethylene, etc.), different carbon/hydrogen ratio, or due to the presence of other elements or additives, which alters the calibration slope for an element. For example, the same concentration of lead may yield a higher LIBS signal when measured in a PVC matrix (because of Cl presence in PVC matrix, which can easily be ionized and increase plasma conductivity) than in a polyolefin matrix. These matrix effects imply that the LIBS calibration for quantitative analysis is not trivial; normally, matrix-matched standards have to be prepared or more complex normalization and chemometric corrections need to be employed [40]. Also, plastics may be inhomogeneous; heavy metal additives may not be dispersed evenly

(e.g., in pigment spots or on painted surfaces). Typically, LIBS samples a very small spot (less than 1 mm in diameter), and a sample with some heterogeneity can vary between shots. This requires the number of shots to be averaged, or rastered across the sample surface to obtain a representative measurement. The other drawback is the difficulty in obtaining the required spectral resolution and to eliminate interferences: LIBS spectra can be intricate, with emission lines of various elements possibly overlapping. For instance, an emission line of chromium may overlap with an emission line of argon, or an intense molecular emission band may be present when ablating plastics (because of their organic composition). Correction of these interferences can be difficult and involve the use of a high-resolution spectrometer or time-gating to avoid early continuum emission. These issues could result in false positive/negatives results in heavy-metal detection if not calibrated carefully and spectrally analyzed. Lastly, even though LIBS instruments are becoming more user-friendly, expertise in spectral interpretation and calibration is still required to perform quantitative analysis, and there are no standardized methods for LIBS in waste analysis (as is the case for XRF or ICP). This situation of lack of standardization and the necessity of method validation in real waste matrices represents a challenge to regulatory acceptance [40].

The way LIBS works is by using a plasma to turn the plastic into a light source and then reading the “light signature” of the heavy metals it contains. It is fast, is multi-element, and has a small preparation volume, which equates to major advantages in practicality for screening of heavy metals in industrial plastic wastes. At the same time, high accuracy and sensitivity for LIBS can be obtained only by taking care to deal with the matrix and interference effects in a robust manner, which may require careful calibration and other suppressor techniques. Table 2 provides a brief comparison of LIBS with traditional analytical techniques for heavy-metal detection in plastics. As shown, LIBS occupies a unique niche of rapid, on-site analysis with moderate detection limits, fitting between the portable simplicity of XRF and the ultra-sensitivity of ICP-based methods.

Table 2. Comparison of analytical techniques for Pb detection in plastics. LOD = limit of detection; Pb = lead; LIBS = laser-induced breakdown spectroscopy; XRF = X-ray fluorescence; ICP-MS = inductively coupled plasma mass spectrometry; and AAS = atomic absorption spectroscopy.

Metal	Major Sources in Plastic Waste	Key LIBS Emission Lines (nm)	Typical LOD Range (mg/kg)	Quantification Approach	Notes/Interferences	Representative Applications and Studies (Year)	Ref.
Lead (Pb)	Stabilizers, pigments, batteries, electronic components, PVC additives	283.31, 405.78, 368.35, 220.35, 217.00	16–547	LIBS–ICP-OES calibration, PLS, RF	Interference: Fe, Zn. Matrix effects high in PVC	Quantification in PVC cables and mixed plastics; industrial plastic recycling streams (2021, 2023)	[47–49]
Cadmium (Cd)	Pigments, stabilizers, rechargeable batteries, PVC	226.50, 214.44, 228.80, 326.11, 346.62	19–61	Internal standard (Ca, Mg), PLSR	Interference: Fe, Zn, Mg	Detection in colored plastic fragments; e-waste plastics (2020, 2022)	[49–51]
Chromium (Cr)	Pigments, stainless steel additives, coatings	425.43, 427.48, 520.60, 360.53, 357.87	2–100	Calibration curve, PLSR, ANN	Interference: Fe, Ni. Matrix dependent	Monitoring Cr in ABS and polycarbonate waste; leather-coated plastics (2019, 2022)	[47,49]
Nickel (Ni)	Stainless steel contamination, pigments	341.48, 352.45, 362.29, 231.60, 305.88	NR	PLS, SVR, Normalization	Interference: Fe, Cr. High self-absorption possible	Ni in engineering plastics and mixed plastic waste (2021)	[27,52]
Copper (Cu)	Wiring, catalysts, pigments	324.75, 327.39, 515.32, 521.82, 578.21	NR	LIBS–ICP-MS calibration, PLSR	Interference: Fe, Zn. Matrix enhancement	Cu quantification in shredded plastic from WEEE (2021, 2023)	[27,53–55]

Table 2. Cont.

Metal	Major Sources in Plastic Waste	Key LIBS Emission Lines (nm)	Typical LOD Range (mg/kg)	Quantification Approach	Notes/Interferences	Representative Applications and Studies (Year)	Ref.
Zinc (Zn)	Stabilizers, pigments, fillers, and rubber/plastic additives	202.55, 213.86, 472.22, 481.05, 636.23	200–215	External calibration, signal normalization, and comparison with LA-ICP-MS measurements	Possible self-absorption and matrix effects; signal intensity may be affected by polymer type, fillers, and Zn concentration	LIBS detection of Zn-containing additives in polymer matrices and quantitative determination of Zn in thermally conductive polycarbonate materials (2009, 2018)	[56,57]
Mercury (Hg)	Contamination from mercury-containing WEEE components; Hg is not generally added directly to polymers	253.65, 546.07	Not established for LIBS in plastic-waste matrices Kayar et al. [58] reported an Hg LOD of 1 mg/kg using matrix-matched LA-ICP-MS calibration	LIBS calibration curve; LA-ICP-MS for plastic-specific quantitative determination	Hg volatility may cause analyte loss; heterogeneous polymer matrices and ablation behavior can affect precision and accuracy	Laser-ablation determination of Hg in waste polymer materials and plastic matrices for RoHS-related elemental screening (2010, 2016)	[58,59]
Arsenic (As)	Flame retardants, pesticide residues, additives	193.70, 197.20, 228.81, 234.98, 279.82	NR	PLS, SVM	Interference: Fe, Ca. Weak lines	As detection in flame-retardant plastics (2020, 2023)	[36]
Antimony (Sb)	Flame-retardant synergist (Sb ₂ O ₃) and polymerization catalyst	276.99; 259.81	50–750	XRF-referenced linear calibration with empirical correction for Fe contribution	Sb lines may overlap with Fe, Si, and Ti. Fe I affects the 276.99 nm region, while Fe II at 259.93 nm interferes with Sb I at 259.81 nm	LIBS determination of Sb in consumer plastics; classification of Sb-containing WEEE plastic fractions; Br and Sb used as screening tracers for BFRs and Sb ₂ O ₃ , respectively (2018, 2019, 2023)	[60–62]

LOD values were obtained from individual LIBS studies of polymer or plastic matrices and are expressed in mg/kg. Values reported as µg/g were converted using 1 µg/g = 1 mg/kg. NR indicates that a directly reported plastic-matrix LIBS LOD could not be verified. LOD values are instrument-, emission-line- and matrix-dependent.

3. Heavy Metals in Industrial Plastic Wastes' Source and Concern in Asia

Common Heavy Metals in Plastic Waste and Their Sources: A variety of heavy metal elements can be found in industrial plastic-waste streams, either as intentionally added ingredients or as contaminants [30]. These include cadmium (Cd), chromium (Cr), mercury (Hg) and antimony (Sb), and others in certain situations (e.g., arsenic, selenium, or tin compounds in some plastics). The periodic table in Figure 3 highlights major heavy metals and metalloids commonly detected in industrial plastic-waste streams using LIBS. Additives in plastic formulation: many heavy metals have been used as additives to give desirable properties to plastics [5]. In the past, PVC plastics were produced with up to a few percent of heat stabilizers, such as lead compounds (lead sulfates or phthalates), which kept PVC from degrading during processing [63].

Traditionally, PVC plastics were used with heat stabilizers, such as lead compounds (lead sulfates or phthalates), to avoid degradation during processing at up to a few percent. Bright yellow, orange or red colors were obtained in plastics (e.g., PVC, polyethylene) by the use of pigments containing lead chromate (Pb) [30]. Cadmium pigments, for example cadmium sulfide yellow and cadmium selenide red, were also frequently used for coloring plastics (particularly in the past) and cadmium stearates were used as stabilizers in PVC. Older polyethylene and polypropylene products may have been made with Cd stabilizers. Chromium in plastics can be found in pigments and lead chromate was used in pigments such as “chrome yellow” and “molybdate orange” [30]. Hexavalent chromium compounds have also been used in dyes and as surface treatments on plastics (e.g., in plating on ABS plastics, though that is on the surface). Mercury was less commonly a plastic additive, but certain polyurethane rubber catalysts contained phenyl mercury compounds, and mercury-based biocides were sometimes added to plastics. Antimony trioxide is not typically thought of as a toxic heavy metal like the others, but it is a significant additive used as a flame-retardant synergist in combination with brominated flame retardants in many

electronics plastics (at a few-percent loading) [64]. As a result, electronics waste plastics often have elevated Sb content (while Sb is not banned in RoHS, it is a regulated substance due to being carcinogenic). Lesser-used additives include barium (as barium–cadmium stabilizer blends), tin (organotin stabilizers, which are actually common in modern PVC in lieu of lead), and arsenic (some older pigments like Paris green and preservatives contained arsenic).

1 H	2 He																
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

Figure 3. Periodic table of elements highlighting the metals discussed in this review [65].

Pigments and Inks: Even when not mixed into bulk polymer, heavy metals can appear in surface coatings, inks, or paints on plastic products. For example, the external ink on some plastic packaging or e-waste components might contain lead or cadmium-based pigments. Aguirre et al. (2013) found that certain internal plastic parts of mobile phones that were coated with paint showed strong LIBS signals for chromium, indicating Cr-based pigments in the coating [66]. Similarly, decorative coatings on toys or labels on plastic electronic housings have historically used heavy-metal pigments. When such painted plastics enter the waste stream, the heavy metals are present even if the underlying polymer had none.

Industrial plastic waste can contain recycled plastics from different sources. Plastics may be cross-contaminated during recycling (particularly if the recycling is poorly separated) with heavy metals [5,13]. For example, e-waste plastics with brominated flame retardants and with Pb/Cd can contaminate a batch of so-called “clean” plastics when they are melted together. It has been demonstrated that there can be significant levels of Pb and Cd in recycled black plastics since black colorant may be produced from plastic from electronics waste [67]. Furthermore, there are physical risks of heavy-metal contamination, such as solder particles (lead-tin solder) or metal attachments mixed with waste plastic from electronic devices. The informal sector for recycling plastics in Asia may be shredding plastics along with the metal parts of e-waste, which can lead to metal particles or oxides sticking to plastic particles. In that way, these contaminants find their way into the recycled plastic pellets, which ultimately leads to an accumulation of heavy metals, even if there is no heavy metal present in the original polymer.

External Absorption: External absorption is not as important as internal absorption, but plastics can absorb heavy metals from external sources as well. For instance, river microplastic debris can bind with lead or mercury ions in the polluted river water [46,68]. But, in industrial applications, this is not a dominant consideration compared to the direct introduction of additives. One scenario of note is PVC cables or plastic equipment that

have accumulated metals on their surfaces (e.g., lead dust in a factory setting coating plastics) [66]. When such materials are recycled, the surface contamination contributes to heavy-metal content. The major sources and environmental pathways of heavy-metal contamination in industrial plastic-waste ecosystems are illustrated in Figure 4.

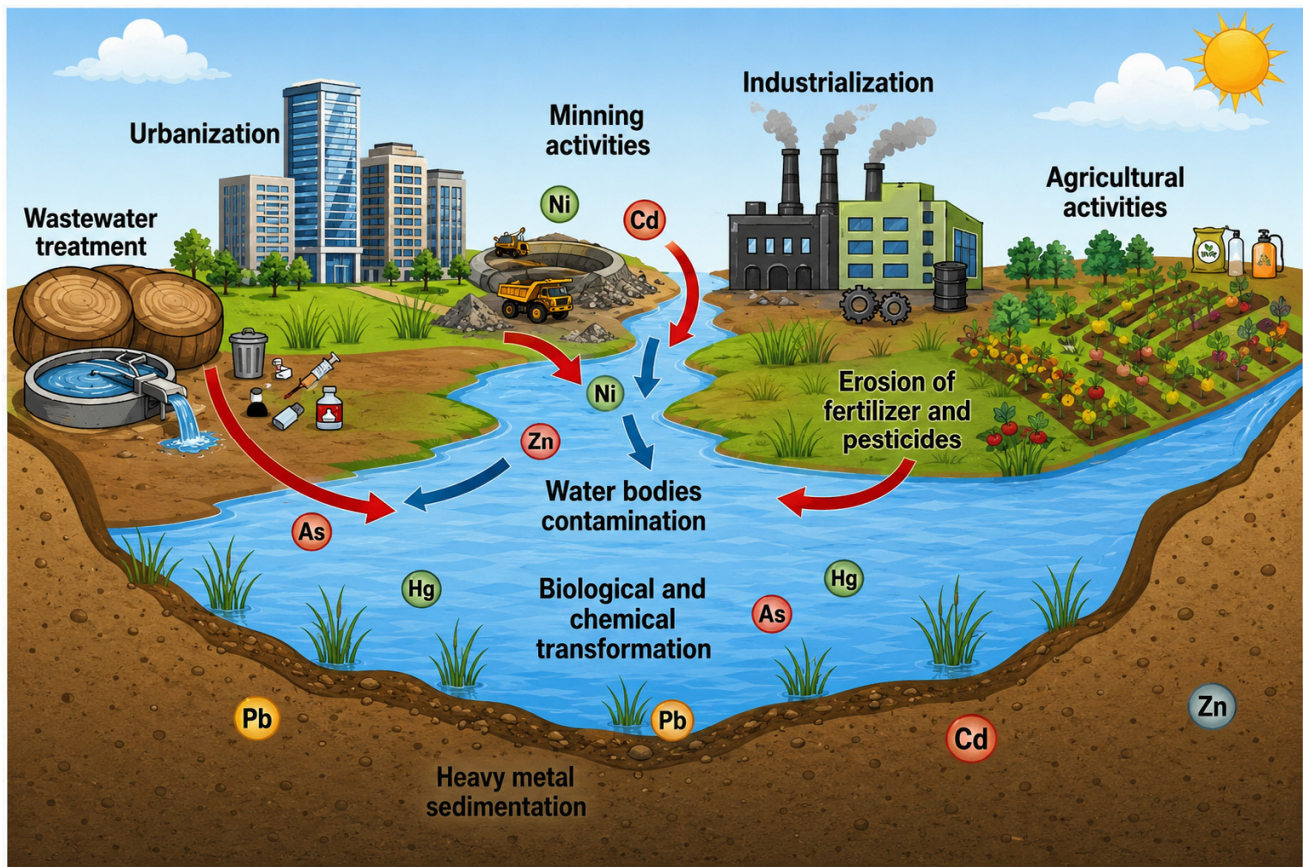


Figure 4. Environmental pathways and sources of heavy-metal contamination in industrial and plastic-waste ecosystems.

Hence, lead and cadmium tend to come from pigments and stabilizers, antimony from flame retardant formulations, chromium from pigments or plating, and mercury/arsenic occasionally from catalysts or biocides. These heavy metals are especially prevalent in electronic and electrical plastic waste (e.g., circuit board plastics, cable insulation, and CRT monitor housings) because older electronics were manufactured before current restrictions. Indeed, plastic flake analyses of WEEE (Waste Electrical and Electronic Equipment) plastics in Europe and Asia have found Pb in ~40–50% of samples and Cd in ~15% of samples, at concentrations ranging from a few ppm up to several thousand ppm. A study of European WEEE plastic found Pb ~200 ppm and Cd ~70 ppm in certain fractions even after basic sorting [69]. In Asia, where a lot of the world's e-waste has been historically imported or processed, the heavy-metal burden in plastics can be considerable. Researchers have measured, for example, 1100 ppm Pb and 130 ppm Cd in mixed plastic granulates from Chinese e-waste recycling plants.

Environmental and Health Risks in Asia: The presence of heavy metals is a risk when plastics are reused or disposed of or burned in the downstream. If the heavy-metal-containing plastics are then recycled to produce new consumer items (toys, packaging, etc.), there is the potential for human exposure to the metals due to contact, mouthing (in the case of children's items) or leaching out of the metals over time [70]. For example,

recycled PVC toys with lead stabilizers might lead to children's exposure to lead beyond the safe limit [71].

The recycling of plastics from e-waste materials for consumer products was also identified as a source of lead and cadmium contamination in recycled plastic products, as reported in a study conducted in Vietnam. Heavy metals may leach from plastic, particularly in landfills (under acidic conditions), into soil and groundwater, as reported in leachate studies at dump sites in Asia [72]. For incineration (a waste disposal practice in some countries), plastics containing high levels of heavy metals do not get destroyed, but rather are concentrated in the ash or emitted as a particulate matter [73]. In the Asian region, fly ash from combustion of mixed plastic wastes contained high concentration of Pb, Cd and Cr, which is a disposal problem [74].

The informal recycling sector in countries such as China, India, Vietnam and Thailand has been heavily affected. There, the workers have to handle the e-waste and plastic offcuts by hand, at times even burning wires and plastic parts to extract the metals. Inhalation of heavy metals, as fumes or through soot particles, takes place during this practice and the spread of heavy metals among communities [75]. Workers and residents in the e-waste hubs of Asia have consistently been found to have elevated levels of lead, cadmium, arsenic, and chromium in their blood and urine, versus controls. Exposure to these metals can lead to neurological damage (lead, mercury), kidney dysfunction (cadmium, lead), respiratory issues (chromium, arsenic) and increased risks of cancer. Children are particularly susceptible, with an estimated 70% of children in Guiyu, China, a major e-waste recycling town, having blood lead levels above the CDC's blood lead reference value in the 2000s, which were linked to the handling and burning of plastics and electronic parts that contain lead [76]. Lead was detected in Guiyu's dust and surface soil at tens of times of background levels, as a result of environmental surveys conducted in the region. The same situations have been noted in informal recycling groups in India, where heavy-metal pollution of groundwater and soil (e.g., lead in soil > 1000 mg/kg) is directly related to improper treatment of plastics for e-waste [14]. These environmental dispersions of heavy metals lead to broader contamination of crops, livestock and water resources and affect the food chain [11].

Even in formal recycling facilities, heavy metals in plastics pose problems. Recycled plastic pellets that contain banned substances can render batches non-compliant with regulations like RoHS or the Stockholm Convention on POPs. For example, the EU now prohibits recycling of BFR-containing plastics above certain bromine limits (~200–500 ppm for specific flame retardants) [65]. Although focusing on organics, this is analogous to heavy metals: if recycled plastic exceeds 1000 ppm lead, it cannot be used in products in jurisdictions enforcing RoHS. Thus, recyclers in Asia aiming to export recycled material or produce high-quality recyclate must be able to identify and remove heavy-metal-rich plastics from their input stream. Failure to do so not only risk regulatory violation but also degrades the quality of recycled plastic (since even low levels of metals can affect material properties and color).

Heavy metals in industrial plastic waste represent a significant regulatory and public health concern across Asia. Many countries have put legal limits in place, but enforcing those limits in the vast and diffuse waste streams is difficult without proper analytical tools. Rapid detection technologies are needed to: (1) monitor waste streams for heavy-metal content, (2) guide sorting and separation of hazardous fractions, and (3) verify compliance of recycled plastics. This is precisely where LIBS can contribute. With its capability to screen plastics on-site for elemental composition, LIBS can empower recyclers and regulators to intercept contaminated materials before they cause harm.

4. Application of LIBS in Analyzing Heavy Metals in Plastic Waste

4.1. Qualitative Analysis

In the context of plastic-waste streams, qualitative LIBS analysis is used to detect the presence or absence of specific heavy-metal elements in different plastics and to identify which items or fragments are contaminated. However, for qualitative LIBS measurement, it is enough to recognize the LIBS spectrum characteristic emission lines of heavy metals of a sample, and it is not necessary to determine the exact concentration. This can be very helpful in sorting, such as the rapid screening of plastic parts on a conveyor, alerting to parts with lead or cadmium over a certain limit. LIBS has been shown to be able to qualitatively detect heavy metals in various plastic materials such as plastics of daily use like PVC, PET, polyethylene (PE), polypropylene (PP), polystyrene (PS), and engineering plastics found in e-waste by researchers in Asia and around the world.

One clear example comes from electronic waste plastics. Aguirre et al. (2013) analyzed plastic components from discarded mobile phones using LIBS and readily detected the heavy metals present [66]. Black plastic casings from phones produced LIBS spectra showing mainly the polymer matrix elements (C, H as CN and C bands, some inorganic fillers like Al, Ti, Ba), but some internal painted parts exhibited intense chromium lines [77]. Those parts were painted with a Cr-based coating, and LIBS could immediately identify Cr qualitatively by its strong emission (notably the Cr I lines in the 425–430 nm range) [42,77]. In contrast, unpainted white plastic pieces from the phones showed no Cr but did show other metals like aluminum and barium peaks from fillers. This review illustrated that LIBS can differentiate even subtle differences in the plastic composition (e.g., different manufacturers or treatments) by qualitatively detecting metals present [78]. Furthermore, it highlighted that heavy metals such as Cr, while not obvious from visual inspection of the plastic, were uncovered by LIBS analysis, knowledge that could be used to segregate those parts for special handling [78].

LIBS qualitative detection has also been applied to single plastic samples to confirm the presence of regulated metals. For instance, when screening various consumer plastic items (toys, electronics housings, etc.), LIBS can be used much like a handheld XRF gun but with the advantage of being able to detect lighter elements and being free of ionizing radiation. In one case, LIBS was used to test children's toys' plastics for toxic elements and successfully identified toys containing lead and mercury that exceeded safety limits [48]. The LIBS spectra revealed lead lines in certain toy jewelry pieces and mercury lines in old plastic play food, correlating with the use of lead-based dyes and phenyl mercuric acetate in those items. Regulatory agencies in some Asian countries are now considering LIBS as a rapid screening tool for imported plastic toys and goods, complementing or substituting XRF in certain scenarios [45,79].

All plastics can be analyzed with LIBS, but the spectrum may be different depending on the base material. The typical LIBS signature (for example, PVC, polyvinyl chloride) is characterized by the presence of chlorine, resulting in the strong emission of CN (from C and N in air reacting with C and Cl), and, to a lesser extent, HCl band emission, which can cause a continuum, slightly obscuring some emission lines of trace metals [80].

However, heavy metal additives in PVC are easy to detect: Pb lines have been clearly identified in waste PVC cable insulation by LIBS analysis, proving that LIBS analysis can detect legacy heavy-metal additives (like Pb stabilizers) in old PVC wiring samples. However, polyethylene and PP plastics result in simpler LIBS spectra, which consist primarily of C bands and H α line, allowing for easier detection of heavy metal if present, with cleaner background [81]. In a study by Chen et al. (2020), single-particle LIBS analysis of numerous micro plastic fragments (primarily PE and PP) from the Beibu Gulf in China was demonstrated that determined the presence of elements embedded in or attached to

the plastics such as Al, Ti and Zn [82]. Their results showed that LIBS is able to detect even very small constituents in environmental plastics debris, although Al and Ti are not main concern heavy metals. More relevantly, they noted high variability in elemental signal among the various types of microplastic particles, with some microparticles revealing the presence of either a detectable peak of Pb or Cu (probably due to local contamination or “hot spots” in the plastic), while others did not. The authors point out that this variability makes it crucial to analyze many individual particles or multiple spots in each particle. In slower methods, scanning a number of microplastics could not have been achieved due to the speed of LIBS [82].

Several case studies from Asia underscore LIBS’s qualitative utility. In China, researchers have applied LIBS in e-waste dismantling facilities to identify plastics containing brominated flame retardants and associated heavy metals [83,84]. By calibrating LIBS to recognize bromine (from BFRs) and antimony above certain intensity thresholds, they could rapidly separate out the high-BFR plastic fractions which often also contained higher levels of Pb and Cd [83]. This approach directly supports compliance with bans on recycling BFR-laden plastics. In India, a recent pilot study used a handheld LIBS device to test shredded plastic from electronic appliances for toxic metals. The LIBS device was able to flag samples with Pb content qualitatively by the presence of the Pb I 405.78 nm line, correlating with independent lab tests [82]. Such flagged samples included pieces from old computer monitors and television casings likely because older CRT monitors often used leaded stabilizers in PVC and high lead glass that contaminated adjacent plastic. The outcome of that study was that LIBS screening could prevent these high-lead plastics from being recycled into consumer products like plastic pellets for toys.

Overall, qualitative LIBS analysis in plastic-waste management is proving to be a fast and reliable screening method to identify heavy metals on site. LIBS spectra give immediate feedback: for example, seeing the green spectral line at 521 nm of chromium or the blue-violet lines around 405 nm of lead is a straightforward confirmation of those metals. Operators can be trained to recognize a few key spectral features, or an automated software can be set to trigger an alarm when certain wavelength intensities exceed a background. Compared to relying on material labels or expensive send-to-lab testing, LIBS provides a much-needed tool for real-time decision-making in recycling facilities. Plastics contaminated with heavy metals can be diverted to hazardous waste processing, while cleaner plastics proceed to normal recycling. This not only minimizes environmental pollution but also enhances quality of recycled plastics (because heavy metal might influence the properties of the polymer and therefore the marketability of recycled plastics).

From the above it is evident that LIBS can effectively “scan and spot” heavy metals from a plethora of plastics. LIBS can identify a batch of black ABS plastic containing bromine and antimony from flame retardants, and it can confirm that a batch of PET bottles is free of the toxic elements. To make the better of these two techniques, many Asian industrial systems are starting to use LIBS in the form of a screening tool along with XRF. Elements such as sodium (Na), magnesium (Mg) and aluminum (Al), which XRF does not always get right, also make themselves known with LIBS, especially when they represent fillers or pigments, and could signal heavy metals. Thus, qualitative LIBS could be a good first-line method for the qualitative identification of heavy metals in plastic waste, in order to perform rapid sorting of the materials and ensure that dangerous materials are identified at the beginning of the recycling process [85,86].

It is worth noting that this kind of qualitative LIBS deployment for heavy metals in plastics remains largely undocumented in some regions with growing waste-management pressure, such as Pakistan and Saudi Arabia, where existing LIBS expertise has so far been applied to environmental and polymer-identification studies rather than plastic-specific heavy-metal screening.

4.2. Quantitative Analysis

The identification of only the presence of a heavy metal is important in many situations; however, it is necessary to quantify the amount of a particular heavy metal present in a plastic sample. To determine if concentrations of a particular material, such as ppm of lead or cadmium, are compliant with regulations or to determine if a material is suitable for recycling, one must make the measurement and compare the concentration against threshold values. LIBS can be applied quantitatively, much as other analytical techniques, but some of the limitations mentioned above (matrix effect, signal fluctuations) must be overcome with calibration and more elaborated data processing techniques. Over the past years, the efforts to develop quantitative LIBS methods for plastics have led to a great advancement in the methods of calibration, univariate vs. multivariate models and even machine learning methods for increasing the accuracy of the quantitative method.

The simplest form of LIBS quantification uses a univariate calibration, where the intensity of a specific emission line from a heavy metal is correlated to its known concentration in a set of standard samples. One could prepare or obtain a series of plastic standards with known amounts of lead in them (for example 0 ppm, 100 ppm, 500 ppm, and 1000 ppm) and measure the intensity of a strong lead emission line, such as the 405.78 nm line, for each of the standards. A calibration curve (intensity vs. concentration) can then be plotted and used to interpolate the concentration of the LIBS intensity of unknown samples [87]. However, the development of matrix-matched standards is not easy; ideally, one would require the heavy metal dispersed in the same polymer type and form as the standards. Several studies have fabricated calibration standards by adding a known amount of metal salts or oxides to clean plastics and pressing them into pellets or melting them into a sheet. For example, Holub et al. (2023) tailored their own calibration materials for the quantification of Pb in recycled polymer matrices, using post-consumer plastics contaminated with different amounts of Pb [47]. They made use of “real” recycled polymer material (from waste polymer debris) and spiked it to create a series of in-house reference materials. With these, they calibrated LIBS and reported that they had a precision > 86% and accuracy > 90% in predicting the Pb in unknown samples [47]. This level of accuracy is quite impressive, indicating LIBS can be made quantitative enough for regulatory purposes (the results were accurate enough to determine if samples met the EU’s 0.1% Pb limit in PVC, for example) [47].

However, univariate calibration can be confounded by matrix differences. Hence, many scientists resort to multivariate calibration techniques in order to enhance the quantitative LIBS analysis of plastics. Multivariate methods (e.g., partial least squares regression (PLSR) or other chemometric models) consider the entire spectrum (or several spectral lines) at the same time [88]. These methods involve the correlation of the whole fingerprint of the LIBS spectrum with the concentration of the target metal instead of considering only one peak of the spectrum. This can help to compensate for the changes in the intensities of the individual lines and can take advantage of the fact that there are internal reference lines (e.g., the carbon emission can be used as an internal standard) [89]. Cacho et al. (2025) have studied the quantification of total bromine in WEEE plastics in real-time by LIBS in combination with PLSR on a sorting line [64]. The bromine quantification is similar to

heavy-metals quantification because they are both susceptible to matrix effect. Partial least squares regression (PLSR) was used to account for matrix-dependent spectral variations among acrylonitrile butadiene styrene (ABS), high impact polystyrene (HIPS), and polycarbonate (PC) blends, as well as spectral interference from co-occurring elements such as antimony (Sb). The model obtained was able to predict Br concentrations and thus enable the classification of plastics above or below the regulatory threshold (e.g., 2000 mg/kg Br). The same procedure can be used for metals; several investigations have demonstrated that in plastics, LIBS quantification can be carried out by using PLS or artificial neural network (ANN) models [65]. In other words, the algorithms determine the most optimum set of spectral features (peaks, or even slight intensity differences) that relates best to the amount of metal and minimize any error that might be caused by shot-by-shot variation or matrix differences.

Detection Limits and Accuracy: LIBS can detect heavy metals in plastics at the tens-of-ppm level if care is taken in calibrating the instrument. The detection limit of the typical heavy metals such as Pb and Cd, in a plastic matrix using a benchtop LIBS with an ICCD detector, is reported as 5–50 ppm [77]. This is sufficient to determine if a sample is above or below common regulatory limits (100 ppm Cd, 1000 ppm Pb). For instance, if the concentration of Cd in a recycled plastic pellet is 50 ppm, then LIBS will, in general, detect and approximately quantify it, but LIBS may be near the detection limit if it is 5 ppm. In practice, quantification accuracy of $\pm 10\%$ relative is attained for major and minor elements, and it is larger for trace elements near the LOD. LIBS quantification is well suited for relatively high concentrations (hundreds of ppm) which are the typical concentrations of legacy additives. In another comparative study, the amount of the elements Pb and Cr was quantified in the mixed plastic samples by LIBS technique and the results were found to be almost the same as that obtained by ICP-OES within $\pm 15\%$, for the concentrations that are in the range of 0.1 to 0.2% [77]. This is a very encouraging development since it provides a means to generate reliable quantitative data with a well-calibrated LIBS. Notably, LIBS is much faster; in that study, each LIBS measurement took ~10 min (including multiple shots and averaging) vs. days for ICP when considering the digestion and lab analysis turnaround [77]. New developments such as double-pulse LIBS or spark discharge-assisted LIBS have further reduced the limits of detection of metals in polymers by increasing the emission signal in some cases to sub-ppm.

Machine Learning and Advanced Techniques: Other than classical PLS regression, machine learning and other advanced techniques have been applied to enhance the LIBS quantification in plastics. The artificial neural networks (ANNs) have been developed using the LIBS spectra for the simultaneous prediction of concentrations of Pb, Cd and Cu. The non-linear relationship and complex interferences of these kinds of ANNs are better than that of the linear model and sometimes predictions on the validation samples are more accurate than the linear model [90]. For instance, an ANN model could be used to predict the Cd in plastics, even when the Cd emission lines are buried in the Ar lines from the air in the LIBS spectrum, by identifying patterns in the other parts of the spectrum that correlate with the presence of Cd [90,91].

Another promising route is the fusion of LIBS with other spectroscopic techniques: for instance, an integrated LIBS–Raman system was proposed to tackle both identification of polymer type (via Raman) and quantification of metals (via LIBS) simultaneously [92]. By knowing the polymer type from Raman, one can apply polymer-specific LIBS calibration automatically, thus reducing matrix effect errors. Shameem et al. (2017) employed a unified LIBS–Raman setup to detect microplastic particles and any heavy metals attached to them in water, using machine learning to analyze the combined data [92]. Such multimodal

approaches are still in research stages but show the direction of future quantitative analysis, combining complementary data streams to improve robustness.

In China, Tianjin University researchers (Chen et al., 2020) developed a method to quantify heavy metals in single microplastic particles using LIBS with a specialized thin-film substrate to minimize interference [82]. By placing tiny plastic fragments on a low-background polyethylene film, they effectively reduced the optical interference from the sample holder and achieved quantitative measurements of elements like Cu and Pb in individual particles. They demonstrated linear calibration curves for Cu in microplastics in the 10–100 ppm range with good correlation, enabling them to estimate how much heavy-metal pollution each microplastic had accumulated [82]. Indian researchers have also applied LIBS for the classification and elemental characterization of post-consumer plastic waste in recycling streams, demonstrating its effectiveness for rapid material identification and spectral-based discrimination of polymer types [93–95]. Researchers at the University of Hyderabad developed low-cost, portable LIBS systems combined with chemometric analysis to enable real-time waste segregation, confirming the feasibility of LIBS for rapid elemental profiling of recycled plastics and demonstrating strong classification accuracy using spectral signatures. To ensure quality control, standardization efforts are underway. Researchers are working on standard reference materials (SRMs) for LIBS calibration in polymers. For instance, NIST in the USA has developed some polymer SRMs doped with metals [96], and Asian institutes are considering creating their own references that match regional waste plastics [82]. Validating LIBS methods against certified values from these SRMs helps to establish the accuracy and traceability of LIBS results [77]. In a regulatory context, LIBS could potentially be standardized and adopted as an officially approved method for the rapid screening of plastics, similar to established EPA analytical methods used for environmental monitoring. Pilot proficiency tests have already been conducted, in which multiple laboratories used LIBS to quantify Pb in the same blind plastic samples. The results were comparable within approximately 20% of the true values, demonstrating the potential of LIBS as a field-portable analytical method. Quantitative LIBS analysis of heavy metals in plastic waste is now a reality. Through proper calibration, often using multivariate and machine learning models to cope with complex spectra, LIBS can measure heavy-metal concentrations with an accuracy sufficient for most industrial and regulatory needs. The detection limits in the low-ppm range mean that LIBS can comfortably detect if a plastic exceeds, say, a 100 ppm Cd limit or 1000 ppm Pb limit, and provide an estimate of how far above (or below) the limit it is. This capability is crucial for certifying recycled plastics (ensuring they meet safety standards) and for determining the fate of a waste batch (e.g., whether it can be recycled or must be treated as hazardous). Compared to sending samples to off-site labs for ICP analysis, quantitative LIBS empowers on-the-spot decision making. For instance, a recycler can measure that a batch of shredded plastic has ~1200 ppm Pb and know it is unsafe to reuse, then isolate that batch for special processing, or a factory receiving recycled pellets can audit them to ensure, for example, “Cd < 5 ppm”, using LIBS as a quality check.

4.3. Comparative Studies: LIBS Versus Other Techniques

It is useful to compare the performance of LIBS with other well-established analytical methods in real industrial situations, particularly when it is important to detect heavy metals. In Asia, a few comparative studies and pilot projects have been performed to compare LIBS with traditional methods (such as XRF, ICP-MS, and AAS) for the analysis of plastic waste for the content of heavy metals. The factors taken into account in these studies are, as a rule, speed, accuracy, cost and usability in an industrial environment (factories,

recycling centers, ports of entry for imported waste, etc.). The results of these comparisons are summarized here, with points outlining the advantages and disadvantages of the use of LIBS compared to the alternatives.

Speed and Throughput: One of the clearest advantages of LIBS is its high analysis speed. Comparative tests have shown that LIBS can analyze a sample (from placement to result) in a matter of seconds to a minute, whereas preparing and analyzing the same sample by ICP-MS or AAS can take hours or days [40,97]. Holub et al. (2023) noted that each LIBS measurement for Pb in their polymer debris took about 10 min including multiple laser shots and data processing—still a stark contrast to the multi-day process of digesting plastic samples in acid and running ICP-MS in a centralized lab [47].

Conveyor-based, in-line LIBS systems have been demonstrated for real-time screening of waste polymers and WEEE plastics. Stepputat and Noll set up an online LIBS measuring unit to detect heavy metals and brominated flame retardants in moving end-of-life WEEE pieces on an automatic sorting line, incorporating an autofocus unit to accommodate objects passing at varying distances from the sensor [49]. Huber et al. performed in-line LIBS measurements of chlorine-containing waste polymers directly on the conveyor belt (2 m/s) of an industrial sorting plant, using a laser with a repetition rate of up to 100 Hz to enable quasi-real-time correlation analysis of the chlorine signal [28]. More recently, Cacho et al. applied a commercial Secopta Fiber LIBS inline analyzer, also operating at up to 100 Hz and mounted on a dedicated conveyor belt, combined with partial least-squares regression to classify WEEE plastics by total bromine content for regulatory compliance sorting [64]. Collectively, these studies demonstrate that conveyor-mounted LIBS systems can support high-throughput, real-time detection of heavy metals and brominated flame retardants in waste-plastic streams [28,49,65].

Conveyor-mounted LIBS systems have proven capable of fast, automated analysis of plastic waste, but their in-line implementation in continuous recycling lines raises several technical and safety issues. The pulsed lasers used in LIBS can be Class 3B or Class 4, both of which may cause eye or skin damage from direct or reflected radiation. The laser source, beam-delivery optics, and sample-interaction zone should therefore be contained within a suitable enclosure. This enclosure should include access panels, beam stops, warning signs, restricted entry, and an emergency laser disconnect. The locations of the conveyor entry and exit gates should also be planned so that direct or reflected laser radiation cannot escape the measurement zone. During maintenance or optical alignment, trained personnel, wavelength-specific protective eyewear, and a temporary laser-controlled area may be required. Collectively, these measures should meet IEC 60825-1 and IEC 60825-4, as well as applicable occupational laser-safety regulations [98–100].

Another major challenge arises from the irregular geometry of mixed plastic waste. Materials transported on a conveyor may include flat flakes, curved housings, shredded fragments, overlapping pieces, and items of varying thickness. These variations alter the distance between the focusing optics and the sample surface, thereby affecting the focal spot size, laser fluence, breakdown efficiency, plasma stability, and the amount of material ablated. Surface curvature and inclination can also change the direction of plasma emission and reduce the efficiency with which the emitted light is collected. For very thin fragments, the laser may penetrate the plastic and produce spectral contributions from the conveyor belt or the underlying material. Some of these effects can be mitigated through real-time distance measurement and autofocus. Stepputat and Noll investigated objects moving at different distances from a LIBS sensor using an autofocus system [49]. However, at high conveyor speeds, or under conditions involving inclined surfaces, overlapping fragments, or belt vibration, the autofocus system may not respond reliably. Rapid height sensing, synchronized object tracking, optics with

an appropriate depth of field, and measurements at multiple positions on the sample surface can improve measurement reliability, although these measures also increase the mechanical and optical complexity of the system [28,49].

Laser ablation of plastics also generates particulate matter, fumes, and gaseous degradation products. Experimental studies on polyvinyl chloride and polyethylene have confirmed the formation of aerosol particles and volatile thermal-degradation compounds during polymer laser ablation [101]. More generally, industrial laser processing of polymers can release fine particles and a range of gaseous pollutants, depending on the polymer composition and processing conditions [102]. If the waste contains lead, cadmium, chromium, arsenic, antimony, or other hazardous additives, the ablation plume should be treated as potentially contaminated. The measurement area should therefore be enclosed or clearly delimited and equipped with local exhaust ventilation positioned close to the ablation zone. The extraction system should include a high-efficiency particulate filter and, where required, suitable filters for gaseous and volatile contaminants. General room ventilation alone is insufficient because it does not capture pollutants directly at the source. The extraction system should be regularly inspected for airflow performance, filter loading, leakage, and pressure drop. Filters containing deposited metals or other hazardous residues should be handled and disposed of as potentially hazardous waste [101–103]. However, excessive airflow near the plasma should be avoided, as it may disturb plume formation and reduce the reproducibility of the collected emission signal.

Black plastics present another major challenge in automated sorting. One of the main advantages of LIBS over near-infrared techniques is that it does not depend on surface color or reflected optical intensity, as the laser directly ablates the material. LIBS-based automated systems have therefore been developed for the identification and sorting of black plastic waste [104,105]. However, carbon black, pigments, fillers, and flame-retardant additives can affect laser-energy absorption, ablation efficiency, plasma formation, and the intensity of atomic and molecular emissions. Polymer LIBS spectra commonly contain strong carbon emission lines and molecular bands associated with CN and C₂. Their intensities, together with the overall spectral intensity and signal-to-background ratio, are strongly influenced by laser energy, detector gate delay, and the surrounding atmosphere. These effects may increase the spectral background and make weak heavy-metal emission lines more difficult to distinguish.

Calibration models developed using clean or light-colored polymers may therefore not be directly applicable to black or additive-rich industrial plastics. Reliable classification may require recalibration, optimization of laser energy and gate delay, background correction, signal normalization, selection of informative spectral variables, and the application of multivariate or machine-learning methods. Measurements at several locations may also be necessary when carbon black, pigments, or metal-containing additives are not uniformly distributed within the material [81,104,105]. Nevertheless, studies have shown that appropriate optimization of experimental conditions and chemometric processing can improve discrimination, even in the presence of carbon black and other common additives [81].

The overall performance of an industrial conveyor-based LIBS system depends on the coordinated operation of the laser enclosure, focusing and distance-control system, optical collection unit, plume-extraction system, spectral-processing software, object-tracking system, and mechanical sorting unit. Pilot-scale systems should therefore be evaluated using representative waste streams under realistic operating conditions, including variations in object geometry, black and colored plastics, surface contamination, overlapping fragments, conveyor vibration, and industrial belt speeds.

Despite these technical and safety challenges, LIBS offers clear advantages for practical screening applications because it provides rapid, direct, and multi-element analysis compared with laboratory-based digestion methods. Chen et al. demonstrated that LIBS can rapidly characterize heavy metals in individual microplastic particles without extensive sample preparation, and a related study further used LIBS for source analysis of heavy-metal contamination in microplastics, highlighting its usefulness for fast, particle-level screening. In a separate comparative study conducted in China, Xu et al. evaluated the robustness of a LIBS-based classification model for several industrially relevant plastics, showing that combining spectral preprocessing with feature selection improved classification robustness over time from 58.4% to 98.47%, illustrating how methodological refinements can substantially affect the real-world reliability of LIBS-based plastic classification. However, for exact regulatory quantification, laboratory methods such as ICP-MS, ICP-OES, or AAS remain more sensitive and reliable. This distinction is supported by Klingenberg et al. [27] who compared ICP-MS, AAS/ETAAS, and LIBS for regulated-metal analysis in recycled post-consumer polypropylene and suggested LIBS as a preliminary screening method, while ICP-MS or ETAAS should be used for exact quantification. Therefore, LIBS is best considered as a rapid screening and sorting-support tool, whereas laboratory-based methods remain necessary for confirmatory analysis and certification [27,55,82,106].

Sensitivity and Detection Limits: Traditional methods like ICP-MS and AAS are more sensitive than LIBS by orders of magnitude [107]. ICP-MS can detect metals in the parts-per-billion range or lower, making it suitable for trace analysis that LIBS cannot reach [108]. For instance, if the question is whether a plastic contains 5 ppb of mercury, ICP-MS would be the method of choice, as LIBS simply cannot detect such an ultra-trace level (5 ppb is far below LIBS's typical LOD). However, for concentrations above ~1–10 ppm, LIBS is often sufficient. Studies from Malaysia (Arab et al., Haider et al.) have evaluated laser-induced breakdown spectroscopy for rapid analysis of heavy metals in environmental and material samples, demonstrating that analytical sensitivity, repeatability, accuracy, and limits of detection depend substantially on spectrometer configuration and experimental conditions. Consequently, controlled measurement environments, optimized signal acquisition, and enhanced excitation configurations may be required when increasingly low trace-element detection limits are targeted [109–111].

In such cases, hybrid approaches could be used—e.g., using LIBS to screen the vast majority of samples and sending in borderline or critical ones to ICP-MS for confirmatory analysis. This is analogous to security screening: use a fast method to scan everything, and a slow method for suspicious cases. In Asia, some e-waste processors have adopted exactly this approach: LIBS for on-site bulk screening, and ICP-OES for final certification of batches that are supposed to be free of heavy metals [112,113].

Accuracy and Precision: When it comes to the quantitative accuracy, ICP-MS and ICP-OES are considered the reference standard (with typical reproducibility of just a few percent and high accuracy if calibrated). LIBS cannot yet consistently match the precision of laboratory methods; studies often report LIBS relative errors of ~5–15% for quantification, vs. <5% for ICP [27,113]. However, in many practical cases, this level of accuracy is acceptable. For example, if a plastic is supposed to have <1000 ppm Pb, a LIBS measurement of 900 ppm vs. an ICP measurement of 850 ppm is not a meaningful difference in terms of the decision (both indicate compliance). What matters is that LIBS correctly categorizes compliance. Comparative trials indicate LIBS has high success in classification accuracy: one report notes that LIBS results for Pb in plastics correctly identified 28 out of 30 samples as either below or above the limit, whereas handheld XRF misclassified a few due to borderline readings [27,108]. The misclassifications by XRF were attributed to

short measurement times leading to high uncertainty at ~1000 ppm level, whereas LIBS, by taking multiple shots and averaging, got a more confident result. In terms of precision, LIBS measurements can vary shot-to-shot because of inhomogeneity, but by averaging 10–20 shots the precision improves markedly (often to <5% RSD for homogeneous samples). AAS/ICP are more precise for a given sample portion, but they actually face an averaging issue of their own: they measure the digested sample, which could hide inhomogeneities. LIBS could potentially show if a sample is inhomogeneous by variation between spots, which is extra information beyond the scope of ICP (ICP gives one number for the whole sample) [114].

Practicality and Cost: From a practical standpoint, LIBS and XRF are both field-deployable, but they have different safety and cost profiles. Handheld XRF uses ionizing X-rays and requires radiation safety measures and certification in many countries. LIBS uses a laser (class 3B or 4) and while one must protect from laser beam exposure and plasma glare, it does not have the regulatory burden associated with X-rays. This makes LIBS attractive in countries where obtaining XRF devices is bureaucratically difficult or where operators may be less trained in radiation safety. In terms of cost, a high-end handheld XRF and a handheld LIBS are in a similar price bracket (tens of thousands of USD). However, automated XRF sorting systems (with X-ray transmission or fluorescence units over a conveyor) are quite expensive and, as noted, not widely used in industry in Asia [27,113]. LIBS-based sorting systems are still emerging; their cost is also high currently, but potentially lower than complex X-ray systems because LIBS optics can be simpler and do not require heavy shielding. A comparative economic analysis in a Chinese recycling plant showed that implementing a LIBS quality control step reduced the incidence of batches rejected for high heavy-metal content by 90%, saving the company considerable costs in penalties and returned goods (the LIBS unit paid for itself within a year by improving compliance) [46]. Another cost factor is consumables and maintenance: ICP-MS and AAS have ongoing consumable costs (gases, acids, etc.), whereas LIBS and XRF essentially do not. This makes LIBS/XRF per sample cost extremely low, which is advantageous when scaling up to thousands of samples.

Use Case Suitability: Each technique may be favored in different use cases. ICP-MS/AAS are unbeatable for comprehensive certification of a material's composition when maximum sensitivity is needed or when multiple elements, including non-metals, must be quantified accurately [108]. These would be used, for instance, by a regulatory lab to verify that a children's product has <90 ppm lead (the strict limit for lead in paint coatings in some jurisdictions), something LIBS might not reliably quantify if the lead were only present in a thin coating. Handheld XRF is very convenient for quick screening of larger objects for heavy metals (it is widely used by customs and regulators globally for RoHS enforcement). It penetrates a small depth (maybe up to a few mm) which is fine for well-mixed plastic, and it provides a yes/no answer in seconds for major toxic elements [80]. Its weakness is with small or irregularly shaped pieces, black plastics with carbon black (which can attenuate X-rays), and elements like Be, B, or even Mg/Al which are of interest sometimes (for example, Al or Mg can indicate certain fillers or alloys present). LIBS, in comparison, excels with small fragments (it can test millimeter-scale particles by focusing the laser accordingly), and it can handle black or transparent plastics alike since the laser ablates the material directly [115]. LIBS can also detect elements like chlorine and bromine, which XRF can as well but requires higher energy X-rays and longer times. LIBS can easily pick up the strong H-alpha line at 656 nm, CN bands, etc., giving additional info like if the plastic is halogenated (presence of Cl emission below 200 nm, requiring a UV-sensitive spectrometer). In fact, LIBS is one of the few techniques that can measure light elements and heavy metals in one go. A direct comparative study

on automotive shredder residue plastics found that LIBS could detect chlorine (from PVC) and also lead, whereas XRF detected lead but completely missed chlorine; using LIBS, operators could remove PVC pieces (to avoid HCl emissions in recycling) at the same time as removing lead-containing pieces, something not possible by XRF alone [49].

In Asian industrial settings, some facilities employ a combination: XRF for routine inspection of known product types and LIBS for more complex or mixed waste streams. In WEEE-plastic recycling facilities, handheld XRF can be used for fast screening of restricted elements or for the detection of tracers associated with material additives in relatively homogeneous plastic parts, while LIBS in combination with multivariate analysis has the potential for real-time classification and automatic sorting of mixed plastic wastes in the WEEE stream based on the elements present in the waste.

LIBS can be integrated with sorting machinery when the laser source, optical collection system, spectrometer, distance-control unit, and classification software are configured for online or in-line measurement of moving waste pieces. Stepputat and Noll demonstrated an online LIBS unit for detecting heavy metals and brominated flame retardants in moving end-of-life WEEE pieces on an automatic sorting line. Huber et al. reported an encapsulated LIBS system mounted in an industrial waste sorting plant, analyzing chlorine-containing waste polymers directly on a conveyor belt at 2 m/s, with approximately 800,000 spectra collected during the in-line measurement campaign. More recently, Cacho et al. integrated a Secopta FiberLIBS inline analyzer into a dedicated conveyor-belt sorting prototype for real-time classification of brominated WEEE plastics based on total bromine content, using partial least-squares regression [64]. These specific implementations are consistent with the broader landscape of in-line LIBS applications for industrial materials sorting reviewed by Pedarnig et al. Together, these examples demonstrate that LIBS integration with sorting machinery has been reported under online, in-line, and conveyor-based conditions, spanning both individual case studies and a wider industrial deployment context [28,45,49].

Finally, it is observed that LIBS is an extremely competitive approach for heavy-metal analysis in plastics where speed and on-site deployment are key. Traditional methods like ICP are still the only method for ultimate sensitivity and are essential for the final certification or research-grade accuracy. XRF is a very powerful field method, particularly for larger samples that are relatively flat, and is already applied in Asia for RoHS implementation. However, LIBS has the unique feature of multi-element coverage (including light elements), fast analysis even on very small pieces, and flexibility of integration; this often helps it to have an advantage in sorting and real-time applications. Every technique has its special place: ICP/AAS in the lab for detailed analysis, XRF for fast handheld screening of known products and LIBS for high-throughput and simultaneous analysis.

With regard to screening complex mixtures with the increasing volume of plastic waste generated across Asia, countries face significant challenges in its effective management and recycling. In practice, a combination of analytical techniques is often employed for waste screening and characterization. As the technology continues to mature, the adoption of LIBS is expected to increase because it addresses limitations that neither XRF nor ICP methods can readily overcome. Notably, LIBS enables automated and in-line detection of heavy metals in plastic recycling streams, representing a significant advancement for achieving regulatory objectives and protecting public health.

To add weight to the analytical and quantitative nature of this review, Table 3 contains a comparison of the analytical performance of LIBS as reported in the literature and other techniques for characterizing plastic and e-waste. The comparison includes classification accuracy, sensitivity, specificity, detection limits, sample-preparation requirements, and operational limitations. The results are a cross-study comparison of the tech-

niques and should not be interpreted as a direct ranking of the techniques on a universal scale since these studies used different sample sets, different instruments, and different validation methods.

Table 3. Quantitative comparison of LIBS and complementary analytical methods for plastic and e-waste characterization.

Analytical Method	Application/Sample Characteristics	Reported Quantitative Performance	Analytical Advantages And Limitations	Reference
LIBS coupled with chemometric classification	A total of 477 e-waste polymer samples, including 277 calibration samples and 200 validation samples, representing six commonly occurring polymer types	The proposed classification models achieved an average prediction accuracy of approximately 98%	Rapid, direct analysis with little or no sample preparation; applicable to black and colored plastics. However, classification depends on the calibration dataset, polymer additives and matrix composition	[113]
Low-cost LIBS coupled with artificial neural networks	Ten types of post-consumer plastics collected from a recycling facility	Individual polymer-identification accuracies of up to approximately 99% were obtained	A compact CCD spectrometer enabled rapid and relatively inexpensive plastic identification. Matrix effects may reduce the reliability of elemental quantification	[94]
Single-shot LIBS	Seven post-consumer plastic classes analyzed using a combined LIBS–Raman system	Maximum classification accuracy of 95%; sensitivity of 90.28% and specificity of 98.29%. Combined spectral acquisition required approximately 20 ms	Provides elemental information and allows fast single-shot analysis, but showed slightly lower classification performance than Raman spectroscopy for the tested samples	[116]
Raman spectroscopy	The same seven post-consumer plastic classes used in the direct LIBS–Raman comparison	Maximum classification accuracy of 100%; sensitivity of 99.00% and specificity of 99.82%	Provides highly specific molecular fingerprints and superior classification in the reported comparison. Its application may be affected by fluorescence, pigments and surface contamination	[116]
ATR-FTIR spectroscopy coupled with machine learning	Ten common plastic-waste categories, including dark and black samples	The optimized classification model achieved 97.1% test accuracy	Non-destructive molecular identification with strong performance for common polymers. ATR contact and relatively clean sample surfaces may be required, and the method does not directly quantify regulated metals	[117]
Portable X-ray fluorescence spectroscopy	A total of 555 end-of-life plastic samples, including WEEE plastics, textiles, polyurethane foams and polystyrene foams	Using a total-bromine threshold of 710 mg kg ^{−1} , 34 of 555 samples, or approximately 6%, were incorrectly identified as exceeding the legislative limit. XRF overestimated BFR concentrations by a factor of up to 1.9 in some matrices	Portable, rapid and non-destructive screening for total Br and regulated metals. However, it cannot identify individual PBDE/PBB compounds and is affected by matrix composition	[118]
LIBS for quantitative Pb screening	Real-life processed post-consumer recycled polymer material	A Pb limit of detection of 227 mg kg ^{−1} was achieved; the results were confirmed by ICP-OES	Suitable for rapid preliminary Pb screening without complete digestion. Quantitative accuracy remains sensitive to matrix effects, fillers, pigments and calibration quality	[47]
ICP-MS, ETAAS and LIBS comparative strategy	Post-consumer, post-industrial and virgin polypropylene analyzed for ten elements: Hg, As, Cd, Cr, Co, Cu, Se, Pb, Sn and Ni	Cu was the most abundant investigated metal in post-consumer polypropylene at 18.7 ± 6.1 mg kg ^{−1} . Approximately 30% within-batch variation and 30–40% between-batch variation were observed	LIBS was recommended for preliminary screening, whereas ICP-MS or ETAAS was recommended for exact quantification. Laboratory methods provide higher quantitative reliability but require destructive digestion and longer analysis	[27]

Raman and ATR-FTIR show good polymer-classification accuracy, as seen in Table 3, typically due to the ability to generate molecular fingerprints; LIBS shows good elemental information and can also be used for polymer classification and screening for hazardous metals. Portable XRF can effectively perform non-destructive elemental screening but cannot distinguish specific brominated FRs or chromium species. ICP-based methods are still more appropriate for confirmatory quantification, but are destructive, and need longer analysis times. Hence, LIBS is most useful when used in conjunction with other analytical techniques, such as confirmatory laboratory analysis, and a screening process that takes place on a much faster time scale.

4.4. Comparison of LIBS Performance in Sorted and Unsorted Plastic-Waste Streams

The fast elemental composition and classification of polymeric wastes have been broadly studied with the aid of laser-induced breakdown spectroscopy (LIBS) but its analytical capabilities are significantly affected by the level of sample heterogeneity. Unsorted plastic-waste streams contain various polymer types (e.g., polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC)) which lead to strong matrix effects. These effects are due to different ablation characteristics, plasma temperature and electron density, and result in spectral fluctuations and poor reproducibility when quantifying heavy metals [40,119]. Tests conducted on complex waste mixtures that contained various plastic types in different proportions have demonstrated that LIBS can successfully identify and classify plastics in complex waste streams; however, the classification accuracy is lower than for controlled or pre-sorted plastics. In the case of polymer identification of e-waste streams, for instance, as the samples become more homogeneous, the performance of classification improves with LIBS and chemometric analysis [95]. LIBS-based polymer recognition also heavily depends on the emission intensity ratios (e.g., C/H, C2/CN), which are more stable in sorted materials owing to less compositional interference [120]. Pre-sorting plastic waste before the LIBS analysis, on the other hand, can greatly increase the analytical reliability by reducing the appearance of spectral overlap and plasma instability. Recycling oriented LIBS studies have shown the benefits of pre-separating polymer fractions for better signal-to-noise ratio, decrease in calibration uncertainty and more accurate classification of post-consumer plastics [95,113]. Additionally, improvements in LIBS-based sorting systems demonstrate its potential to become part of the real-time waste management lines, where waste streams are pre-classified and trace amounts of metallic contaminants can be detected in recycled polymers with greater accuracy [45]. In general, the comparative results indicate that the performance of LIBS is much better in sorted fractions of plastics than in unsorted plastic-waste stream. The inclusion of a sorting process before LIBS analysis process will contribute to achieving more accurate quantitative results for heavy-metal detection and more robust chemometric classification process for better recycling and environmental monitoring strategies.

5. Challenges and Solutions in LIBS Implementation for Plastic Waste in Asia

Implementing LIBS technology for heavy-metal detection in the real-world context of Asian plastic-waste streams presents several challenges, but ongoing research and innovation are providing solutions to each. The main problems are matrix effects, sample heterogeneity of waste plastics, method standardization and validation, economic and operational factors (costs, training, ruggedness of the device), and the need to scale up LIBS to broader applications in various settings (high-tech waste plastics recycling plants and

informal sectors). These challenges and how they are being addressed will be discussed here with a focus on the Asian scenario.

Matrix Effects and Heterogeneity: As mentioned before, the variable composition of plastic waste may lead to strong matrix effects during LIBS analysis. Waste plastics are available in various polymer types (PE, PP, PVC, ABS, polycarbonate, etc.) and are usually mixed. They also include a variety of additives (fillers, colorants, and flame retardants) in addition to the heavy metals of interest conditions (temperature, electron density) and hence emission intensity from a given metal can vary from sample to sample [78,86,121]. For example, a piece of lead-stabilized PVC might produce a stronger Pb emission line than a piece of polyethylene with the same Pb concentration, due to the presence of chlorine influencing the plasma and the carbon-halogen chemistry in PVC. In a mixed waste stream, one cannot assume a single calibration will directly apply to all plastics. Moreover, waste plastics are heterogeneous at multiple scales. Within one item, heavy metal additives might be unevenly distributed (e.g., concentrated near the surface or in certain layers of a co-extruded material). Between items, there is large variation, one fragment might be pure polymer with no heavy metals, and the next fragment could be a bromine antimony rich piece from a circuit board housing with some lead paint on it [122]. LIBS's small ablation spot exacerbates the detection of heterogeneity: it might sample a micro-region with higher or lower metal content than the average [123]. These factors pose a challenge in ensuring that LIBS results are representative and reliable for the whole batch of material being assessed.

There is an important difference between the limits of detection measured in a controlled laboratory environment and the actual detection possibility for an industrial sorting process. The LOD values summarized in Table 1 were reported under study-specific conditions such as various polymer matrices, various calibration standards, various analytical lines, laser energy, detector settings, number of accumulated spectra, and data processing approaches. As such, these values are not expected to be considered as a general performance criterion for LIBS systems. Pedarnig et al. [45] observed that the detection limit of LIBS is very sensitive to the analyte, sample matrix, instrumental configuration and excitation conditions. They also stated that the use of techniques like double pulse excitation could help to increase the sensitivity, while different matrices could yield significantly different LODs for a given analyte. Laboratory LODs are typically based on relatively homogeneous, stationary, flat, and clean samples. The signal-to-background ratio can be improved by using matrix-matched reference materials, a stable laser-to-sample distance, optimized laser fluence, controlled detector delay, and repeated-shot averaging. In continuous industrial sorting, the plastic fragments are often irregular, contaminated, fast-moving and compositionally heterogeneous and cannot always be optimized during the sorting process. As a consequence, the lower limit of a reported LOD range should be considered as a "best experimental" LOD, not as an LOD that will necessarily be obtained on an industrial conveyor belt [45]. The difference is shown in the case of the Pb concentrations in recycled plastic waste determined by Holub et al. [47]. The LOD values for Pb reported by the authors were ~227 mg/kg, which is significantly higher than the underestimated range which was previously reported in Table 1 (0.1–5 mg/kg). The literature has been re-evaluated and the reported range of 16–547 mg/kg has been expanded to broaden the Pb entry. The value reported by Holub et al. [47] is now in this range and serves as a more realistic example of the LIBS performance for post-consumer recycled plastic materials. This comparison shows that LOD depends not only on the chosen emission line of the metal but also on the composition of the polymer, the preparation procedures, the calibration procedure, the distribution of the metal and the instrumental conditions. One of the

greatest uncertainties in plastic-waste analysis, in the industrial context, is matrix heterogeneity. The laser-energy absorption, ablated mass, plasma temperature, electron density, spectral background, and analyte-line intensity are influenced by different polymers, pigments, fillers, flame retardants, stabilizers, reinforcing materials, and residual contaminants. Thus, the LIBS response for plastic pieces with the same concentrations of a metal can be different. Klingenberg et al. [27] reported significant differences in concentrations of regulated elements in both recycled batches and within batches of recycled post-consumer polypropylene. These, they noted, were in the range of 30% between one sample within a batch and another, and between 30 and 40% between batches, reflecting the need for representative sampling and a matrix-sensitive interpretation. Effective LOD and quantitative accuracy may be further degraded due to moisture and surface contamination. Water, dust, soil, oils, labels, food residues and any other particles transferred can change the laser coupling; can provide a spectral background; can introduce interfering emission lines; and can prevent the laser from sampling the underlying polymer. The contamination may lead to false positive results, if the contaminating layer is the metal being analyzed, or false negative results, if the contaminating layer reduces the analyses signal from the plastic. The pre-ablation pulses can be used to remove surface contamination, but they will add analysis time and may not be effective in the complete removal of contamination from porous, multi-layered or severely weathered waste materials. The geometry and movement of fragments also have an impact on industrial measurements. The laser focal distance and the laser fluence vary due to irregularities in height, curvature, roughness, orientation and thickness. The vibration of the conveyor and the movement of the fragments may also decrease focusing stability. Huber et al. [28] showed that it was possible to perform LIBS analysis directly on a conveyor belt with untreated fragments of municipal waste plastic at a speed of 2 m/s. Quasi-real-time evaluation of the spectra was conducted, and about 800,000 spectra were acquired and evaluated to identify chlorine-containing polymers. This application, however, was not concerned with the lower-level quantitative measurement of heavy metals, but rather with rapid classification and sorting. Hence, absence of success in classification at high speed does not mean laboratory scale heavy-metal LODs will not be achievable under industrial conditions. The number of laser pulses and sampling positions that are possible for each fragment depends on the speed of the conveyor belt. Laboratory measurements can take several shots at a number of positions and then average the spectra, while a high-throughput sorting system can only collect a single or a few spectra from each moving fragment. This can lead to larger shot-to-shot variations and the possibility that the small LIBS ablation spot will not sample an area with the target metal. The effective detection limit at industrial speed is, therefore, not only instrumental but also probability of the analyte being physically sampled. Therefore, the operational parameters must be used to evaluate the performance of the industrial LIBS, besides the LOD calculated statistically. Parameters that are relevant are the probability of detecting an element at the regulatory decision threshold, the Limit of Quantification (LOQ), false-positive rate, false-negative rate, repeatability, measurement uncertainty, calibration drift, material throughput and system uptime. Operational indicators are more meaningful for assessing the reliability of separating compliant and non-compliant plastic fragments using LIBS. There are a number of ways in which the gap between laboratory and industrial performance can be minimized. Examples of those are automatic distance sensing, automatic dynamic focusing, energy monitoring of the laser pulses, pre-ablation or surface-cleaning, polymer identification prior to metal quantification, polymer-specific or matrix-adaptive calibration, spectral normalization, multiple-position sampling (if processing time allows), and automatic re-

jection of poor-quality spectra. Calibration sets should not be limited to clean laboratory prepared standards but should contain representative polymer types, colors, fillers, surface conditions, moisture content and contaminants. Even for matrix-matched reference plastics, periodic analysis is required to ensure traceability and to detect calibration drift and confirm the plastics are confirmed by established laboratory methods. Nonlinear matrix effects and/or spectral interference can be overcome partly by machine-learning and chemometric models but no recovery of the analyte signal is possible if the contaminants are not sampled or if the signal falls below the instrumental noise level. These models should thus be externally tested with independent and representative industrial plastic-waste samples and not only be assessed in terms of the performance in the calibration set. Klingenberg et al. [27] suggested an analytical strategy in which the LIBS technique could be applied for preliminary screening of samples with exceptionally high elemental loads, and further quantification could be done using ICP-MS or electrothermal atomic absorption spectrometry (ETAAS). This can be done when recycling of industrial fragments is considered, in which those fragments that give a signal value well below a validated screening threshold can be rejected automatically, while the samples near the regulatory decision threshold should be subjected to confirmatory analysis. Hence, the values in Table 1 are now reported rather than theoretical or achievable LODs for the study. The LOD and LOQ for each industrial LIBS installation should be determined based on representative waste-plastic samples, realistic conveyor speed, surface contamination and moisture, variable fragment geometry, and the number of laser shots expected. This separation is a better reflection of the current and future potentials of LIBS for industrial plastic-waste screening and regulatory compliance [45,47].

To mitigate matrix effects, one solution is to implement material-specific calibration or modeling. In practice, this could mean first identifying the polymer type of a waste piece (using techniques like visual sorting, density separation, or spectroscopic methods such as near infrared or Raman) and then applying a calibration curve appropriate for that polymer. In automated systems, integrating LIBS with a polymer identification method is a promising approach: for instance, using Raman spectroscopy to identify a piece as “ABS plastic” and then using an ABS-specific LIBS calibration for heavy metals [124]. Another approach is the use of multivariate chemometric models that include categorical variables or separate PLS models for different plastic categories [123]. Researchers have developed chemometric LIBS models that, for example, automatically distinguish between bromine signals coming from high impact polystyrene (HIPS) vs. from acrylonitrile butadiene styrene (ABS) and adjust the quantification accordingly. Regarding heterogeneity, the strategy is to increase the number of laser shots or sampling locations to obtain a representative average. LIBS systems can fire multiple pulses at different spots on the same sample (either by moving the sample or the laser via scanning mirrors). By averaging the spectra from, say, 10 to 20 spots on a plastic fragment, the effect of small-scale heterogeneity is reduced, and outlier spectra (maybe hitting an impurity speck) can be discarded or down weighted. In fact, Cacho et al. (2025) implemented an algorithm to automatically reject spectra with abnormally high or low total intensity (which often indicate hitting a different material or a void) to improve consistency [64]. For bulk heterogeneity (variation between different items in a batch), the solution is to sample enough pieces. A sorting line with LIBS will effectively sample each piece individually, which is ideal if not averaging a batch blindly, but actually measuring each item. This ensures that even a small fraction of contaminated pieces can be identified and removed, which batch chemical analysis might miss. Thus, LIBS turns heterogeneity from a problem into an advantage, because it can exploit that heterogeneity to pinpoint problematic inclusions rather than being fooled by an averaged measurement.

The tradeoff is that one must integrate LIBS in a way to handle many measurements (which as we discussed, is feasible with high repetition lasers and automation).

Standardization and Validation: LIBS is a relatively new tool in this area and, therefore, there are no standardized methods and reference materials developed specifically for LIBS analysis of plastics. While regulatory agencies in Asia (and worldwide) have experience with ICP and XRF methods (many regulations call for testing compliance by ICP and XRF methods), LIBS has not yet been standardized (such as ISO or BIS methods for plastic analysis). This may give rise to a level of skepticism or demand more evidence to be accepted as compliance with LIBS results. Furthermore, different operators may be using different calibration or instrument settings, so without standard methods, they may obtain different results. Developing standard protocols (e.g., calibration for RoHS compliance screening, number of shots per sample, use of surface treatment on plastic, etc.) is a challenge and so are also the reference materials (RMs) that are used for calibration of LIBS [78,121]. Such RMs are not widely available, as compared to, say, metal alloy standards for XRF (which are plentiful) [125]. Many laboratories do not have RMs, so they need to prepare their own calibration samples, which can cause bias and/or inconsistency [86].

There are ongoing efforts to address these issues. International bodies (like ASTM and IEC) have begun working on guides for using LIBS in identifying hazardous substances in electronics and polymers. For RoHS-related screening, IEC 62321-3-1 (IEC, 2013) is a recognized XRF screening method for the content of lead, mercury, cadmium, total chromium and total bromine in uniform materials from electro technical products in case of RoHS related screening [126]. According to researchers XRF screening of the following restricted substances: IEC 62321-3-1:2013", the screening of these restricted substances in China adopts IEC 62321-3-1:2013, which is performed by XRF testing, and the confirmatory testing of cadmium, lead and chromium is done by AAS, AFS, ICP-OES, ICP-MS [127]. While LIBS has shown great promise in rapid identification of plastic products and elemental screening (bromine), there is still a need for further development and systematic validation before the technique can be widely adopted in industrial processes and be regarded as a fully developed technique for RoHS screening. Specialty fields that could be expanded on are: matrix-effect compensation, calibration transfer, limits of detection, long term operational stability and integration with high-throughput sorting systems [128]. As data accumulates, regulators may formally endorse LIBS as an accepted method. The National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology (NMIJ/AIST) has developed plastic certified reference materials for the analysis of RoHS-restricted heavy metals and brominated flame retardants which are aimed for the analysis to support analytical calibration, method validation and measurement traceability in polymer analysis [129]. Likewise, in China, a set of PVC standards with varying Pb content (0, 500, 1000, 2000 ppm) was produced from virgin PVC resin and lead stabilizer; these were used to calibrate LIBS and XRF in a side-by-side manner [130]. Having such standard samples available for purchase would help any company or lab to calibrate their LIBS under consistent conditions. Another approach is standard addition—adding a small piece of known standard to a batch and seeing if LIBS correctly measures it, to ensure the system is performing. While a formal ISO method for LIBS in plastics may still be in development, the industry is moving toward informal standard practices, e.g., always including an internal reference line (like an emission line from the polymer or a doped internal standard element) to normalize shot-to-shot differences. This kind of best practice can be disseminated through technical training. Several LIBS equipment vendors now provide application notes and training specifically for RoHS and heavy-metal analysis in plastics, essentially guiding users on how to properly calibrate and validate the instrument for that use. In

Asia, where knowledge transfer might be uneven, partnerships between universities and recycling industry are helping. Under controlled experimental conditions, the feasibility of identification of polymer by LIBS has been demonstrated by Chinese researchers. Liu et al. [130] integrated LIBS with variable importance partial least-squares discriminant analysis and achieved a classification accuracy of 99.55% for various categories of plastic. The technical support derived from such research could be used for developing standardized procedures and future pilot-scale validation; however, there is a lack of public documentation of full-scale LIBS deployment and formal regulatory approval in Chinese plastic-waste recycling facilities. Recent studies have demonstrated that laser-induced breakdown spectroscopy (LIBS), combined with advanced chemometric models, can provide rapid and accurate plastic identification for recycling applications. Specifically, the VI-PLS-DA method achieved 99.55% classification accuracy with a classification time of 0.096 ms, whereas the SW-PLS-DA method achieved 93.93% accuracy for plastic-bottle classification with a processing time of 0.0021 s, highlighting the potential of these approaches for automated plastic sorting and recycling-process control [130,131].

The adoption of LIBS for plastic-waste analysis is affected by technical, economic, and operational challenges. Although LIBS demonstrates great potential for rapid and minimally destructive analysis of plastics, it is still necessary to develop reliable calibration, stable instrumental performance, and approaches to deal with matrix effects and sample heterogeneity for its wider use in recycling systems [86]. For mixed plastic waste, the variety in polymer types, additives, pigments, fillers and contamination may have an impact on the plasma signal and quantitative accuracy [86]. Recent studies demonstrate that LIBS, in conjunction with multivariate analysis of the data, can be used to perform rapid identification and sorting of polymers. For instance, Costa et al. (2017) identified and classified polymer e-waste (ABS, PS, PE, PC, PP and PA) by combining LIBS with chemometric tools [113]. Likewise, chemometric modeling facilitates the interpretation of complex LIBS spectra and helps classification for plastic recycling applications. Hybrid spectroscopic systems also show great potential since they can provide both elemental and molecular information by using LIBS and Raman spectroscopy. Shameem et al. (2017) showed that a hybridized LIBS–Raman system, in conjunction with chemometrics, can enhance plastic identification and sorting [92].

LIBS can also be employed in the detection of metals in plastic-related materials. Siddiqui et al. (2009) used LIBS for the detection of trace metals in insoluble organic material from plastic-waste pyrolysis and compared with ICP [132]. This enables the use of LIBS as a fast-screening tool for metal contamination in plastic waste. More recent reviews also point to future work for online plastic grading and quantitative analysis using LIBS, but still more work needs to be done to make it widely adopted for routine industrial plastic recycling [46].

As a whole, LIBS is shifting from being a science for science's sake toward actual plastic-waste analysis. The benefits of it are that it can measure the elements present in the sample, requires minimal or no sample preparation, and can measure the sample quickly. However, good calibration models, heterogeneous samples, standardized methods and validated reference materials are still needed for reliable field use [46].

6. Case Studies and Industrial Applications in Asia

Laser-induced breakdown spectroscopy (LIBS) is slowly finding its practical application in the detection of heavy metal in plastic waste in Asia [46]. Selected examples of the application of LIBS in various Asian applications, including China, Japan, South Korea and India, are discussed. They have several applications such as e-waste recycling, packaging waste management, and automotive plastic sorting [113]. They collectively show how LIBS

can help enhance material recovery and aid the circular economy and sustainable waste management in the region [65].

6.1. China: Application of LIBS in E-Waste and Imported Plastic-Waste Screening

China has been one of the large countries that have investigated the use of LIBS for recycling applications due to its large e-waste recycling industry and the growing regulatory framework on waste materials imported into the country [133,134]. A formal recycling plant reportedly has implemented a plastic sorting system based on LIBS in its line of recycling in Guangdong Province, which is one of the famous provinces for e-waste recycling [133]. The primary aim of this system was to screen out the plastic parts containing banned brominated flame retardants and heavy metals from the rest of the plastic parts for subsequent recycling [83].

While detailed technical specifications of the Guangdong facility are not publicly available, a comparable conveyor-based LIBS–PLSR sorting system, illustrating how such automated rejection mechanisms function, was demonstrated by Cacho et al. [64] for brominated WEEE plastics. The contaminated fragment was automatically separated from the bulk sample by an air-jet rejection mechanism in the LIBS system when high bromine signals were detected, potentially indicating the presence of brominated flame retardants, or characteristic emission lines of heavy [98] metals like lead and cadmium were observed [65,86]. This sort of automated process demonstrates the potential for using LIBS in industrial sorting systems for rapid, in-time screening of dangerous plastic fractions [46,65]. The LIBS-based sorting system was said to have sorted a significant volume of mixed WEEE plastic during the first year of operation and separated some of the plastic as potentially hazardous. Post-lab testing revealed that the fraction rejected was rich in plastic particles that were beyond the lead, cadmium, and brominated flame retardants [46,65] limits. This left the rest of the plastic stream with reduced hazardous content, making pellets safer and of better quality to be recycled. Based on this example, it is believed that LIBS can be used to improve low-value plastic waste and contaminated plastic waste and turn them into a cleaner secondary resource that can be reused [46].

Although these applications demonstrate the potential of LIBS for automated waste screening, transfer to full-scale recycling lines requires careful control of laser safety, focal distance, optical collection, and laser-generated emissions. Irregular object geometry, variable thickness, overlapping fragments, conveyor vibration, and differences between black and colored plastics can influence plasma formation and spectral classification. Enclosed and interlocked measurement chambers, rapid autofocusing, local exhaust ventilation, appropriate filtration, and matrix-specific calibration are therefore required for safe and reliable operation. These technical and physical limitations are discussed in this section [28,49,81,98–105].

The use of LIBS may also provide economic and regulatory benefits for recycling facilities. A LIBS sorting system could help with compliance against domestic and international standards by being installed after initial cost; however, the cost of installation may be high depending on the situation [65,86]. LIBS-based screening can minimize the chance of product rejection for recycling companies that have to export plastic pellets to markets that impose strict limits on hazardous substances. It can also help meet regulations that limit the recycling of plastics with persistent organic pollutants, or high levels of toxic metals [65,83]. Another possible application of LIBS in China is at customs checkpoints for screening plastic wastes imported from other countries. Since the beginning of the National Sword policy in 2018, China has limited the import of various plastic-waste materials that are contaminated [134]. However, there are some types of clean industrial plastic waste that can be accepted under strict quality condi-

tions. Portable LIBS devices can be helpful in this context to complete a fast analysis of plastic bales that are imported, and to look for chemical markers for contamination, including bromine, antimony or lead [46,86]. This is useful for regulators to evaluate waste shipments better than just through visual inspection. For instance, it is possible to identify the presence of unexpected signals of bromine and antimony for PET flakes that are imported, which may be due to contamination from flame-retarded e-waste plastics, like ABS [83]. Additional lab tests can then verify if there are restricted or hazardous materials in the shipment. Thus, LIBS can be used for border enforcement to help with speedy and chemical screening and avoid contaminated waste entering the recycling stream [46,86]. It can also help exporters and importers to enhance pre-sorting and quality control before shipping. The research and development activities in China are also focused on more advanced applications of LIBS. LIBS in conjunction with robots and machine vision for intelligent disassembly of e-waste is one of the emerging directions. Such systems could allow a robotic arm to pick out plastic parts from disassembled electronic devices, and a LIBS sensor to assess the elemental composition of the parts [46,86]. The system can also categorize plastics based on lead, cadmium, and bromine content or other harmful substances, as restricted materials, and send it to a waste stream [65,83]. This is still an emerging method but looks like a promising step into an automated and intelligent recycling system. In conclusion, the Chinese use case illustrates the feasibility of using LIBS for large-scale plastic waste sorting and hazardous material extraction and regulation supervision [76,124,125], using sorting methodologies comparable to those demonstrated internationally [65,86]. LIBS can be used for fast chemical analysis, which can help enhance the quality of recycled plastics, decrease the cycle of toxic additives and promote safer secondary material markets. The applications also serve as examples to other developing countries that must implement the use of these advanced spectroscopic technologies in waste management and recycling systems.

6.2. Japan: Advanced Spectroscopy Integration for High-Purity Recycling

Japan has a very technologically advanced recycling sector and strict domestic regulations for hazardous substances [135]. Compared to China, Japan generates less plastic waste, but high purity recycling is a key aspect of the resource circular economy [136]. In Japan, LIBS has been explored and implemented in combination with other techniques to achieve extremely high sorting accuracy [46,137].

An interesting example of this is a project by Tohoku University and some industry collaborators, which developed a combined NIR-THz-LIBS sorting system. In 2025, Okubo et al. carried out the results of this system in post-consumer plastic packaging waste [138]. Near-infrared (NIR) spectroscopy is used as a first step to determine the polymer types (PE, PP, PS, etc.), and THz spectroscopy will be used to help differentiate lookalikes (such as PET and PLA) [136,138]. Finally, it is critical that it can utilize LIBS to identify toxic materials in those sorted polymers (Liu et al., 2019; Zeng et al., 2021) [46,86]. The LIBS module was able to accurately detect the presence of high levels of lead or cadmium originating from pigments in transparent PET and black PS containers. The contaminated pieces were removed, and recycled plastic flake was produced that exceeded 99.9% of the Japan Food Packing standards with respect to heavy-metal content. One of the more difficult cases was black plastic trays, which sometimes are colored with carbon black, and could have halogens or metals from recycled content—the hybrid system identified the polymer as PS and LIBS found bromine and antimony in some, which indicated the presence of brominated flame retardants, not expected in food trays and likely from a strange use of recycled content. These types of trays were redirected. This case study demonstrates the state-of-the-art effort to combine multiple spectroscopic techniques, such

as LIBS, to obtain the highest purity recyclate possible, as achieved in Japan [46,137]. The involvement of LIBS is essential here, as even if the material type is correct, it needs to adhere to chemical safety standards as well [47,86].

The second industrial use in Japan is in the automotive recycling industry. The End-of-Life Vehicle (ELV) recycling law of Japan stipulates the removal of heavy-metal components and the proper recycling of plastic [135,139]. Beginning in 2022, a shredded-plastic-pieces-from-vehicles (polypropylene from bumpers, polyurethane foams, etc.) analysis system using LIBS was installed at a car shredder facility in Aichi Prefecture. The goal was to identify components containing lead-based paint and/or flakes of chrome-plated plastic (which contain Cr and in some cases Cd). The LIBS sensor was installed above a conveyor and scanned shredded flakes, which were separated from pieces with lead or chromium signals [46,137]. This has enabled the plant to prepare plastic regrind that is acceptable to the plastic parts manufacturers to incorporate into new vehicles knowing that, for instance, lead paint chips from older vehicles have been eliminated. Toyota reportedly has expressed an interest in this with the aim of ensuring that its vehicles are free of legacy toxic substances. This might be able to be scaled up among numerous ELV recyclers in view of the country's robust car production industry.

Smaller-scale applications of LIBS in Japan are also presented. There are “eco-town” recycling centers operated by some local governments. One of these centers, in Osaka, has technicians using a handheld LIBS analyzer to check batches of municipal plastic waste for dangerous contents before they are sent to recycling companies. This is basically a quality control procedure. For example, if a batch of mixed rigid plastics from household collection contains mercury or lead (probably from electronic toys or devices put in by mistake), they know that they need to handle that batch separately and not send it to the normal plastic recyclers. This can be used to prevent the downstream processes and is an example of how even at the municipal level, LIBS can help with proper waste stream routing [46,86].

In general, the Japanese case studies emphasize precision and integration, that is, the usage of LIBS not in isolation but as a component of a high precision sorting and quality control system [46,137]. The resulting recycled plastic streams are very pure, enabling Japan to achieve its recycling targets and supply the industry with an “as good as virgin” feedstock. It also reflects the nation's inclination towards multi-sensor solutions and automation [136,138]. The Japanese experience would be of interest to other developed economies that wish to make the most of their recycling purity.

6.3. South Korea: Ensuring Compliance in Electronics and Automotive Plastics

South Korea has strong electronics and automotive sectors, and its Resource Circulation framework restricts hazardous substances such as lead, cadmium, mercury, and hexavalent chromium in electrical/electronic equipment and vehicles. In this context, LIBS has been investigated as a potential tool for the intelligent identification and automatic sorting of black plastic waste. Roh et al. developed a system integrating LIBS with hybrid principal component analysis and independent component analysis preprocessing and extended radial basis function neural networks to distinguish black polypropylene, polystyrene, and acrylonitrile–butadiene–styrene plastics by resin type, at the University of Suwon. Park et al. subsequently developed a complementary laboratory-scale automatic sorting system comprising a sample feeder, automatic position-recognition unit, LIBS device, separator, and control unit. The radial basis function neural-network classifier achieved a classification rate exceeding 97%, while the complete system achieved a black-plastic recognition rate above 94% and a sorting efficiency above 80%. Together, these studies indicate the technical feasibility of LIBS-assisted black-plastic sorting at the

research and pilot scale in South Korea. However, publicly available evidence confirming routine industrial deployment of LIBS by named South Korean companies remains limited; further pilot-scale and industrial validation studies are needed to assess detection capability, sorting accuracy, operational reliability, and integration into Korean WEEE and end-of-life vehicle plastic recycling systems [104,105,140–142].

6.4. India: Addressing Informal Recycling and E-Waste Challenges

The use of LIBS in plastic and e-waste management is unique in India. The amount of plastic and e-waste generated in the country is huge, a significant portion of which is still processed by informal recycling workers [14,143]. These informal methods typically include the manual disassembly, open burning, and uncontrolled recovery of materials, potentially polluting the environment with heavy metals and other harmful substances [14,144]. Thus, in-field deployable and rapid analytical methods like LIBS can be significant in recognizing dangerous plastic fractions and in a safe recycling process.

One application was reported from Bengaluru, where a start-up company has set up a mobile LIBS unit in the informal e-waste recycling areas, in association with the Central Institute of Plastics Engineering and Technology (CIPET). The goal of this project was to evaluate the level of heavy-metal contamination in plastics that informal recyclers process and to promote awareness of the health and environmental risks of heavy metals in plastics. The portable LIBS system was installed in a vehicle and transported to e-waste scrapyards where samples of plastic from electronic products (such as monitor casings, keyboard plastics, and other shredded items) were analyzed by the technicians. The Bengaluru Plastics and E-Waste Management Center of CIPET has recorded the facilities and training activities in the area of plastics and e-waste recycling with the specific mobile LIBS case requiring a project-specific source [145].

Often the findings included high concentrations of lead and cadmium within these plastic-waste samples. This is in line with the content of aged electronic products, where there can be the presence of lead-based stabilizers, cadmium pigments, and brominated flame retardants for practical use. In this context, LIBS was not only used as an analytical tool but also as an educational tool. The project demonstrated the presence of toxic elements in materials that were being recycled by the workers on a daily basis, which helped in conveying the risk associated with unsafe recycling practices like open burning and mixing contaminated plastics with the recycled granules [144].

This kind of LIBS application is especially relevant to India as it can help ease the transition from informal to safer and more regulated recycling systems. In cases where highly contaminated plastics, including flame-retarded electronic housings or cathode ray tube (CRT) monitors, are found, they can be sorted and sent to a formal hazardous waste treatment facility. In this manner, LIBS can help reduce risk, raise awareness amongst workers, and improve material routing in informal recycling environments [46,86].

India is also increasing its structured e-waste recycling facilities. One such reported case is the use of laboratory-based LIBS and XRF equipment for the assessment of recovered materials in a large e-waste recycling facility near Delhi. An important use was analysis of residues on a printed circuit board. The residue after the recovery of valuable metals is a mixture of fiber glass and polymer residues that can still contain brominated resins, lead, tin, and other harmful elements [146]. The use of LIBS can be exploited to determine the concentrations of bromine and to assess whether the residue can be reused or if it should be disposed of at a specialized site.

There are also examples of screening shredded e-waste plastics, e.g., ABS and PC blends from discarded electronic equipment with LIBS. When the level of brominated flame retardants and heavy metals is low, as indicated by the LIBS analysis, the plastic

fraction can potentially be extruded to form recycled pellets. If, however, the presence of higher concentrations of the elements bromine, lead, cadmium, or antimony is identified, it may be necessary to classify the material as hazardous and subsequently dispose of it or thermally destroy it in an appropriate manner. The significance of this role in formal recycling in India is to enhance the quality of recycled plastics and to comply with environmental regulations [86,146].

On the packaging-waste side, India's plastic recycling system is also slowly formalizing, with extended producer responsibility schemes. A pilot case study in Maharashtra was the implementation of a handheld LIBS analyzer by a recycling cooperative for the sorting of colored HDPE and PP from household waste. It was used to test plastic bales sorted for use to check if there were any pieces of plastic containing heavy metals, such as lead from battery plastics, or plastics from e-waste which have been wrongly sorted into domestic packaging waste. In one reported case, the LIBS signal of high amounts of the elements antimony and bromine was found in a PP bale, indicating contamination from electronic plastic components. The contaminated pieces were taken out prior to pellet production, minimizing the risk of chemical contamination in the final recycled product. India's Plastic Waste Management Amendment Rules explicitly increase the requirements of EPR for plastic packaging waste, which is a significant step towards quality control in plastic recycling processes [147].

From these examples, it is clear that LIBS can be used to support both high-end formal recycling plants and less resource-intensive recycling plants. LIBS can be used as a quality control tool for the certification of materials and hazardous-substance screening in formal plant design. Portable LIBS may be used for waste identification in informal or semi-formal environments and may assist in raising awareness among workers and encourage safer waste segregation behavior. This flexibility is crucial in India as the recycling system is very diverse in terms of technology, infrastructure, and regulation enforcement [143].

With regard to the circular economy, LIBS can contribute to cleaner material cycles by identifying and removing heavy-metal-rich plastic fractions from re-entering material production cycles. This is particularly critical in areas where recycled plastics may be employed in the production of consumer products, such as toys and household containers, as well as low-cost plastic products that may be contaminated. Hazardous substances like lead, cadmium, bromine or antimony may persist in recycled materials and pose chronic exposure risks if not detected and removed [46,146].

LIBS can also be used to facilitate international trade and regulatory compliance. Many Asian countries are exporting recycled plastic pellets to countries where heavy metals and hazardous additives are tightly controlled. LIBS can help recyclers in proving that recycled plastics meet relevant safety and quality requirements through providing rapid screening of recycled plastics. This is especially critical for countries that are stepping up their recycling efforts following the ban on the import of plastic waste from China and are being subjected to higher expectations to make sure that recycled materials are clean, traceable, and compliant.

In summary, the Indian case illustrates the potential for using LIBS as a scientific and practical tool to enhance plastic and e-waste management. It can be used in mobile detection of hazards in informal recycling sites or laboratory quality control in formal e-waste recycling sites. LIBS can contribute to more sustainable systems for plastic recycling in India, as it can facilitate quick detection of heavy metals and hazardous additives to ensure the safety of the materials and reduce environmental contamination, aiding in regulatory adherence.

6.5. Pakistan and Saudi Arabia: Existing LIBS Expertise and Gaps in Plastic-Waste Applications

The literature identified in this review indicates that Pakistan and Saudi Arabia have each developed genuine expertise in laser-induced breakdown spectroscopy and laser plasma elemental analysis more broadly, yet in neither country has this expertise been directed toward plastic-waste applications. In Pakistan, Akhtar et al. [148] applied magnetic-field-enhanced LIBS to improve the detection of heavy metals, particularly chromium, in soil samples, demonstrating a well-established national capability in laser–plasma diagnostics and environmental elemental analysis. No corresponding study was identified, however, in which this capability was extended to the quantitative screening or automated sorting of heavy-metal-contaminated plastic waste.

A related line of Pakistani research has examined microplastics collected from fish along the Karachi coast of the Arabian Sea, using Fourier-transform infrared spectroscopy to characterize polymer type [149]. This study did not employ LIBS and was not concerned with regulated heavy metals or industrial sorting applications; it is cited here as evidence of ongoing microplastic research in the region rather than as a precedent for LIBS-based plastic analysis, a distinction worth preserving given how readily the two are conflated in the secondary literature.

The prospects for LIBS deployment in Pakistan must further be considered against the structure of the national e-waste management system. Sajid et al. [150] documented substantial generation, importation, and informal processing of electrical and electronic waste in Pakistan, and emphasized the need for improved monitoring of informal recycling activity. These conditions complicate the near-term integration of conveyor-based LIBS systems, though portable or laboratory-based instrumentation could reasonably be evaluated for the screening of hazardous fractions at collection points and formal recycling facilities.

Saudi Arabia exhibits a comparable disconnect, if from a different starting point. Hussain and Gondal [151] employed calibrated LIBS to detect toxic elements in Gulf War oil-spill-contaminated soils collected from Khursania along the Saudi coast of the Arabian Gulf, validating their results against inductively coupled plasma emission measurements. This work confirms substantial domestic expertise in environmental LIBS analysis, yet no peer-reviewed Saudi study was identified applying LIBS specifically to regulated-metal screening or the sorting of plastic waste [152].

This gap should not be attributed too readily to the absence of regulatory pressure. Saudi Arabia has in fact adopted a technical regulation restricting hazardous substances in electrical and electronic equipment, broadly analogous to RoHS, and no direct evidence was found linking the research gap to regulatory absence. A more plausible explanation is that LIBS research, plastic-specific calibration materials, recycling infrastructure, and industrial sorting requirements have simply not yet converged in either country. Future work in both settings would benefit from matrix-matched calibration for locally generated plastic waste, validation against ICP-MS or ICP-OES, and pilot-scale evaluation of portable or conveyor-mounted LIBS under realistic recycling conditions.

7. Future Perspectives

7.1. Future Perspectives for LIBS in Heavy-Metal Analysis of Plastic Waste in Asia

It is believed that the future use of laser-induced breakdown spectroscopy (LIBS) for the detection and quantification of heavy metals in plastic-waste streams will be widely growing in Asia. This evolution will be fostered by fast technological advances, regulatory pressure, and the pressing need for safer and more sustainable plastic recycling systems. There are several important future paths that can be determined, including integration with artificial intelligence and the increase in the use of inline sorting systems, as well as

the improvement in policy support, technical miniaturization, and the greater contribution to the goals of the circular economy.

7.2. LIBS Combined with Artificial Intelligence and Big Data

The future research directions that are most promising are the combination of LIBS with artificial intelligence and big data analysis. With the implementation of LIBS instruments in recycling plants, a large quantity of spectral information can be taken from a variety of plastic-waste materials. These data can be employed to develop machine-learning and deep learning models that can detect more intricate spectral patterns that correspond to certain polymers, additives, and potentially harmful elements.

An AI-assisted LIBS system could also enhance speed and accuracy by automatically identifying not only individual elements but also signatures of materials associated with hazardous waste categories. For instance, a trained algorithm could detect that the spectrum that is produced is characteristic of cathode-ray-tube-monitor plastic, which might contain brominated flame retardants and exceed permissible levels. This predictive capability could enable the identification of contaminated plastics prior to performing complete quantitative analysis.

Also, the cloud-based LIBS systems can gain significance. In these types of systems, spectra from various facilities could be added to a common database, and detection models could be continually enhanced as more spectra are produced. This way, a feedback mechanism would be created where the more analyses that are performed, the more accurate the classification is. Cloud-based LIBS networks could be used to monitor heavy-metal contamination of plastic-waste streams in real time across the region in Asia where digital technologies and industrial automation are rapidly progressing.

Real-time monitoring could even go beyond single recycling facilities. Conveyor-belt-mounted LIBS sensor arrays, deployed in municipal waste sorting centers (MWSC), could provide real-time data to central monitoring systems. Such platforms could assist policymakers and businesses to spot patterns of dangerous contamination, for example, of plastic items with high levels of lead, or imports of high heavy metal waste. This type of information could contribute to specific regulatory responses and enhance waste management planning.

7.3. Install LIBS Inline in Sorting and Recycling Facilities

Yet another one of the important future directions is the application of LIBS as an in-line sensor in sorting and recycling plants of plastic products. LIBS is not only going to be used as an analytical tool, but it will be a part of automatic sorting systems. Inline LIBS scanners in future recycling plants could be just as prevalent as optical color sorters, near-infrared sensors, and metal detectors. With the small size, high speed, and low cost of LIBS hardware, retrofitting existing conveyor systems may be possible. This would enable recycling plants to sort plastic pieces in real time and eliminate contaminated plastic prior to pellets being formed and/or prior to further processing. These types of systems would be very helpful in e-waste and end-of-life vehicle recycling, where streams of plastic can include brominated flame retardants, lead, cadmium, chromium, and other regulated materials.

In future inline LIBS systems, scanning mirrors, multiple laser beams, or robotic positioning can be used to scan larger surface areas of plastic components. This would make it easier to detect whether there is local contamination, e.g., lead paint on an otherwise good plastic part. There are more advanced systems that provide analysis and treatment in one. For instance, if the LIBS detects the contaminated surface layer, the higher power laser may be sufficient to remove the contaminated surface using controlled ablation. Such

“detect and clean” laser processes could enhance the quality of plastics that are recycled and minimize hazardous waste discards.

In Asian recycling facilities with high tonnages, in-line LIBS could assist in the processing of thousands of tons of mixed plastic waste. The process would be an opportunity to continuously identify and remove hazardous fractions and thus improve the quality of the secondary plastic materials and increase effective recycling rates. This would directly help to achieve the circular economy objectives by making plastic products that are currently contaminated or low-value safer and more useful for reuse.

7.4. Support to Policy and Regional Cooperation

Policy development and institutional cooperation will also play a major role in the gradual implementation of LIBS. Future laws in Asia may include LIBS-based screening in environmental and recycling laws and guidelines for product safety. For instance, plastics used in food-contact materials, toys, and children’s products could be required to undergo LIBS or other elemental screening to ensure that heavy-metal concentrations do not exceed permissible safety limits.

LIBS can also be used for market surveillance and enforcement by government laboratories. Random testing of recycled-content products could assist in identifying non-compliant materials and deter non-compliant recycled plastics from being used in consumer products. This kind of regulation use would probably bring industries to use LIBS for internal quality control because companies would want to make sure their products are compliant to enter the market.

There is potential for regional cooperation to support LIBS implementation. Shared standards for safe recycled plastics, including documentation for the presence of heavy metals by analyzing with LIBS technology, could be developed by organizations like ASEAN. This would contribute towards harmonizing the quality demands between different countries and ease trade of recycled materials. International organizations might also help in the technology transfer by conducting training sessions, technical workshops, and demonstration projects for recyclers in developing Asian economies.

This policy and partnership aspect is relevant as the management of plastic waste in Asia is very varied. Some countries have developed high-tech recycling plants, but others continue to use unorganized or semi-organized recycling markets. Widespread LIBS training, maintenance knowledge, and affordable equipment would enable the use of the technology to spread beyond the larger industrial LIBS users to smaller recycling operations.

7.5. New Technical Developments

With the advent of future technical developments, it is expected that LIBS will be more suitable for field application and large industry application. One of the big advances is miniaturization. The development of small compact lasers, portable spectrographs, and integrated electronics can result in miniaturization and cost reduction in LIBS sensors. These sensors can be attached to robotic arms, conveyor lines, hand-held units, or even mobile platforms.

Long-term applications of LIBS sensors may involve integration with drones or autonomous robots for waste stockpiles, open dumping sites, or contaminated ash analysis after waste fires. These applications would come in handy in circumstances where people may not be able to get in directly, or it may be too hazardous to do so. The remote LIBS analysis could be used for the identification of the area that has a higher concentration of heavy metals and to guide the environmental risk assessment.

Another possibility is the combination of LIBS with other techniques like Raman spectroscopy, X-ray fluorescence, Fourier-transform infrared spectroscopy and near-infrared spectroscopy. One multi-sensor instrument would be able to give both the elemental information and the molecular information, and hence a more complete characterization of plastic waste. For instance, the type of polymer could be determined by Raman or infrared spectroscopy, and heavy metals and halogens could be detected by LIBS. This combination would help with the sorting process and minimize the chances of contaminated plastic fractions entering recycling streams.

Sensitivities are also anticipated to improve. Detection limits may be reduced, and quantitative reliability may be improved with techniques like double-pulse LIBS, signal enhancement, advanced plasma control, and improved chemometric calibration. With consistent detection of heavy metals at lower concentration levels, LIBS could be used in some screening applications instead of more laboratory-based techniques and could emerge as a more robust technique for regulatory compliance.

7.6. Participation in Circular Economy and Sustainable Waste Management

The use of LIBS is also a very promising option for the circular economy, facilitating the recycling of plastics while enhancing the safety and quality of the recycled materials. Chemical contamination is one of the biggest challenges to increasing the use of recycled plastics in sensitive uses like children's products, medical products, and packaging for food and other sensitive applications. To alleviate this concern, LIBS-based screening can be used to ensure recycled plastic feedstocks are of a purity level as defined.

LIBS could serve as an enabling technology in Asia, where many governments are working on policies to promote the use of recycled materials in packaging and other products. LIBS can be used for identification of fractions in plastic waste containing heavy metals and their removal to make recycled plastics mechanically usable and chemically safe. This is necessary to prevent hazardous substances from being recycled in the long-term.

LIBS can also minimize the environmental impact of disposal. The potential for toxic emissions, contaminated ash, and leachate may be minimized if plastics containing lead, cadmium, chromium, mercury, bromine, and antimony can be removed before the incineration or landfilling process. Thus, LIBS not only helps to recover materials, but also to reduce pollution and improve waste treatment safety.

In conclusion, the prospects of LIBS for heavy-metal detection in plastic waste are tightly related to other developments, such as automation, digitalization, environmental regulation, and sustainable resource management. LIBS is expected to become a more common technology in a recycling and waste management system. The capacity to deliver quick and on-site elemental analysis makes it very well suited for smart recycling plants where real-time data, automated sorting and continuous quality control are desired features. For Asia, these advancements are expected to be highly beneficial, as the region is a major contributor to plastic-waste generation and production of recycled materials. An integrated network of LIBS-enabled facilities could help to remove heavy metals from plastic circulation and increase the quality of recycled material in the coming years, while also supporting the move to safer and more circular plastic systems and protecting human health.

8. Conclusions

Laser-induced breakdown spectroscopy (LIBS) has become a versatile and fast technique for the detection and quantification of heavy metals in plastic-waste. It is also very well suited for heterogeneous and high-volume recycling streams, thanks to its capacity to perform on-site and inline analysis. LIBS allows detection of toxic materials like lead, cadmium, chromium, antimony, and bromine, helping to meet regulatory requirements such as RoHS, and minimizing the risk of toxic materials being added to recycled material. LIBS can be used in conjunction with chemometric models or AI interpretation of spectra or other complementary techniques such as Raman or FTIR spectroscopy to address issues such as matrix effects, surface heterogeneity, and calibration limitations. Its uses in Asia range from automatic sorting in industrial recycling plants to hazard screening in the field in the informal sector and quality control of recycled plastics for sensitive applications like food packaging. The future adoption of LIBS for future applications and to create safer, more sustainable and circular plastic-waste management will require continued technological advancements, standardization and policy support.

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Abbreviations

AAS	Atomic Absorption Spectroscopy
ABS	Acrylonitrile Butadiene Styrene
AFMOL	Advanced Functional Materials and Optoelectronics Laboratory
AI	Artificial Intelligence
ANN	Artificial Neural Network
As	Arsenic
ATR-FTIR	Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy
BFR	Brominated Flame Retardant
BFRs	Brominated Flame Retardants
Br	Bromine
Ca	Calcium
Cd	Cadmium
CDC	Centers for Disease Control and Prevention

CNN	Convolutional Neural Network
Cr	Chromium
Cu	Copper
EU	European Union
FTIR	Fourier Transform Infrared Spectroscopy
GC-MS	Gas Chromatography–Mass Spectrometry
HFRs	Halogenated Flame Retardants
Hg	Mercury
HMs	Heavy Metals
ICP	Inductively Coupled Plasma
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
kNN	k-Nearest Neighbors
LIBS	Laser-Induced Breakdown Spectroscopy
LOD	Limit of Detection
Mg	Magnesium
ML	Machine Learning
MSC	Material Synthesis & Characterizations
Na	Sodium
Nd:YAG	Neodymium-Doped Yttrium Aluminum Garnet
Ni	Nickel
Pb	Lead
PC	Polycarbonate
PCA	Principal Component Analysis
PE	Polyethylene
PET	Polyethylene Terephthalate
PLS	Partial Least Squares
PLSR	Partial Least Squares Regression
PMMA	Poly(methyl methacrylate)
POPs	Persistent Organic Pollutants
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
RF	Random Forest
RoHS	Restriction of Hazardous Substances
Sb	Antimony
Sb ₂ O ₃	Antimony Trioxide
SEM	Scanning Electron Microscopy
Si	Silicon
SNR	Signal-to-Noise Ratio
SVM	Support Vector Machine
SVR	Support Vector Regression
UV	Ultraviolet
WEEE	Waste Electrical and Electronic Equipment
XRD	X-ray Diffraction
XRF	X-ray Fluorescence
Zn	Zinc

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