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Greenness of analytical methods for isolation and identification of microplastics in environmental and food samples - A critical review

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ABSTRACT

Efforts to standardize microplastic extraction methods for environmental and food samples have often overlooked their environmental impact and sustainability. This study comprehensively reviews various analytical methods and assesses their sustainability using the Analytical GREEnness calculator. Toxic chemical usage was found to have the greatest impact, rendering in situ and chemical-free analysis the most sustainable method. Conversely, multi-step pretreatment involving chemical use was deemed the least sustainable. Selective sampling and micro/spectroscopy were identified as greener options than bulk sampling and thermal analysis, respectively. Magnetic/electrostatic separation has emerged as an optimal method for routine analysis, while solvent extraction is suitable for precise and extensive research purposes. For enhanced sustainability, it is crucial to replace, reduce, and reuse hazardous reagents. Additionally, promoting miniaturization, automation, and in situ imaging methods for routine monitoring of microplastics in environmental and food samples is essential for advancing green practices.

1. Introduction

Plastic, a crucial synthetic material in the modern world, has witnessed a substantial increase in production and utilization since 1950s [1]. Microplastics (MPs), defined as synthetic plastic particles measuring less than 5 mm, are currently considered an "emerged threat" due to their presence in nearly all environmental media [2]. The prevalence of MPs has led to their increased uptake by aquatic organisms, including fish and shellfish, which are vital food sources for humans [3,4]. In addition, numerous land-based and processed foods are also susceptible to MP pollution [5], as contamination can occur during processing and packaging [6]. Consequently, humans are inevitably exposed to MPs and their associated chemical additives. For example, research indicates that the average adult Korean likely ingest 3.1×10^{-4} g of MPs per week from 13 different food types [7].

The number of scientific papers published yearly on MPs has increased by two orders of magnitude from 2011 to 2021 [8]. Considerable efforts have been devoted to developing MP analytical methods, ranging from in-field direct analysis [9,10] to more complex laboratory methods involving multiple pretreatment steps and analytical instruments [11]. This upward trend in MP research is expected to continue, as MP analytical techniques have not yet been standardized and harmonized. However, there has been little concern regarding the safety, waste, and energy consumption of these methods [12]. As a result, intensive investigation of MPs using certain analytical methods might inadvertently generate other pollutants that could be even more detrimental [8]. For instance, classical MP pretreatment methods often involve using toxic reagents such as hydrogen peroxide (H_2O_2), Fenton's reagent, and zinc chloride ($ZnCl_2$), which can negatively impact the environment and pose risks to the safety of operators. In contrast, advanced and miniaturized techniques, including pressurized liquid extraction (PLE), microwave assisted extraction (MAE), and thermal analytical techniques have the potential to minimize waste generation and labor while possibly increasing energy efficiency. Therefore, it is crucial to assess the greenness and sustainability of different analytical methods used to determine MPs in various matrices. Such assessments are essential for developing appropriate and environmentally friendly methods for routine analysis.

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Green analytical chemistry (GAC) is a concept that focuses on reducing or eliminating the use or generation of toxic solvents, reagents, and wastes in analytical methods to protect the environment and ensure operator safety [13]. Galuszka [14] proposed 12 fundamental ethics of GAC as essential guidelines for creating greener analytical methods. Based on these principles, several metric systems such as Analytical Eco-Scale [14], National Environmental Methods Index (NEMI) [15] or Analytical GREEnness Metric Approach (AGREE) [16] have been developed to assess the greenness of analytical procedures. While Eco-Scale and NEMI include only a few assessment criteria, AGREE, one of the most widely used metrics, inclusively covers all the GAC principles and provides intuitive outputs [16]. Since the implementation of GAC in the analytical methods of MPs is becoming increasingly mandatory [8], AGREE serves as an appropriate tool for comparing the comprehensive greenness indexes of analytical procedures for determining MPs in environmental and food matrices.

To date, the evaluation of the greenness of MP analytical methods for environmental and food matrices has been limited, despite extensive efforts in reviewing the performance of sampling, extraction, and instrumental techniques [3,17]. Therefore, this study employs the AGREE calculator to conduct a systematic review of the comprehensive greenness profile of various methods utilized to determine MPs in environmental and food matrices. Additionally, the study discusses the cost of greenness to aid decision-making in selecting the appropriate MP analytical methods for different research purposes. Finally, we have addressed current challenges, proposed solutions, and outlined future directions to highlight the importance of GAC and promote sustainable developments in novel analytical methods.

2. Evaluation of the greenness of analytical methods

Most of the reviewed articles have been published within the last 5 years (2018–2023), focusing on the analysis of MPs in diverse environmental and food samples. The most widely used pretreating techniques (chemical oxidation, density separation, and filtration) and identification techniques (optical microscope, fourier transform infrared (FT-IR), and Raman spectroscopy) [3,4] were referred to as “classical methods”. Conversely, the techniques considered as “alternative methods” were described in the literature as “new”, “novel”, “alternative”, “innovative”, “modified”, “simple”, “green” or “optimized”. Default weights were assigned to all 12 GAC principles evaluated, assuming equal importance for all assessment criteria. In case of missing information for AGREE measurements, the minimal sample weights and amount of chemicals used were assumed (Table S1, Supplementary Material). The information regarding the MPs analysis methods was extracted, and their AGREE scores were determined and summarized in Table S2 and S3, **Supplementary Material**.

2.1. Overview of AGREE scores of MP analytical methods of environmental and food samples

Overall, the AGREE scores of analysis methods used for analyzing MPs in environmental and food matrices ranged from 0.2 to 0.94 (median 0.43) and 0.2–0.74 (median 0.39), respectively (Table S2, **Supplementary Material**). Food samples were further categorized into solid foods (seafood, seaweed, salt, sugar, honey, corn flour, fruits/vegetables, and meat) and liquid foods (water, sauces, and beverages). Similarly, environmental samples were divided into aqueous, solid (sediment, soil, sand, and dust), and air samples. The median AGREE score of methods analyzing liquid foods (0.48 ± 0.16) was higher than those of solid foods (0.37 ± 0.11). In environmental samples, the median score was in the decreasing order of methods for water (0.47 ± 0.18), air (0.45 ± 0.19), and soil/sediment (0.41 ± 0.19) samples. Green analysis methods were categorized as excellent (scores >0.75), acceptable ($0.50 \leq$ scores ≤ 0.75), or inadequate (scores <0.50). Consequently, the methods reported for analyzing MPs cannot be considered green, which is consistent with the findings of a previous study [8]. In the upcoming sections, the variation of AGREE scores by different matrices and methods (sampling, sample preparation, and identification/quantification techniques) will be discussed in detail based on the 12 GAC principles [14]:

1. Direct analytical techniques should be applied to avoid sample treatment.
2. Minimal sample size and minimal number of samples are goals.
3. In situ measurements should be performed.
4. Integration of analytical processes and operations saves energy and reduces the use of reagents.
5. Automated and miniaturized methods should be selected.
6. Derivatization should be avoided.
7. The generation of a large volume of analytical waste should be avoided, and proper management of analytical waste should be provided.
8. Multianalyte or multiparameter methods are preferred versus methods using one analyte at a time.
9. The use of energy should be minimized.
10. Reagents obtained from renewable source should be preferred.
11. Toxic reagents should be eliminated or replaced.
12. The safety of the operator should be increased.

2.2. Evaluation of the greenness of sampling procedure

The selection of sampling methods for MPs depends on the matrix under investigation, the minimum detectable particle size, and the research objective [17]. The impact of the sampling procedure on the overall sustainability evaluation is relatively minor, as it primarily affects the scores of the first and second principles in the AGREE assessment. There are three main sampling strategies: selective, bulk, and reduced volume [18]. Selective sampling of aqueous [19–21] and solid [9,10] samples, which entails gathering and identifying visible particles without any additional pretreatment or instrumental analysis, is considered the greenest method. However, it carries a high risk of missing smaller MPs (<1 mm) and has been rarely used in current studies [18]. Reduced volume sampling, used mainly in aqueous and air sampling, involves methods such as on-site filtration of samples to reduce the sample size, thus easing the laboratory transfer and experimental handling [22]. However, the MP size is limited to the pore size of the net or sieve. The second principle of AGREE received the highest score due to the significant reduction in sample size, which was considered as almost negligible (Table S2, **Supplementary Material**). Meanwhile, environmental solid and food samples are commonly collected in bulk and retain particles of all sizes. Solid environmental samples can be collected using grab samplers or box cores [17], while food samples can be acquired through direct capture in the wild or by purchasing them from markets. The score of the first principle in cases of volume-reduced and bulk sampling depends on whether pretreatments are necessary, varying from 0.02 for multi-step pretreatment methods to 0.06 for offline analysis without pretreatment. However, the latter is rarely employed (Table S2 and S3, **Supplementary Material**) due to the need for pretreatment to prepare appropriate samples and/or increase selectivity and sensitivity in subsequent identification and quantification. For the second principle, when sampling in bulk, the minimal amount ranged from 200 to 10000 mL (median 1000 mL), 0.005–3000 g (median 100 g), and 0.0025–1000 g or mL (median 10 g or mL) for environmental aqueous, solid, and food samples, respectively. The median minimum sample amounts exceeded 100 mg (or μL), which is not considered green [16]. Overall, selective sampling is the most sustainable method, followed by volume-reduced and bulk sampling in terms of greenness and sustainability.

2.3. Evaluation of the greenness of sample preparing methods

Laboratory pretreatment is necessary to isolate MPs from potential interferences, such as organic matter and particles of other materials. The pretreatment process involves four basic steps: drying, sieving, isolation or elimination of interferences, and filtration. The greenness score is primarily influenced by the choice and quantity of chemicals used during pretreatment. This significantly affects all principles except for the third and ninth. The information on chemicals and their amount employed in the pretreatment of environmental and food samples are summarized in Table S2 and S3, **Supplementary Material**. Selective sampling and in situ analysis confer the most favorable environmental impact, scoring from 0.77 to 0.94 (median 0.93) for environmental samples (Table S2, **Supplementary Material**). However, at least one pretreatment step was included in all reported cases of MP analysis in foods (Table S3, **Supplementary Material**). In situ analysis can be performed either by naked eyes or with the aid of modern imaging techniques, which limit the size of MPs that can be determined. Chemical-free pretreatments have the second-highest levels of greenness, scoring between 0.52 and 0.77 (median 0.69) and 0.57–0.74 (median 0.67) for environmental and food samples, respectively, which are within the acceptable greenness range according to Picó and Barceló [8]. While chemical-free pretreatments are typically sufficient for low organic matter matrices (e.g., aqueous samples and drinking water), additional pretreatment is necessary to isolate MPs from complex interfering matrices, such as solid environmental and biota samples.

Various techniques are available for separating MPs, including chemical oxidation, enzymatic digestion, density separation, extraction in lipophilic/solvent media, and magnetic/electrostatic separation. While chemical oxidation and density separation are the most widely employed methods [17], they are the least sustainable. Chemical oxidation is a process that utilizes acids, bases, and oxidants to break down or digest organic matter. The most widely used agents for this purpose were H_2O_2 and Fenton's reagent in both environmental and food samples, while potassium hydroxide (KOH) was mainly used for seafood samples (Table S3, **Supplementary Material**). Strong acids such as hydrochloric acid (HCl) and nitric acid (HNO_3) are seldom used due to possible damage to polymers [23]. The use of these chemical reagents increases waste production and poses safety concerns, such as corrosion or oxidation to operators, leading to the reduction of AGREE score for principles 7, 10, 11, and 12. Chemical oxidation can be used alone or coupled with a density-based separation method to enhance the MPs extraction efficiency. This separation, widely used for sediments, can be achieved using gravity or elutriation [24]. Examples of separating solvents reported frequently are sodium chloride (NaCl), zinc chloride ($ZnCl_2$), sodium iodide (NaI), and lithium metatungstate (LMT). NaCl, the most widely used brine to isolate MPs from environmental samples, is considered an environmental-friendly reagent, yet its density is not sufficient to float high-density MPs such as polyethylene terephthalate and polyvinyl chloride [25]. However, $ZnCl_2$, NaI, and LMT are embryotoxic for aquatic organisms, and $ZnCl_2$ is also corrosive, which demonstrates their hazardousness to the environment [26]. The AGREE scores calculated from analyses utilizing chemical oxidation, density separation, or a combination of both ranged between 0.22 and 0.50 (median 0.38) and 0.20–0.56 (median 0.35) for environmental and food samples, respectively. These median scores were the lowest among all methods reviewed, demonstrating that chemical oxidation and/or density separation method are the least sustainable. This can be attributed to the highest usage of toxic chemicals, multiple analytical steps, highest waste production, and longest experimental time (up to 10 d). For instance, several studies employed a large volume of oxidative (1–750 mL) and separating (10–31600 mL) reagents in a multi-step pretreatment (2–15 steps) (Fig. 1). Moreover, to enhance the MPs extraction efficiencies from complex solid matrices, repeated density separation [27–30] and flotation devices (froth flotation) were developed, possibly increasing waste, time, and labor. For example, the MicroPlastic Sediment Separator (MPSS, Hydrobios GmbH) [31] utilized in several studies [32–34] can generate up to 33200 mL of waste per sample [32]. In contrast, circular extraction [35] and fluidization/floatation devices [36] were designed to automatically and semi-automatically isolate MPs while allowing for the recovery and reuse of the flotation solution. Both miniaturized methods, especially the circular extraction device [35], are cost-effective and environmentally friendly, offering promising prospects for sustainable applications [37].

An alternative method for chemical oxidation is enzymatic digestion that involves the use of enzymes alone or in combination with other substances. As enzymes are not toxic, enzymatic digestion could be considered one of the greenest methods [8,25]. The uses of ethylenediaminetetraacetic acid, a surfactant (e.g., sodium dodecyl sulfate and Tween 20), and different enzymes (cellulases, proteases, lipases, chitinase, and amylases) have been reported in previous studies (Table S2 and S3, Supplementary Material). While enzymatic purification is typically accompanied by chemical oxidation and/or density-separation methods, it can reduce the reliance on oxidative chemicals (15–30 mL), thus producing less waste (Table S2 and S3, **Supplementary Material**). Although enzymatic digestion has the potential for removing soil organic matter to extract MPs, research on its use in soil media has been relatively limited because it is

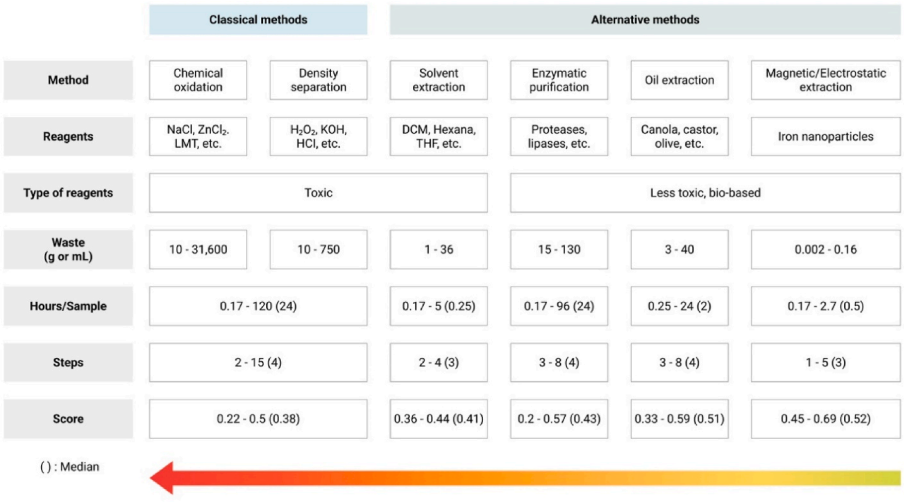


Fig. 1. Data extracted from literature for the AGREE scoring of pretreatments.

time-consuming (up to 96 h) or expensive compared to other digestion methods [37]. Enzymatic purification methods achieved AGREE scores ranging from 0.2 to 0.57 (median 0.43), which were slightly higher than those obtained from chemical oxidation and/or density separation methods. Therefore, to promote sustainable practices, enzymatic purification could be employed alone [38,39] or in combination with environmental-friendly separating agents such as NaCl [38–40], suitable for low organic matter matrices such as environmental aqueous samples, drinking water, and beverages.

Alternative methods, such as oil (e.g., canola, castor, and olive) separation and solvent (e.g., dichloromethane, acetonitrile, tetrahydrofuran, toluene, and xylene) extraction have also been reported as effective in isolating MPs. Oil separation utilizes the oleophilic properties of plastics to extract MPs from hydrophilic matrices, while solvent extraction separate MPs through either emulsification or solubilization [41]. Oil extraction is typically used as a standalone method (Table S2 and S3, **Supplementary Material**). However, for matrices with a high biomass content, it can be coupled with a chemical oxidation step with less reliance on the oxidative chemicals [42,43]. While the use of bio-based oils to isolate MPs is a greener alternative to other pretreating methods, additional usage of methanol or ethanol is required to remove residual oil from samples and filters [12]. The AGRRE scores of oil extraction methods ranged from 0.33 to 0.59 (median 0.51), which is judged greener than chemical oxidation/separation and enzyme purification methods (Fig. 1). Meanwhile, solvent extraction is an increasingly popular method [25], with the aid of miniaturized techniques such as MAE [44], PLE [45,46], and pressurized fluid extraction (PFE) [47]. These techniques have been proven particularly effective in improving extraction efficiency and reducing extraction time while enabling quantification regardless of particle size [44,45,47]. However, the use of thermal techniques, such as pyrolysis-gas chromatography/mass spectrometry (Pyr-GC/MS), often following solvent extraction, makes the overall process energy intensive. Dichloromethane is the most favorable solvent to expand the range of detectable polymer materials by both MAE and PLE, despite its potential health risks [8,25]. The AGREE scores of solvent extraction methods varied from 0.36 to 0.44 (median 0.41), indicating that they are greener than chemical oxidation/density separation methods but not as sustainable as enzyme purification and oil extraction.

Another recent promising alternative is magnetic and electrostatic separation. The magnetic separation method involves the surface modification of iron nanoparticles to functionalize them and create a hydrophobic tail. These nanoparticles can then attach to the surface of the MPs, making them magnetizable and easily separable from the sample matrix [48]. However, this method may cause fragmentation of the MPs, potentially leading to inaccuracies in analysis. The electrostatic separation method [49] takes advantage of the electrostatic difference between conductive media and non-conductive MPs. This method allows for automated and efficient removal of non-MPs from the sample but is less effective for extracting smaller MPs (<63 μm) or reducing the initial sample containing high percentages of silt and clay minerals [49,50]. Despite these limitations, magnetic and electrostatic separation methods consume less time and labor, and do not rely on potentially hazardous chemicals. The AGREE scores of magnetic and electrostatic extraction methods varied from 0.45 to 0.69 (median 0.52), indicating that they are the greenest pretreatment methods available (Fig. 1). However, the use of iron nanoparticles may pose potential health hazards, and further studies are necessary to evaluate their toxicity [51].

2.4. Evaluation of the greenness of the identification and quantification methods of microplastics

From the AGREE perspective, the use of analytical methods to identify and quantify MPs has a significant impact on the third, eighth, and ninth principles. Most studies require off-line analytical devices, resulting in a low score for the third principle. The identification and quantification of MPs is typically performed by visual inspection, either by direct observation or microscopy, depending on the particle sizes. Optical microscopy is the most widely used pre-selection method of particles suspected as MPs prior to chemical characterization (Table S2 and S3, Supplementary Material). However, optical microscopy based on the appearance of particles can be subjective and may lead to potential misclassifications of other materials as MPs. To improve accuracy, fluorescence-based methods and electron microscopy have emerged as promising tools to screen non-plastic particles more effectively. Fluorescence-based method utilizing the affinity of staining dyes towards polymers, allows for more precise screening of particles suspected as MPs under specific emission wavelengths while avoiding staining of biogenic materials [17,52]. Following visualization, chemical characterization by FT-IR or Raman spectroscopy (μRaman) are the most exploited strategies to identify the polymer types of particles (>20 μm) by comparing their spectrums with known reference spectra. While microscopy and spectroscopy methods are considered "green" due to their low energy usage (<0.1 kWh per sample) [25], they often require extensive pretreatment to remove interfering organic and biological materials, thus lowering the method's overall sustainability, although counter-staining of biogenic polymers helps lowering false-positive detection of MPs [52]. Meanwhile, electron microscopy techniques, such as scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS), are the least sustainable due to the high energy usage (>1.5 kWh per sample) [25]. SEM-EDS can provide high-resolution imaging of surface structures and elemental composition signatures that can distinguish between organic particles and MPs. Nonetheless, the application of SEM is limited as the equipment is expensive, and the procedures require significant time and effort.

Thermal analyses have emerged as an alternative to spectroscopy for the chemical identification of MPs based on the degradation products of polymers. While spectroscopy is a non-destructive method that provides information on the number, size, and shape of MPs, thermal analysis is a destructive method that quantifies the mass of MPs and nanoplastics in a shorter time, providing practical data for health risk assessment [7]. Techniques such as differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), and Pyr-GC/MS, have been proven to effectively differentiate and quantify certain polymer types (PP, PE, and PS) [53]. Moreover, complementary thermal methods such as TGA-FTIR, TGA-FTIR-GC-MS, and TED-GC-MS have also been developed to compensate for the shortcomings of each instrument [53]. Nevertheless, from the GAC point of view, chromatography methods require the highest energy consumption and high cost and generate a large amount of waste (solvents and gases used as a mobile phase). Although these techniques are not very "green", they often require less sample size and pretreatment steps. Since the pretreatment carries more weight than the choice of analytical equipment on the greenness score of the method, it is more sustainable to employ analytical methods that include greener pretreatment rather than selecting greener instruments. For instance, although micro/spectroscopy may rank greener than thermal analysis in the ninth principle, the overall sustainability of using thermal analysis in MP methods outweighs that of micro/spectroscopy, typically combined with chemical oxidation and/or density separation methods. Therefore, methods utilizing thermal analysis should be regarded as a more sustainable option, especially for routine MP analysis.

Pretreatment techniques, such as the use of a hot plate (>150 min), MAE, and electrostatic metal separator, can be more energy-intensive than instrumental techniques. While MAE and electrostatic metal separator have a potential to reduce toxic chemical consumption, thus improving the method sustainability, the use of a hot plate during oxidative or enzymatic digestion lowers the overall sustainability of the method. In addition, some studies have also reported the use of emerging technologies, such as X-ray fluorescence [54], near IR [21], and vis-Raman spectroscopy [55], in the identification of MPs. While these methods hold potential for addressing current identification challenges, their adoption may require the development of new

extraction, purification, and concentration techniques, possibly leading to increased waste generation. Therefore, the advantage of a new technique should also be evaluated with respect to its greenness and sustainability.

3. Challenges and future directions

Although previous research has discussed the advantages, disadvantages, and environmental impact of MPs analysis methods, a clear consensus on the most appropriate methods has yet to be reached. The ideal method for a study depends on its specific objectives, the minimum particle size to be analyzed, and the way of quantifying MPs in environmental and food samples. There have been only two studies focused on the efficacy and greenness of different methods [12,25]. Bellasi [12] determined the more promising protocols based on precision, reproducibility, economic viability, and environmental impact (in terms of reagent usage), while Picó and Barceló [25] provided a critical overview of analytical methodologies assessing their environmental impact using three different greenness metrics. However, these studies did not consider the variety of chemical identities, volumes, and characteristics of the reagents used or the number of steps in each method. To address this knowledge gap, we conducted a comprehensive and updated evaluation of the environmental impact of current methods analyzing MPs in comparison with the recovery rates extracted from a recently reviewed study [56] to suggest the ideal method for different research purposes. Way [56] evaluated the efficiency of various methods for isolating MPs from both environmental and food samples by reviewing 77 papers [56], which align with the scope of this study. The recoveries of all methods except enzyme purification and magnetic/electrostatic extraction (Table S4, Supplementary Material) were extracted from Way [56]. As a result, the recoveries of MPs using solvent extraction, enzymatic purification, chemical oxidation and/or density separation, and oil extraction all fall within an acceptable range (80–100%) (Fig. 2). However, their AGREE scores are mostly below acceptable (<0.5). In contrast, magnetic/electrostatic extraction is the most sustainable method, but its recovery was scattered between 45 and 103%, casting doubts on the reliable measurement. Solely based on the greenness evaluation, magnetic/electrostatic extraction coupled with staining/fluorescence microscopy would be an ideal option for routine analysis and quick screening. The high capital cost of the electrostatic metal separator [12] is another obstacle for this analytical option. Among other methods, solvent extraction is the best suited for extensive laboratory analysis that requires better quality assurance and control measures. Moreover, solvent extraction can be coupled with both thermal and spectroscopic analysis, as no significant chemical changes of polymers have been reported during the extraction process [47].

There is currently a lack of harmonization and standardization regarding methods for extracting MPs. Before the wide acceptance of suitable and greener methods, some courses of action are suggested to quantitatively evaluate the environmental impacts of current analytical methods. Since pretreatments have the most significant impact on the greenness of the overall process, it is recommended that all pretreatments, except magnetic/electrostatic extraction, be eliminated or only applied within the laboratory. When pretreatments and toxic chemicals are required for better extraction efficiency, the "3Rs" (Replace, Reduce, and Reuse) should be employed to improve the greenness of the process. For instance, toxic chemicals should be replaced with more environmentally benign reagents (e.g., NaCl, $CaCl_2$, NaH_2PO_4, enzymes, and oils). Additionally, the reduction of toxic chemical usage could be achieved via miniaturized and automated techniques (e.g., elutriation, PLE, and MAE). Moreover, toxic salts, such as $ZnCl_2$, can be refiltered and reused at least five times without losing its separating efficiency [57]. Given the growing importance of environmental sustainability, suitable and green methods have been proposed with good AGREE scores (Table S2, Supplementary Material). For example, Bellasi [12] developed a density separation method using a mixture of NaCl and sucrose, achieving a mean recovery rate of approximately 82.5% for five types of polymers. Similarly, Wenzel [58] optimized a hydrophobicity-water/air-based enrichment cell for MPs (μSEP), which achieved recoveries of approximately higher than 70% for three polymer types. In addition, recent advanced in situ imaging techniques [59–61] detected MPs with different sizes, shape, and material, while achieving the greenest score of 0.93. However, their practical application is currently limited to laboratory settings, and further research is needed to extend the applicability domain of these techniques to compensate matrix effects on imaging quality. Although further validation is necessary, these greener methods represent a promising start and should be encouraged for future use. Finally, more research is required for developing a systematic metric capable of assessing the environmental impacts of anthropogenic particles, particularly nanoplastics, in a manner that can be compared with the greenness of analysis methods. Consequently, valuable insights into the better environmental options can help policymakers, industries, and researchers make informed decisions, contributing to a more sustainable future.

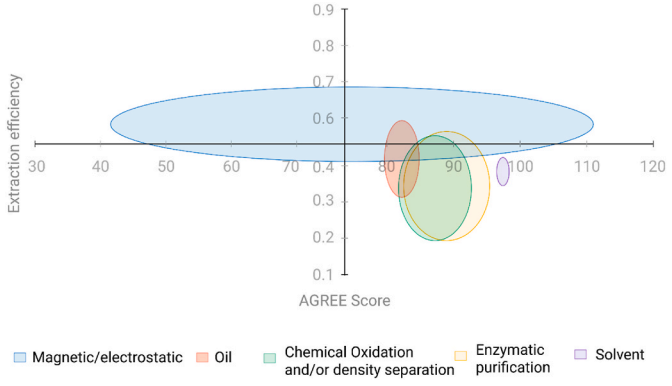


Fig. 2. Comparison between extraction efficiency and AGREE score of pretreatments.

4. Conclusion

This review evaluates the sustainability of methods for analyzing MPs in the environmental and food matrices based on the AGREE metric. The findings suggested that selective sampling and in situ visual identification are the most environmentally friendly methods. Subsequently, chemical-free and magnetic/electrostatic pretreatments achieved acceptable greenness scores. However, other methods including oleophilic extraction, enzyme purification, solvent extraction, and chemical oxidation/density separation are not considered as "green". Therefore, magnetic/electrostatic methods could be considered as a primary option for routine monitoring although the equipment cost should be lower, while solvent extraction is more appropriate for academic research purposes owing to its greater extraction recovery. As the implementation of GAC principles attracts more attention, the number of steps should be minimized to lower the environmental impacts associated with unit analytical step. This includes replacing, reducing, reusing, and recycling hazardous reagents, as well as promoting the application of miniaturizing, automating, or in situ imaging methods especially for routine monitoring of MPs in environmental and food samples. Standardized methods especially applied for routine monitoring of MPs should consider the sustainability of the proposed methods toward the goal of achieving a more sustainable future.

Author statement

Dat T. Pham: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Supervision; Validation; Visualization;

Writing–original draft preparation. Hee-Jin Park: Formal analysis; Investigation; Visualization. Dana Fahad M.S. Mohamed: Formal analysis; Investigation. Pil-Gon Kim: Formal analysis; Investigation; Visualization. Abhrajyoti Tarafdara: Formal analysis; Investigation. Jung-Hwan Kwon: Conceptualization; Supervision; Funding Acquisition; Writing – Review & editing.

Declaration of competing interest

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trac.2023.117263.

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