Hyperspectral imaging: An early systematic review of emerging applications for rapid microplastic analysis

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Authors' contributions

Corresponding author Andrea Faltynkova is responsible for literature research, selection and review of literature and drafting of an article to be submitted for publication. Martin Wagner will also review literature to be included in the review, as well as contributing with critical feedback on drafts of the final article. Geir Johnsen contributes with his expertise in hyperspectral imaging and thus assists in the development of inclusion and exclusion criteria, review the written article and provide feedback on content and structure.

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Introduction

Background and Rationale

Microplastics and their impact on the environment has become an environmental concern in both scientific communities and the public. With this emerging attention, researchers have been developing new technologies and strategies to study microplastics in natural environments, especially aquatic ecosystems. The various methods in current use include visual, spectroscopic and spectrometric techniques that range greatly in their effectiveness, efficiency and cost (Wang *et al.* 2019, Fu *et al.* 2020). There is currently no agreed standard for sampling, characterization and quantification of microplastics. This complicates comparisons between studies and results in a large but incoherent body of knowledge. Raman spectroscopy and Fourier transform infrared (FTIR) spectroscopy are the two methods which currently achieve the best results with respect to particle characterization (Käppler *et al.* 2016, Shim *et al.* 2017, Araujo *et al.* 2018). However, these widely applied methods are time consuming and/or expensive, thus rendering high-quality analyses limited in throughput and available to few research groups (Serranti *et al.* 2018). Accordingly, the methods for microplastics analysis should satisfy the following criteria: effectiveness (ability to achieve the desired task), efficiency (unit of effort per result) and cost (accessibility for researchers).

This systematic review will assess a relatively novel technology for its performance according to these criteria and, thus, its applicability for analyzing microplastics in environmental samples. Hyperspectral imaging (HSI) has recently been used for identification of both macro- and microplastics but has received little attention in methodological reviews. Our aim is to summarize the current applications of HSI as it relates to the identification of synthetic polymers from the environment. Compilation of published scientific works will allow for a critical appraisal of technical approaches and challenges, which will result in a snapshot of the limits and capabilities of HSI as it is used today. Based on this review, recommendations can be made about future research directions and standardization of methodologies.

Key concepts and definitions:

Plastics: For the purpose of this review, plastics are defined as synthetic and semisynthetic polymers. We will mainly consider so-called commodity plastics (e.g., polyethylene, polypropylene, polystyrene etc.) as these have the largest production volumes and are found most in natural environments. For an in-depth account of the definition of classification of plastic debris the reader is referred to Hartmann et al. (2019).

Microplastics: For the purposes of this review, microplastics will be defined as polymer particles with their largest dimension being less than 5 mm.

Macroplastics: For the purposes of this review, macroplastics will be defined as polymer particles with their largest dimension being more than 5 mm.

Infrared: Infrared is defined as the region of electromagnetic radiation with wavelengths longer than visible light, between 700 and 1 000 000 nm. The infrared spectrum can be divided into specific regions, including near infrared (NIR) from 700 to 2500 nm, mid-wavelength infrared (MWIR) from 2500 and 25 000 nm and far infrared (FIR) from 25 000 to 1 000 000 nm (Lindon *et al.* 2016). Additional categories such as short wavelength infrared (SWIR) are also used. SWIR lies between NIR and MWIR and is approximately from 1000 to 3000 nm depending on the source (Ben-Dor *et al.* 1997). These are general boundaries which can vary depending on the source. For example, some sources use 33 000 nm as the threshold between mid and far infrared (Koenig 2001). Most characteristic spectral patterns of plastics can be observed in the infrared region of the electromagnetic spectrum, and thus most studies use this region when analyzing polymers for identification.

Hyperspectral imager: an imaging device producing a pixel array where each pixel contains a spectrum of values. Values can be reported as reflectance, transmittance or fluorescence.

Remote sensing: Environmental monitoring using airborne or *in situ* instrument-carrying platforms and imaging technology. Surveys are often either acoustic or optical in nature and cover large surface areas.

Machine Learning: a branch of artificial intelligence which uses algorithms capable of improving automatically without explicit programming.

Objectives

The review will address the following research questions:

1. What are the performance parameters (resolution, analysis time, cost), instrumentation, and applications (sample types) of HSI used for microplastics analysis?
2. How do these parameters (of HSI) compare to current best available technologies?
3. What is the potential of HSI as a microplastic analysis tool and what themes should be the focus of future research?

Methods

Eligibility criteria

Materials to be included in this review will be restricted to those in English. Both grey and white literature will be considered without restrictions of the publication date, while books and book sections will be excluded. The literature will be classified by level (see Table 1) where level 3 is entirely excluded and level 1 is included in the full systematic review. Level 2 literature will be reviewed but not included in any systematic evaluations. Criteria for classification are here described.

HSI and its application to polymer identification will be the main subject of this review. To further narrow the scope, the polymers in question must be sampled from natural environments. The recycling industry uses HSI to sort plastic waste at waste management facilities; this application of HSI will be classified as level 3, i.e. excluded from this review (Table 1). Other exclusion criteria include the use of spectroscopic methods which do not have an "imaging" component. Spectroscopy using fiber optic cables, FTIR instruments, Raman spectroscopy or point measurement apparatus will not be included.

The body of research on HSI of polymers as environmental pollutants can be coarsely divided into two groups: remote and *in-situ* sensing, and discrete sample analysis. Remote sensing using drones, airplanes and other airborne platforms has long integrated HSI as a tool for remote sensing of the earth's surface. Detection of macroplastics floating on the ocean surface or on land is a new application which is relevant to the current review, but not its primary focus. Likewise, in-situ monitoring using HSI on other platforms such as surface vehicles or underwater drones is only tangentially relevant to this review. Literature discussing remote sensing and in-situ applications of HSI will be classified as level 2 (Table 1). Articles on this topic will be collected from database searches and reviewed for relevant contributions to the main topic of the review. No systematic review of this literature will be performed.

The focus of this review is the application of HSI to microplastics. Microplastics are defined as synthetic polymers < 5 mm in their largest diameter. This threshold is possibly most commonly applied in microplastics research despite not being universally agreed upon (Hartmann *et al.* 2019). As other size definitions are more restrictive, we keep the < 5 mm definition to be as inclusive as possible. Identification of particles < 5 mm from any medium (soil, sediment, water, air, biota) will be classified as level 1. Reviews of pertinent analytical methodologies will be treated as a level 2 resource only to evaluate the degree to which HSI is included in the broader context of microplastics analysis.

Table 1: Classification of literature acquired from database searches.

Level	Description	Themes
1	Included, full systematic review	Microplastics or macroplastics which have been analyzed in environmental samples using HSI
2	Included, literature reviewed for relevant details	Reviews of analytical methods if they include HSI, remote sensing using airborne platforms, in-situ sensing using surface/underwater platforms
3	Excluded	Application of HSI in waste management, e.g., recycling, methods including FTIR and Raman spectroscopy, methods lacking an imaging component e.g. IR spectroscopy, books and book sections, materials not in English

Information sources

Three databases are used to conduct literature searches. Peer-reviewed articles were sourced from the following databases:

1. Scopus
2. Web of Science
3. Science Direct

Search strategy

Since the use of HSI in microplastics research is still a new application, the body of work on this topic is expected to be relatively small. To ensure a comprehensive if not exhaustive search, Scopus, ScienceDirect and Web of Science were chosen as the databases for searches. Four search terms will be used in each database (Table 2) in the following combinations 1+3, 1+4, 2+3 and 2+4. After collecting all items from the described searches in Endnote, duplicates will be removed. All search results will be screened for inclusion/exclusion first by title and second by abstract by two authors independently. Further screening by full text will narrow the collected literature to a final set of materials which will be considered in the systematic review.

Table 2: Search terms and databases used for acquisition of literature

	Search term	Topic/rational for term
1	microplastic*	Studies on small plastic particles
2	macroplastic* OR “plastic litter” OR “plastic debris”	Studies on larger plastic particles, covering synonyms used in the literature
3	hyperspectral	Studies on HSI
4	“imaging spectroscopy” OR “spectral imaging”	Alternative terms for hyperspectral imaging

Study records

Data management

Endnote X9 will be used to collect and manage all literature while the literature is being acquired from databases. The online platform Rayyan QCRI (Ouzzani *et al.* 2016) will be used to compare the categorization of materials between reviewing authors. Following the selection of the final materials, an excel spreadsheet will be used to catalogue details of each piece of literature.

Selection process

The selection process will be carried out by Andrea Faltynkova and Martin Wagner. After completing searches in Web of Science, ScienceDirect and Scopus, both authors will independently screen articles first by title and then by abstract. If there are any discrepancies between the works selected by the two authors, each item will be discussed and reviewed further to come to a consensus on inclusion or exclusion. If no consensus can be reached, the third author will be consulted for input. Inclusion or exclusion from the review will be considered based on the selection criteria discussed above. The final selection of articles will be unanimously agreed upon by all authors, at which point the review can begin.

Data collection process

Data will be extracted from original sources by the corresponding author. The pdf files of the original sources, their search term and database of origin will be managed in Endnote X9. Reasons for exclusion will be noted if the full text is reviewed and ultimately deemed irrelevant. Key data items will be logged in an excel sheet as the source material is read. These data items will also be considered when synthesizing data for quantitative analysis and comparisons between published works. Data items are listed and described in table 3. Any missing data concerning instrumentation, methodological detail or data handling will be sought in supplementary material or other available documentation (e.g., user manuals, datasheets for instruments, references to previous works).

Data Items

Table 3: Descriptions of data items to be collected from the literature chosen for meta-analysis

Data item	Definition/description	Simplifications/assumptions
Reference information (author, data, journal, title, abstract)	Administrative information	n/a
a) method development or study design b) environmental sampling	Categorization as either a purely methodological study with lab work using known polymers or a study which collects environmental samples for analysis of unknown particles	Some studies can include both method development and environmental samples. If environmental samples are at all included, the source will be classified as b
Sample matrix (if applicable)	If the study falls into design category b, the sample matrix will be identified as one of the following: water (fresh or seawater), soil/sand, sediment, air, biota	Discrimination will not be made between studies evaluating bulk materials and those extracting particles onto filters
Number of polymers identified	A discrete number of polymers which serve as “classes” for identification of particles	Low-density and high-density polyethylene will be considered as one polymer
Size of plastic particles analyzed	Will be noted as a min-max range of particle size analyzed in the study	
Instrumentation (imager, light source) used	Brand, model and description of hyperspectral imagers	
Wavelength range	Range (min-max) of wavelengths detected by a hyperspectral imager given in nanometers	
Spatial resolution	Denoted as pixel pitch: the distance from the center of one pixel to the center of an adjacent pixel	Can be estimated or calculated from instrumental details if not explicitly given
Spectral resolution	Given in nanometers, the sampling rate across a range of wavelengths	
Limit of size detection	Smallest particle size detectable by the given instrumental setup	If not explicitly described, will be considered synonymous with spatial resolution
Data handling strategy	Multivariate statistical method to analyze hyperspectral data and classify pixels by polymer	
Processing time	Time used per one sample	Sample size/medium may vary
Cost of instrumentation	Cost of hyperspectral imager used, not including hours of work	If not explicitly mentioned, retail cost of instrumentation will be used

Outcomes and prioritization

For the purpose of this review, the outcomes are synonymous with the data items listed in table 3. The discussion of these data items and how they compare to best available technologies will be the main outcome of this review. For assessing the performance of other technologies, reviews will be used. Additional outcomes include assessing how remote sensing applications of HSI can contribute to the development of micro-HSI and introducing HSI as an analytical technique to the broader community of microplastics researchers.

Risk of bias

Due to the relatively small body of work addressed in this review, the risk of publication bias, meta bias or other individual biases cannot be assessed. HSI for microplastic analysis is a developing field and most studies are thus exploratory in nature. Accordingly, there will be no specific strategy for the analysis of bias.

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