Journal of Environmental & Earth Sciences
https://journals.bilpubgroup.com/index.php/jees

REVIEW

Detecting Plastic Pollution in Aquatic Environment Using Remote Sensing Technology: Cost-Saving Method in Pollution and Risk Management for Developing Countries

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ABSTRACT

One of the crucial elements that is directly tied to the quality of living organisms is the quality of the water. However, water quality has been adversely affected by plastic pollution, a global environmental disaster that has an effect on aquatic life, wildlife, and human health. To prevent these effects, better monitoring, detection, characterisation, quantification, and tracking of aquatic plastic pollution at regional and global scales is urgently needed. Remote sensing technology is regarded as a useful technique, as it offers a promising new and less labour-intensive tool for the detection, quantification, and characterisation of aquatic plastic pollution. The study seeks to supplement to the body of scientific literature by compiling original data on the monitoring of plastic pollution in aquatic environments using remote sensing technology, which can function as a cost saving method for water pollution and risk management in developing nations. This article provides a profound analysis of plastic pollution, including its categories, sources, distribution, chemical properties, and potential risks. It also provides an in-depth review of remote sensing technologies, satellite-derived indices, and research trends related to their applicability. Additionally, the study clarifies the difficulties in using remote sensing technologies for aquatic plastic monitoring and practical ways to reduce aquatic plastic pollution. The study will

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ARTICLE INFO
Received: 2 April 2025 | Revised: 24 April 2025 | Accepted: 28 April 2025 | Published Online: 12 June 2025
DOI: https://doi.org/10.30564/jees.v7i6.9315

CITATION
Mugudamani, I., Oke, S.A., Ikrema, H., 2025. Detecting Plastic Pollution in Aquatic Environment Using Remote Sensing Technology: Cost-Saving Method in Pollution and Risk Management for Developing Countries. Journal of Environmental & Earth Sciences. 7(6): 395–413. DOI: https://doi.org/10.30564/jees.v7i6.9315

improve the understanding of aquatic plastic pollution, health hazards, and the suitability of remote sensing technology for aquatic plastic contamination monitoring studies among researchers and interested parties.

Keywords: Remote Sensing; Plastic Pollution; Water Sources; Micro-and Macro-Plastics; Aquatic Environment; Risk Management

1. Introduction

The survival of all known life forms depends on water, a scarce and valuable resource [1]. Lagoons, streams, dams, rivers, and seas are examples of water resources that are crucial for aquatic life and human well-being [2]. They are essential resources for aquatic habitation, reproduction, domestic use, economic productivity, leisure, agricultural endeavours, and industrial growth [3]. Since plastics have short-lived or single-use uses, they are frequently thrown away as waste [4], making them a major source of pollution for water which is an essential component of life [5]. Plastic waste is a major environmental issue, especially in countries with emerging and developing economies [6]. An estimated 370 million tonnes of plastic were produced worldwide in 2019, with Asia accounting for the majority at 51%, America at 23%, Europe at 16%, Africa at 7%, and other independent states at 3% [7]. Plastics wind up in the aquatic environment as a result of inadequate waste management techniques like unregulated open disposal of waste, littering, fishing, shipping, and other industrial operations [8]. According to Iskakova et al. [9], plastic contamination is the amount of plastic particles and products in the environment that negatively affects people, ecosystems, and natural habitats. Worldwide release of plastic waste is projected to be 400 million tonnes annually, and if left unrestrained, production rates are predicted to double over the next several decades [10]. Every year, over 10 million tonnes of plastic fragments end up into the aquatic environment [11].

Notwithstanding the fact that there are thousands of different kinds of plastic polymers, substances such as polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polyurethane (PUR), polyterephthalate (PET), and polystyrene (PS) dominate the market and the litter found in aquatic environments: polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polyurethane (PUR), polyterephthalate (PET), and polystyrene (PS). These substances together account for about 80% of the overall amount of plastics produced [6]. These plastic waste materials (macroplastics) may take thousands of years to decay once they are in the environment, but through the photo-oxidation process they eventually fragment into smaller pieces that are below 5 mm in size (micro-plastics) to a few nanometres (nano-plastics) [12]. In addition to seriously harming aquatic life, plastic contamination also has a deleterious effect on human health and impacts the travel and tourism sector [13]. It is projected that over 16,000 diverse chemicals are in plastic materials and thus in plastic waste [14], with approximately 4,200 of them being toxic [15]. They pose serious problems for aquatic ecosystems because tiny plastic particles are easily consumed by aquatic life, changing hormone levels, affecting tissues, metabolism, the neurological, reproductive, and respiratory systems, and potentially causing death [16–18]. Several plastic contaminants are recognised to be endocrine disruptors [19]. Aquatic organisms that consume microplastics run the risk of causing a gradual build-up of bioaccumulation and concentration increase in the food chain, which is harmful to both humans and animals [20]. Certain plastics can cause allergies, asthma, and abnormalities in living things [21]. Additionally, plastic pollution costs the world's shipping, fishing, and tourism industries money [22].

In aquatic environments, research and mitigation of plastic pollution are essential due to the effects on environment, organisms, and human health [9]. These can assist in creating efficient plans for managing, preventing, and monitoring plastic pollution in various aquatic environments [20]. Traditionally, floating aquatic plastic pollutants are identified via in situ spatial and temporal sampling surveys, with visual census for macro-plastics and manta trawl sampling for micro-plastics being the main methods to monitor plastic pollution [23]. Furthermore, for physiochemical properties determination, in situ water samples are collected at various depths using boats [24]. Notwithstanding the fact that these techniques are always necessary to provide accurate information about the study area, they are frequently costly, timewasting, and have limited coverage [25,26]. These elements fuel the pressing need for improved aquatic plastic pollution detection, characterisation, quantification, monitoring, and tracking at the local and global scales [27]. For the quantification and characterisation of aquatic plastic pollution, remote sensing technology offers a promising new and less labour-intensive tool that can be used as a cost-saving approach to water pollution and risk management in many developing nations [28].

Remote sensing is a very cost-effective approach used in a variety of studies [29]. Because of its wide coverage and regular monitoring, it is one of the instruments required for the detection of aquatic plastic pollution [30,31]. Large areas are covered by satellite sensors, which are becoming more and more free and capable of capturing images almost instantly [32]. Remote sensing that gathers multi- to hyperspectral imagery has recently begun to demonstrate extensive possibility for detection of aquatic plastic pollution [33–36]. Satellite images such as Sentinel-2, WorldView-2, Landsat, SAR, etc. can be used to identify plastics in aquatic environment [33,37–39]. Using Sentinel-2 imagery, Topouzelis et al. and Themistocleous et al. successfully detected huge plastic targets in coastal zones [40,41]. Based on the differences in spectral reflectance of various materials, a number of researchers have classified floating pollutants in aquatic environments [42–44]. Plastic waste has undoubtedly exacerbated environmental pollution, and given that remote sensing technology is applicable in aquatic plastic pollution detection, taking advantage of this existing technology should be considered, as it may serve as a cost-effective method in water pollution and risk management for developing countries [28].

To date, there has been insufficient work on the detection of plastic pollution in aquatic environments using remote sensing technology, particularly in developing countries. However, none of them have ever attempted to offer an all-inclusive review of plastic pollution, including types, sizes, chemical properties, and health risks, as well as the use of remote sensing technologies. The majority of them concentrated on specific elements of either emphasising remote sensing technologies or plastic pollution. Therefore, the categories, sizes, characteristics, sources, potential hazards, and use of remote sensing technology in plastic pollution detection must all be covered in a thorough review that provides a comprehensive picture of aquatic plastic pollution. The scope of this work is to:

(1) Review the available literature on aquatic plastic pollution, categories, sources and distribution.

(2) Review the chemical characteristics and associated health risks of plastic pollution.

(3) Discuss the types of remote sensing technologies and satellite derived indices available for monitoring of aquatic plastic pollution.

(4) Provide research trends and challenges in application of remote sensing technologies in aquatic plastic contamination monitoring.

(5) Discuss strategies for minimisation of the aquatic plastic pollution.

2. Aquatic Plastic Pollution

2.1. Plastic Pollution: Concept, Definition and Sizes

Often composed of polymers, plastics are synthetic or semi-synthetic materials that are adaptable and can be moulded into a variety of shapes [16]. They are composed of synthetic organic polymers that find extensive use in a variety of products, including construction materials, medical supplies, food packaging, apparel, water bottles, and electronic devices [45]. There are two categories of plastics: thermosetting and thermoplastic. Through a process known as curing, a soft solid or liquid prepolymer (resin) is permanently hardened to create thermosetting plastics, which have a cross-linked arrangement that assures high mechanical strength, thermal stability, and corrosion resistance [46]. Thermoplastics, which include polyethene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polyethene terephthalate (PET), are a class of polymers that can be softened by heating and then processed using techniques like extrusion, injection moulding, thermoforming, and blow moulding [47]. As a result of their affordability and durability, plastics are produced at high rates by humans [48].

Although plastic is a fantastic material that contributes to economic development and synthetic modernity, it is known as plastic pollution when it is disposed of carelessly and unethically in any environment [16]. Iskakova et al. defined plastic pollution as the presence of plastic products and particles in the environment that harm ecosystems, natural habitats, and humans [9]. Plastic contaminants are categorised on the basis of their size: macro-plastics (over 20 mm), meso-plastics (between 5 and 20 mm), micro-plastics (below 5 mm), and nano-plastics (below 1 μm) [49,50]. Because plastics are difficult to break down, they pose a special threat as pollutants. They consist of a range of substances, including polymers, plasticisers, and dyes, which are linked to numerous environmental and health problems because of their incredibly slow natural biodegradation and the discharge of hazardous elements [51]. In addition to seriously harming living organisms, plastic pollution may have effects on the travel and tourism industry [13]. The outflow of plastic pollutants into the environments is taking place at an unparalleled amount, posing substantial tasks to waste management for intensifying populations, particularly in developing nations, necessitating the need for cost-effective methods in water pollution monitoring and risk management [52]. It is worth noting that, smaller plastic particles (micro-plastics) might be challenging to resolve with the usual spatial resolution of satellite data, while larger ones (macro-plastics) are easier to detect because they have a more noticeable optical signature that helps them stand out from the background [49,50].

2.2. Categories of Plastics in Aquatic Environment

Plastics are classified into different types based on their constituents and the materials used in their production [53]. To date, a wide variety of plastics have been synthesised. Nonetheless, polyethylene terephthalate, polypropylene, polystyrene, low-density polyethylene, high-density polyethylene, and polyvinyl chloride are the most often utilised plastics [47].

The plastic known as polyethylene terephthalate (PET) is smooth, transparent, and comparatively thin. It is one of the most commonly used thermoplastic polymer resins in the polyester family, and it is used in manufacturing, clothing fibres, and food and liquid containers. This type of plastic is thought to be anti-inflammatory and anti-air [53,54]. High temperatures must be avoided to stop the leaching of harmful additives like phthalates, antimony, and acetaldehyde. Additionally, PTEs are made to be used just once [45].

The thermoplastic polymer known as high-density polyethylene (PE-HD) is made from the monomer ethylene. They are more appropriate for a variety of uses, such as cutting boards, pipes, and containers, due to their strength, resilience to heat, and resistance to chemicals. They are also a key component of many types of plastic grocery bags, toys, milk containers, detergent bottles, refrigerators, and other items [45,53].

Polyvinyl chloride (PVC) plastics are high-strength thermoplastic materials. It is mostly utilised in construction materials, electronics, packaging, and health care due to its affordability, durability, and chemical resistance. Additionally, toys, furniture, shoes, and other consumer goods use it [55]. Environmental issues are brought up by its manufacture and disposal, including the discharge of hazardous chemicals like as phthalates, dioxins, BPA, and heavy metals [45].

Plastics made of low-density polyethylene (LDPE) are regarded as being lightweight, pliable, and soft. Their low temperature flexibility, toughness, heat resistance, and corrosion resistance are well known. These plastics are mostly used to package food, milk, and beverages because they contain no components that are harmful to human health [53].

Plastics made of polypropylene (PP) are thermoplastic polymers with superior mechanical, flame, and gas and water permeability resistance as well as high heat distortion temperature. Its uses span a wide range of industries, including food containers, textiles, automobile bumpers, industrial pipes, medical devices, and electronic gadgets [47,55].

Polystyrene (PS) is a synthetic polymer derived from styrene, an aromatic hydrocarbon. It can be solid or foamed and is used in a variety of applications, including packaging, insulation, and consumer products [53]. It is a type of petroleum-based plastic that contains benzene, a carcinogen to humans [56].

A class of thermoplastic polymers with carbonate groups in their molecular structures is known as polycarbonate (PC) plastics. Reusable bottles and other consumer goods are packaged with polycarbonates. Because of their strength, durability, and optical transparency, they can be used for a variety of products, including roofing materials, bulletproof glass, and safety goggles. Because polycarbonated plastics contain the toxic BPA, their use has significantly decreased [45].

These plastics can be identified using remote sensing methods because of their distinct chemical makeup, especially the way they absorb light at particular wavelengths. By examining the reflected or emitted light, these spectral characteristics which frequently involve absorption features in the visible and near-infrared to short-wave infrared regions of the electromagnetic spectrum make it possible to identify plastics in aquatic environment [53–55].

2.3. Sources and Distribution of Plastics in Aquatic Environment

Plastic pollution in water sources can emanate from numerous sources and manifest itself in different ways. Both land-based (such as littering, stormwater discharge, industrial operations, wastewater effluent, solid waste disposal, and landfills) and sea-based (such as commercial fishing, recreational boating, and sea exploration) are sources of plastics found in aquatic environments [4]. One of the possible causes of plastic pollution in aquatic environments is the unlawful disposal of waste from domestic and commercial operations. During rainy seasons, these unlawfully dumped wastes may wash into stormwater drains, where they may be released straight into a nearby stream and ultimately into the ocean [57]. If industrial products, like plastic pellets, accidentally spill during production, processing, transportation, and handling, or are disposed of illegally, they could end up as aquatic pollutants (**Figure 1**) [58].

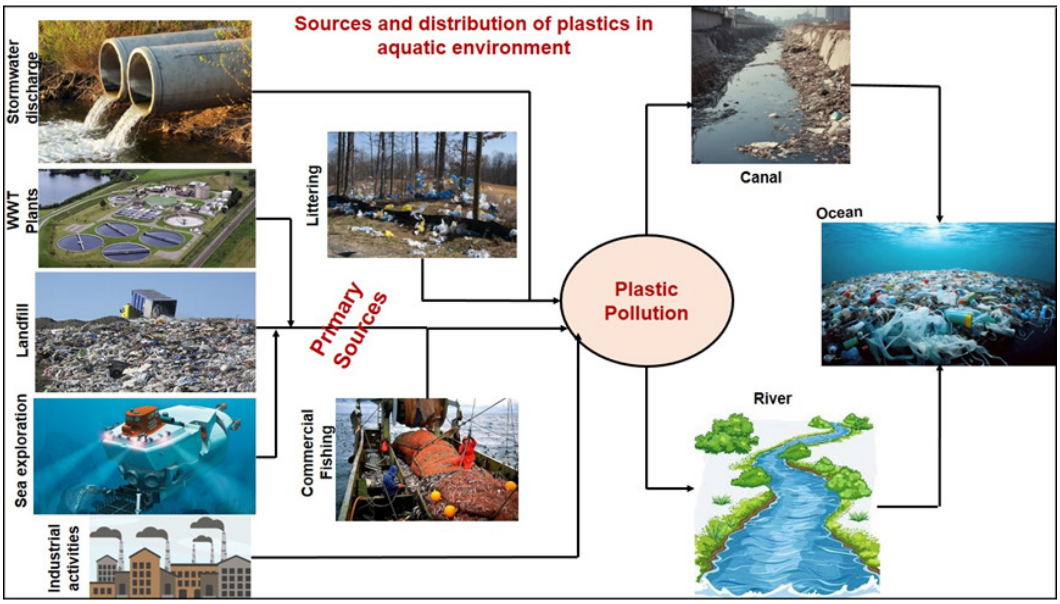

Figure 1. Sources and Distribution of Plastics in Aquatic Environment.

Micro-plastic traces may be introduced into neighbouring streams by wastewater treatment plant effluent releases, and these traces may eventually find their way into the oceans [59]. Pawar et al. claim that runoff from landfills near rivers or along the coast may introduce plastics into the aquatic environment [60]. When commercial fishermen are unable to repossess fishing equipment or throw fishing gear or other waste overboard, they create aquatic pollutants such as bags, household waste, gillnets, lines, and ropes, among other things [61]. Activities like marine exploration may be a contributing factor to marine pollution as a result of the intentional or unintentional release of debris like electronic devices, plastic bags, hard hats, storage drums, etc. [11]. Bags, food packaging, and fishing gear are examples of trash that boaters may throw overboard [60]. Aquatic debris can emanate from numerous sources, including ships, boats, and offshore industrial platforms. These sources could include careless littering, unlawful disposal, or inadequate waste management procedures [62].

Streams and rivers carry pollutants to the coast, causing the ever-increasing issue of aquatic plastic pollution [63]. The pollutants are subsequently carried by ocean currents to isolated locations, where it might take centuries for them to decompose. Unavoidably, a portion of the growing quantities of post-consumer plastic materials gets past the recycling and waste streams and ends up in the oceans [57,64,65]. The oceans serve as the final destination for the world's plastic waste. Ocean tides play an important role in scattering plastics over long distances, resulting in widespread contamination of marine environments. Furthermore, the seawater salt may affect the physicochemical properties of micro-plastics, possibly prompting their behaviour and interactions with marine organisms [66]. Aquatic organisms' consumption of micro-plastics poses environmental problems for both freshwater and marine ecosystems, potentially resulting in gradual build-ups and concentration increase within the food web [20].

2.4. Chemicals Characteristics and Potential Risks of Plastics in Aquatic Environment

The manufacturing process of plastics and potential additives can involve chemicals that are toxic or pose environmental concerns [67]. Plastics are mass-produced with several chemicals and additives like Di (2-ethylhexyl) phthalate used as plasticiser; nonylphenol used as antioxidants, stabilizers, and plasticizers in the rubber and plastic industry; bisphenol A (BPA) which serves as a precursor and stabiliser; triclosan which is a biocide and polybrominated diphenyl ethers (PBDEs), polybrominated biphenyls (PBBs), polybrominated phenols (PBPs) which acts as flame retardants in the fabrication of electrical appliances [68]. Additionally, plastics have been shown to serve as carriers of chemicals and hydrophobic organic pollutants like organochlorine pesticides, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons, as well as inorganic pollutants like heavy metals that are absorbed from the environment [13]. Chen et al. stated that numerous chemicals found in plastics have been connected to possible health hazards [69]. Due to their high stability, plastics have the prospect of accumulating and harming human health over time [70,71].

These plastic particles can evade the human defence system and cause genotoxicity and cytotoxicity by entering blood vessels and forming a protein-plastic complex [72]. Generally, exposure to plastic can affect growth, behaviour, histopathology, sex hormones, reproduction organs, metabolic alterations, and iron transport [18]. Because plastics take decades to decompose into micro- and nanoparticles that impact the aquatic environments and food web, aquatic plastic contamination is in particular problematic [21,73,74]. BPA, a chemical found in plastics, is thought to raise the risk of endometrial hyperplasia, obesity, metabolic diseases, polycystic ovarian syndrome, breast and prostate cancer, and multiple miscarriages [75]. Nonylphenol, phthalates, and flame retardants are considered endocrine disrupting substances that can affect the hormonal system of many different organisms [9,67].

3. Remote Sensing Technology in Aquatic Plastic Pollution Monitoring

Aquatic plastic contamination is one of the universal ecological problems of our time. The aquatic ecosystem is being harmed by the annual increase in aquatic plastic pollution. Accurately and promptly determining the sources of plastic entering water sources, locating its accumulation sites, and monitoring the dynamics of waste movement are all essential to effectively combating this kind of pollution. In light of this, remote sensing technology has become a viable and useful instrument for tracking aquatic plastic pollution [76]. Adamo et al. define remote sensing as the process of gathering and analysing data about an area (an aquatic environment) or an object (plastic waste) without having direct physical contact with it [77]. It entails using tools or sensors to record the spatial and spectral relationships of objects that can be seen from a distance, then evaluating and using the data. Passive and active remote sensors are the two varieties of remote sensing imaging systems. These two kinds of sensors detect light, which is subsequently converted into numerical values that are pertinent to the targeted object's description [31].

Passive remote sensors, such as the passive microwave sensor (TMI) and the moderate resolution imaging spectroradiometer (MODIS), detect radiation emitted or reflected by the object or its surroundings. Passive sensors most commonly measure radiation from reflected sunlight and microwave emissions [77,78]. Active remote sensors, such as RADAR, LiDAR, LADAR, and thermal infrared sensing (TIS), generate their own electromagnetic energy, which is transferred from the sensor to the targets, interacts with the targets, produces a backscatter of energy, and is recorded by the remote sensor's receivers [27,79]. Although passive and active remote sensors exist, the majority of advances in remote sensing for aquatic plastic pollution monitoring have been made using passive remote sensing techniques [27], which will be the focus of this subsection. More information on the potential and limitations of passive and active remote sensors can be found in the work of Adamo et al. [77].

3.1. RADAR

Synthetic aperture (SAR) is an active remote sensing technology that employs microwaves with wavelengths of a few centimetres and operates at optical wavelengths. Both of these sensors use the echoes' time delay to determine the distance between the instrument and the target. One of the primary advantages of SAR is the ability to capture fine and detailed images through clouds. It can function in all lighting and weather conditions [79]. As a result of its sensitivity to surface roughness variations, it can be used for aquatic monitoring. SAR can detect changes in surface roughness caused by the presence of plastic litter, which can help identify areas of pollution. It can be applied to sense anomalies in the backscattering of the water surface, which, with adequate understanding of the scene under surveillance, can lead to the discovery of floating plastic pollutants [27]. Amongst the presently accessible SAR systems, spaceborne SAR sensors can offer sub-metre spatial resolutions [80]. SAR generates 2D image data of the study area by utilising a side-looking imaging geometry. This SAR imagery is generated from the response of an emitted pulse of energy with water sources. The produced information is frequently offered as two-dimensional intensity images that offer data on the quantity of backscattered signal [81]. SAR should be applied in conjunction with additional sensors or ground observations to directly differentiate plastics from other floating materials [27]. Many research works have recognised the use of the SAR method to detect different types of plastic materials [40,82,83].

3.2. Airborne Laser Scanning

LiDAR, or light detection and ranging, is another name for it. Using a pulsed laser, this active remote sensing method can be used to gather data on a size of the target's geometrical-spatial and chemo-physical properties. This active remote sensing method creates intricate 3D models of landscapes by measuring the duration and intensity of backscatter from three-dimensional targets on the surface of the Earth using laser pulses [84]. Since it is an active method, it can be applied day or night and, theoretically, can also offer observations via aerosols and thin clouds [85]. A LiDAR sensor, an inertial measurement unit, and a worldwide navigation satellite system (GNSS) receiver are installed on an aircraft during airborne laser scanning (ALS). After receiving the return signal, ALS systems which are usually grounded on a wavering mirror and scanning patterns measure the signal's travel time and correlate each return pulse with the GNSS time and scan angle at which it was transferred [86]. It is possible to convert the travel time to height and then to distance. In the target area, the ALS method can generate georeferenced 3D point clouds [84]. Single-wavelength single-pulse linear-mode LiDAR and new multispectral ALS systems (such as Geiger-mode LiDAR and single-photon LiDAR) that combine LiDARs at various wavelengths are the main foundations of ALS systems. The main benefit of this method is that the obtained data are shadow-free and unaffected by lighting conditions. Since the laser beam (in case it emits in the blue-green spectral range) penetrates the water more deeply than natural sunlight, using a laser in the UV-VIS range as a source ensures information from both the water surface and the water column. Thus, submerged plastics can also be detected using the LiDAR technique [87]. Dependent on the technical requirements of the LiDAR system being applied and the signal analysis method, the range of procedures that can be evaluated with a LiDAR system provides the opportunity to obtain various kinds of information [27]. Thus, there is a lot of promise for multispectral ALS systems to raise the level of automation in mapping [79]. Ge et al. detected and categorised marine pollutants, including plastics, using a 3D LiDAR scanner on the beach based on their shape characteristics [88].

3.3. Thermal Infrared Sensing

It is a technology that detects and measures thermal radiation using specialised sensors like the Landsat thermal infrared sensor (TIRS). The mid-wave infrared

(MWIR, 3–5 μm) and long-wave infrared (8–14 μm) are the atmospheric windows in thermal infrared (TIR). In these cases, TIR sensing could supplement visible and short-wave infrared (VIS-SWIR) measurements for clear (dark-coloured) plastic materials that are transparent (dark) in the VIS-SWIR spectrum but opaque (bright) in the TIR spectrum. Contrasting spectral remote sensing in the VIS-NIR-SWIR, TIS does not require exterior radiance and can be carried out at any time of day or night. TIS is only applicable to plastics floating on the surface of water because TIR radiance is absorbed in the first microns of water [89]. This approach cannot identify subsurface plastics, with the exception of dark coloured plastic particles that may be near the surface and warm the surrounding waters. TIS for floating plastic pollutants is grounded on thermal emissivity and surface temperature variances between water and plastic. Water has a thermal emissivity (reflectivity) close to one (zero), while plastics have a lower (higher) value [27]. Garaba et al. were able to detect and characterise plastics and natural materials in the laboratory using spectral absorption features in TIR reflectance [90], but this has not yet been applied to air or space.

3.4. MiDAR

This newly patented active multispectral remote sensing system uses high-intensity structured narrowband laser radiation to define an object's nonlinear spectral reflectance and time-resolved fluorescence response spanning the ultraviolet, visible, and infrared bands [91]. For the purpose of detecting macro-plastics, it is composed of a bistatic active optical transmitter and passive receiver [27]. MiDAR is capable of operating in extremely light-limited environments and performing fast underwater multi/hyper-spectral spectral imaging. Additionally, it has fluid lensing compatibility, which helps to intensify the passive fluid lensing tactic's depth range for utilisation in deep aquatic remote sensing applications. With a signal-to-noise ratio between 10 and 103 times greater than passive airborne and spaceborne remote-sensing techniques, it can remotely sense reflectance at fine spatial and temporal scales, permitting for high-frame rate multispectral sensing. In order to sense, and typify aquatic macroplastics (above 1 cm) on the surface, shallow seafloor, and coastal zones, a 13-band active sensing tool was industrialised. MiDAR instruments use UV and other wavelengths to induce fluorescence in plastic materials, which is then detected. Its 13 different spectral bands, which range from 365 to 880 nm, comprise a number of UV bands that are specifically made to be sensitive to the different fluorescence signatures found in aquatic pollutants. When combined with fluid lensing, MiDAR can extend its detection range to deeper water and underwater, allowing plastics to be detected even when submerged [92]. According to Goddijn-Murphy et al. [27], these methods are not yet suitable for imaging across the visible optical regime because of serious restrictions in the efficiency and chemistry of narrowband laser-diode emitters.

4. Satellite-Derived Indices for Aquatic Plastic Classifications

Mukonza and Chiang stated that indices are used as classifier input features in plastic pollution monitoring programs [93]. The likelihood of separating plastics from other aquatic debris is increased when indices are used as input features [94]. Satellite-derived indices for aquatic pollution monitoring include modified NDWI (MNDWI), plastic index (PI), normalised difference vegetation index (NDVI), normalised difference water index (NDWI), The floating debris index (FDI), normalised difference moisture index (NDMI), water ratio index (WRI), and automated water extraction index (AWEI) [95].

4.1. The Plastic Index

It is a specialist debris-identification index used to model and categorise floating plastic trash in water. PI is a plastic feature extraction input grounded on Rrs in the red and NIR spectral regions, which can be calculated with Equation 1. The NIR and RED in PI stand for the reflectance of the pixel in the NIR and red spectrums [93].

$$PI = \frac{R_{rs,}NIR}{R_{rs,}NIR + R_{rs,}RED} \quad (1)$$

4.2. Floating Debris Index

To identify floating contaminants in aquatic environments, the FDI algorithm was created [42]. It utilises the distinct spectral properties that floating materials display, enabling operators to differentiate them from other image features [96]. This version of the floating algae index (FAI) is grounded on data from the Moderate Resolution Imaging Spectroradiometer (MODIS), Medium Resolution Imaging Spectrometer (MERIS), and Landsat [97]. The MSI red edge (RE) band, which is located at about 740 nm, takes the place of the chlorophyll-sensitive red band in the FDI algorithm. Compared to NDVI, PI, and the single band approach, this new index has demonstrated effectiveness in identifying floating objects [93,98]. FDI is calculated using Equation 2.

$$FDI = R_{rs,}NIR - (R_{rs,}RE2 + (R_{rs,}SWIR1 - R_{rs,}RE2 \times \left(\frac{\lambda\, NIR - \lambda RED}{\lambda\, SWIR1 - \lambda RED}\right) \times 10 \quad (2)$$

In FDI, values are calculated using spectral bands from satellite imagery. The Rrs, NIR is the baseline reflectance of NIR; Rrs, RE2 and Rrs; SWIR1 are the remote sensing reflectance of NIR; Red Edge 2 and SWIR1 bands respectively. The greater FDI values show a higher chance of floating debris while lower values indicate less debris or its absence [96–98].

4.3. Water Feature Extraction Spectral Indices

Water absorbs and redirects light in the near-infrared (NIR) and green channels of the electromagnetic spectrum, correspondingly, making various satellite-derived water feature extraction indices applicable to plastic monitoring [96]. The spectral characteristics of coloured and clear plastic pollutants contrast with those of clear water [98]. Water feature extraction indices like the normalised difference water index (NDWI), modified NDWI (MNDWI), normalised difference moisture index (NDMI), water ratio index (WRI), and automated water extraction index (AWEI) can distinguish plastic from clear water due to these different spectral characteristics. Their respective Equation (3)–(7) are presented below [93,95,99].

$$NDWI = \frac{R_{GREEN} - R_{NIR}}{R_{GREEN} + R_{NIR}} \quad (3)$$

$$MNDWI = \frac{R_{GREEN} - R_{MIR}}{R_{GREEN} + R_{MIR}} \quad (4)$$

$$NDMI = \frac{R_{NIR} - R_{MIR}}{R_{NIR} + R_{MIR}} \quad (5)$$

$$WRI = \frac{R_{GREEN} - R_{RED}}{R_{NIR} + R_{MIR}} \quad (6)$$

$$AWEI = 4 \times (Green - MIR) - 0.25 \times NIR + 2.75 \times SWIR) \quad (7)$$

In sentinel-2 imagery, green represent band 3; red represent band 4; NIR represent band 8; MIR represent band 12; and SWIR represent band 11. Like most indices the water feature extraction spectral indices values typically range from –1 to +1. However, for WRI, the index values range from 0 to 3. Areas with high values (indicating high water content) are likely to be areas where plastic debris might accumulate [95,99].

4.4. Normalized Difference Vegetation Index

The normalised difference vegetation index (NDVI) can be amended to identify aquatic plastic materials, despite its primary purpose of monitoring vegetation. It is founded on the idea that red and near-infrared electromagnetic light reflections are connected to the pigmentation of green vegetation [100]. Spectral characteristics that set marine debris apart from natural features are common. Using Sentinel-2 imagery to calculate the NDVI, spectral differences can be used to pinpoint possible pollutant locations. Based on their distinct spectral responses, it measures the variance between the red and near-infrared spectral bands and indicates the presence of plastic pollutants [41,101]. Mukonza and Chiang state that it is computed by normalising the dissimilarity between the reflectance of red and infrared light using Equation 8 [93].

$$NDVI = \frac{R_{rs,}NIR}{R_{rs,}NIR} - \frac{R_{rs,}RED}{R_{rs,}RED} \quad (8)$$

In NDVI, Rrs, NIR is the reflectance values in the near infrared while the Rrs, RED is the reflectance values in the red bands respectively. The NDVI values range from − 1 to +1 with the greater NDVI values indicating a stronger implication while negative values indicate the absence of plastic debris/vegetation [41,93,101].

Although these indices have been successfully used in water pollution monitoring studies, their effectiveness in monitoring and classifying aquatic plastic pollutants from remote sensing imagery has some advantages and disadvantages. In aquatic environments, PI is generally useful for mapping and detecting plastic pollutants; however, its capacity to do so may be constrained in waters that are turbid or heavily shaded. Plastic objects can be identified in the image with FDI, but natural materials like vegetation will cause a definition error. The use of NDVI can assist in locating potential concentrations of plastic pollution by examining the spectral differences between plastic pollutants and other materials in aquatic environments. However, vegetation and other natural materials can cause NDVI to be sensitive, which could result in misidentification [41,93–95].

Due to the distinct spectral properties of plastics and the possibility of interference from other materials in an aquatic environment, water feature extraction spectral indices (NDWI, MNDWI, NDMI, WRI and AWEI) can be useful in separating water bodies, but their efficacy in detecting plastic pollution can vary. Since NDMI is not specifically made for mapping water bodies, it may not be as good at separating out water features as compared to NDWI or MNDWI. Although NDWI is frequently used for mapping water bodies and is reasonably easy to compute, it may not be very effective at identifying plastic pollutants because they can have distinct reflectance characteristics. The MNDWI is more adept at differentiating water from other features but it might still have trouble picking up on minute details about plastic pollution in aquatic environments. WRI's primary focus on water surface characteristics may limit its ability to detect plastic pollution. AWEI might not be the best tool for spotting complex water features like braided rivers, and it might not be very good at spotting plastic pollution, which can have a distinct spectral signature [96–100].

In general, it can be inferred or concluded that a combination of these indices may be required for more accurate identification of plastic pollution in aquatic environments. Numerous researchers have demonstrated the usefulness of these satellite-derived indices for characterising aquatic plastic from Landsat data (**Table 1**) [33,40–44,96,102–106]. Sannigrahi et al. used k-NDVI, NDVI, PI, and FDI as spectral indices for detecting marine plastic in a number of nations [96], including Lebanon, Greece, Cyprus, and Italy. According to the study, the most crucial factor for identifying marine floating plastic was FDI. A thorough study by Biermann et al. used FDI and NDVI to find plastic patches on the ocean surface near Ghana, Scotland, Canada, and Vietnam [42]. According to the authors, FDI was used to identify the majority of plastic patches. A study by Jamali and Mahdianpari [105] on the creation of a cloud-based framework for large-scale marine pollution detection in Mytilene, Greece, also demonstrated the usefulness of FDI and NDVI. When Basu et al. used multispectral Sentinel-2 remote sensing imagery to develop novel classification algorithms for the discovery of floating plastic pollutants in Limassol, Cyprus, and Mytilene, Greece [106], they chose NDVI and FDI indices. According to their findings, the two indices were the most effective at identifying plastic waste. Themistocleous et al. monitored floating plastic using Sentinel-2 imagery in Limassol, Cyprus [41]. For image processing, the study examined various indices such as NDWI, WRI, NDV, AWEI, MNDWI, NDMI, PI and RNDVI. The study reported that the newly developed PI was the utmost active index in classifying plastic pollution in aquatic environment.

Table 1. Applicability of Remote Sensing Technology in Aquatic Plastic Monitoring [33,40–44,96,102–106].

Author	Country	Remote Sensor	Satellite Derived Index	Aquatic Environment
Themistocleous et al. [41].	Cyprus	Sentinel-2	NDWI, WRI, NDV, AWEI, MNDWI, NDMI, PI and RNDVI	Sea
Topouzelis et al. [40].	Greece	Sentinel-2		Natural water
Mansui et al. [102].	Tunisia and Syria			Sea
Martin et al. [103].	Saudi Arabian	UAV		Sea
Gabara et al. [44].		AVIRIS		Ocean
Kikaki et al. [43].	Honduras	Sentinel-2		Marine
Biermann et al. [42].	Ghana, North-West America, Vietnam, and Scotland	Sentinel-2	NDVI and FDI	Coastal Water bodies
Dubbini et al. [33].	Italy	WorldView-2		Rivers
Nivedita et al. [104].	Brazil	Sentinel-2	FDI	Costal water
Sannigrahi et al. [96].	Lebanon, Greece, Cyprus and Italy		k-NDVI, NDVI, PI and FDI	Marine
Jamali and Mahdianpari [105].	Greece	Sentinel-2	NDVI and FDI	Ocean
Basu et al. [106].	Cyprus and Greece	Sentinel-2	NDVI and FDI	Coastal Water bodies

5. Monitoring of Aquatic Plastic Pollution Using Remote Sensing: Research Trends

As shown in **Table 1**, a number of international research have validated that remote sensing is a promising technique that can be used to monitor plastic pollution in aquatic environments in an efficient and reasonably priced manner [107]. In Cyprus, Themistocleous et al. investigated whether Sentinel-2 satellite images could be applied to identify plastic pollutants on the water environment [41]. They discovered that the plastic pollutants target was easily detected in NIR wavelengths. Furthermore, the authors stated that their developed PI was capable of accurately identifying plastic objects floating on the water's surface. In the Hawaiian Islands, aerial imagery and spatial analysis were used to map coastal marine debris. These methods accurately measured the quantity, location, type, and size of macro-plastics, detecting 20,658 total plastic pollutants. The study found that the northeastern shorelines had the highest debris density. Plastics, including nets, lines, buoys, floats, and foam, made up 83% of the total quantity [108]. Topouzelis et al. used unmanned aerial systems and satellite remote sensing to detect plastics in seawater in Greece [40]. In their study, floating targets such as PET water bottles, LDPE plastic bags, and nylon fishing ghost nets were identified. Their research found that plastic debris can be detected efficiently. Mansui et al. simulated marine pollutants floating in the Mediterranean and discovered perpetual build-ups of plastics [102]. Their study discovered that the coastline between Tunisia and Syria had the most plastic pollution. Martin et al. used remote sensing to monitor litter along the Saudi Arabian Red Sea coastline [103]. In their study, pollutants were detected using image acquisition from an unmanned aerial vehicle, and machine learning was used to automatically process the large volume of imagery for debris detection and classification.

Gabara et al. used airborne SWIR imagery to detect ocean plastics [44]. They documented the position, size, colour, and type of each plastic material found in the RGB mosaics. The study confirmed that the ~1215 and ~1732 nm absorption features can detect ocean plastics using spectral information. Liubartseva et al. modelling study classified Adriatic Sea as a very dissipative basin where the plastic pollutants are accumulated at the shoreline [109]. Their study showed that the coastline of the Po Delta receives a plastic flux of approximately 70 kg (km day)$^{-1}$. In Honduras, Kikaki et al. investigated the capability of high-resolution multispectral satellites in detecting marine plastic debris [43]. According to the study, plastic waste from rivers in Guatemala and Honduras finds its way into the Caribbean Sea during rainy seasons. The discovered spatial trajectories showed that floating plastic pollutants travel with a mean speed of 6 km d^{-1}. The study concluded that satellite remote sensing is a valuable and cost-saving tool for monitoring the sources and pathways of aquatic plastic pollutants and thus could ultimately support management approaches in the global water sources. A case study covering the coastal waters of Ghana, North-West America, Vietnam, and Scotland conducted by Biermann et al. showed that novel FDI was able to detect patches of floating macro-plastics [42]. According to the authors, floating aggregations were detectable on sub-pixel scales. Dubbini et al. employed multispectral proximal sensing to detect plastic waste in river ecosystems [33]. The data were collected using a proximity sensor in the electromagnetic spectrum range that includes the ultraviolet, visible, and near infrared bands, similar to the WorldView-2 satellite. The in-depth analysis of the spectral signatures obtained revealed typical plastics trends and reflectance values in the near infrared bands. Nivedita et al. conducted case studies in Brazil to monitor macro-plastics in Sentinel-2 data using FDI and achieved sub-pixel-scale detection of macro-plastics combined with seaweed and sea foam [104].

6. Challenges in Application of Remote Sensing Technology for Aquatic Plastic Pollution Monitoring

The application of new-generation satellite imagery carries an assurance for enhanced plastic detection owing to improved spatial and spectral features that enable more accurate detection of plastic pollutants in the aquatic environment. However, resolving the remaining obstacles to thorough and precise plastic pollution detection and assessment is necessary for these new tools to be effective [110]. Some of the limitations of remote sensing technologies are:

Since the quantity of plastics in a single pixel defines the light intensity, these technologies, like Sentinel-2, have a spatial resolution of up to 10 m, which has a substantial influence on the detection capability of methods. Given that the water sources typically contain a variety of pollutants concentrated in a single patch, this decreased reflectance restricts the detection capability [111]. Particularly for plastic patch tracking applications, satellite optical imagery's ability to gather continuous data is limited by its propensity for cloud cover, inability to generate data at night, and lengthy revisiting times. It can be difficult to find adequate data for atmospheric correction, and it can be expensive to obtain high-quality satellite imagery with the required data [112].

Disparities in plastic characteristics, shape, surface texture, environmental conditions, and the presence of algae, debris, or driftwood in aquatic ecosystems can all affect the spectral reflectance of floating plastics as measured by multispectral imaging sensors [42]. Sometimes it is difficult to distinguish fine-scale variations in aquatic plastic pollution monitoring due to the spatial and spectral resolution limitations of remote sensing data, especially when closely spaced objects or materials coexist [113]. The spectral signature of aquatic plastics can be extremely variable, making it challenging to come up with a one-size-fits-all spectral index that reliably identifies plastics across diverse aquatic environments [114].

7. Minimization of the Plastic Pollution in Aquatic Environment

Finding a solution to the environmental problem caused by single-use plastics is preferable to outright banning the products [115]. Several methods, strategies, or technologies have been proposed to reduce plastic pollution [73]. Minimisation of plastic pollution in aquatic environment can be achieved through:

Policies to decrease the manufacture and utilisation of single-use plastics must be developed and put into effect by the government and pertinent authorities [116]. Encouragement should be given to the adoption of plastic bag bans or fees as well as the promotion of alternative uses for reusable containers and bags [4,16]. To inform the communities, businesses, and policymakers about the effects of plastic contamination in the aquatic environment, awareness programs like community outreach, conferences, and fieldwork are essential. Changes in consumption patterns and the creation of supportive policies addressing plastic pollution can result from this [115]. The government and pertinent government agencies should take into consideration the development and application of novel and economical technologies, such as filtration systems, skimmers, and other sophisticated analytical methods, to capture and remove plastics from aquatic environments [73].

Additionally, nations ought to encourage recycling and upcycling also known as creative reuse. People should be encouraged to turn waste, unwanted, or useless products, as well as by-products, into new materials or goods that are thought to be of higher quality, like those with artistic or environmental value [115]. Recycling is widely recognised as one of the most effective route to manage plastic pollution. It is the process of reusing waste to create new products rather than continuously utilising natural resources. Recycling and upcycling will both create new economic value in addition to assisting in the reduction of aquatic plastic contamination [75]. Financial incentives and rewards should be introduced worldwide to encourage the return of used plastic. Returning used plastics for cash can be very important because it will facilitate the collection process and aid in the recycling and recovery sorting process [117].

The process of turning plastic pollutants into energy is an additional approach to lessen plastic contamination [118]. Since plastics are mostly made from hydrocarbon-based energy feedstock like coal, oil, and natural gas, they can be thought of as a type of stored energy [119,120]. According to Pratt et al. [121], wastewater effluent is another key source of micro-plastics in water sources. The government should control and limit the discharge of wastewater in water bodies and encourage the use of cutting-edge treatment techniques prior to discharge, given that the majority of effluents contain micro-plastic traces and are dumped into adjacent streams [122].

To stop plastic debris from getting into the aquatic environment, waste management infrastructure needs to be improved, especially in developing countries. To decrease the possibility of plastic pollutants inflow into aquatic environments, this can be accomplished in full by putting in place efficient recycling programs, waste collection systems, and waste disposal facilities [123]. Countries should encourage sustainable practices in industries, which include promoting eco-friendly packaging, cutting back on unnecessary packaging, and implementing the concepts of the circular economy, in order to minimise the production and introduction of plastic waste in aquatic environments. Additionally, to better comprehend the origin, scattering, and related risks of plastics, developing nations should fund research and ongoing monitoring [124].

8. Conclusions

Uncontrolled plastic waste disposal and degradation in aquatic environments can undoubtedly result in the release of micro- and nano-plastics, which can be harmful to living organisms. To effectively address this issue and protect aquatic ecosystems, it is critical to identify and monitor areas affected by plastic pollution. According to the study's findings, remote sensing technologies with various spatial, spectral, and temporal resolutions have a prospect of being a dependable source of long-term qualitative and quantitative information on large geographical areas. Many researchers have demonstrated that Sentinel-2 is a cost-saving and valued dataset for monitoring aquatic plastic pollution due to its combination of wavebands, high spatial resolution imagery, and systematic acquisitions. It offers a potential way to cut down on the amount of fieldwork needed for conventional techniques, which would save money and sampling time. Therefore, it can be said that it has a great chance to improve society and help make water ecosystems plastic-free. It is recommended that developed countries transfer technology and knowledge to developing countries in order to help reduce aquatic plastic pollution, given that remote sensing is not commonly applied in these nations to monitor aquatic plastic pollution. Future research should combine remote sensing and in situ surveys to comprehensively track the dynamics of plastic debris accumulation. It should also concentrate on creating a thorough framework for tracking aquatic plastic pollution and evaluating the harm that plastic pollutants cause to ecosystems and human health. This will assist in directing choices and activities towards the creation of secure and long-lasting remedies for the issues of aquatic plastic pollution. This review article is essential because it will improve the understanding of aquatic plastic waste, its impacts, and the use of remote sensing technology in monitoring studies by researchers and interested parties.

Author Contributions

Conceptualization, I.M., H.I., S.A.O.; methodology, I.M., H.I., S.A.O.; formal analysis, I.M., H.I., S.A.O.; investigation, I.M., H.I., S.A.O.; data curation, I.M., H.I., S.A.O.; writing—original draft preparation, I.M., H.I., S.A.O.; writing—review and editing, I.M., H.I., S.A.O. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding. The Article Processing Charge (APC) was paid by the Central University of Technology, Free State's University Research Grants and Scholarships Committee (RGSC).

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All the data generated and analysed during the current study are available on the manuscripts.

Acknowledgments

The authors will like to acknowledge the Central University of Technology, Free State's University Research Grants and Scholarships Committee (RGSC) for their monetary support. The authors further acknowledge the anonymous reviewers and editors for their constructive criticism that made this work robust.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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