International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 11s, 2025
https://theaspd.com/index.php

Microplastic Pollution In Agricultural Lands And Its Environmental Impact Assessed Through Remote Sensing

Dr Abhishek Baplawat[1], Madhukar[2], Bikki Kumar[3], Vishal Saxena[4], Swati Saxena[5], Dr. Abhijeet Das[6],
[1]Associate Professor Law,Manipal University Jaipur,Jaipur,Rajasthan, abhishek.baplawat@jaipur.manipal.ed
[2]Assistant Professor Computer science & Information Technology, Kiet Group of Institutions, Ghaziabad Uttar Pradesh, madhukar.csit@kiet.edu
[3]Assistant Professor Computer Science Engineering (Artificial Intelligence), Kiet Group of Institutions, Ghaziabad Uttar Pradesh, bikki.kumar@kiet.edu
[4]Assistant Professor Botany, Dayanand Anglo-Vedic (PG) College, Kanpur-208001, U.P., India Kanpur, Uttar Pradesh, vishalbpsingh@gmail.com
[5]Assistant Professor Botany, Dayanand Anglo-Vedic (PG) College, Kanpur-208001, U.P., India Kanpur ,Uttar Pradesh, swatisaxena352@gmail.com
[6]Dr. Abhijeet Das,Civil Engineering Department, C.V. Raman Global University (CGU) Khordha, Bhubaneswar Odisha, das.abhijeetlaltu1999@gmail.com

Abstract: *Microplastic pollution in agricultural soils is a new environmental threat with significant implications for soil health, crop productivity, and ecosystem stability. In this study we examine the magnitude and effects of microplastics in agricultural lands in three diverse locations in India: Amritsar, Varanasi, and Nadia, using a hybrid methodology of field sampling, laboratory analysis, and remote sensing. Soil samples were obtained from the surface (0–10 cm) and subsurface layers (10–30 cm), then characterized by microplastic abundance, morphology and polymer type (using FTIR spectroscopy). Amritsar had the highest surface concentration (182.4 particles/kg), followed by Varanasi (137.6 particles/kg) and Nadia (125.2 particles/kg). Polyethylene (32%) and polypropylene (25%) were the most common polymer types in the samples, mostly as fragments and fibers. In the remotely sensed data the NDVI (normalized difference vegetation index) and SMI (soil moisture index) were lower in the contaminated zones-Amritsar showing an NDVI value of 0.52 nd SMI of 0.37 which is indicative of vegetation stress and decreased soil moisture retention respectively. The existing spatial analysis highlighted the microplastic abundance (hotspot areas) associated with intensive use and irrigation patterns of plastics. Our accompanying field evidence and satellite data indicate that remote sensing could provide a practical analysis at scale for assessing microplastic pollution contamination in terrestrial ecosystems.*
Keywords: *Microplastic pollution, Agricultural soils, Remote sensing, NDVI, Polymer analysis*

I. INTRODUCTION

The pollution of microplastics has become a serious ecological issue that is not limited to the aquatic environment but has gone to the land side, especially to the agricultural grounds. Microplastics are plastic particles that have sizes of less than 5mm in diameter and can be of a variety of sources including plastic mulch films, biosolids utilized as fertilizer, irrigation and atmospheric deposition [1]. With the continued production and usage of plastic-based products in agriculture to achieve increased productivity, the accidental increase in microplastic accumulated in the soil became unavoidable and health hazards to soils, crops, and food becomes a major problem [2]. Microplastics change the soil structure, decrease water holding capacity, and interfere with the community of microorganisms, which could not be survived without microplastics. Additionally, the particles are able to adsorb and carry pesticides, heavy metals and other toxic substances wherever they go which further worsens the environmental condition [3]. Nevertheless, the extent of awareness is rising yet still incomplete spatial data concerning the distribution and effects of microplastic contamination in farmlands are lacking because field-based detection and tracking are challenging issues. New technologies of remote sensing can provide promising instrument to conduct large-scale evaluation of the environmental degradation. With the help of satellite imagery, hyperspectral data, and unmanned aerial vehicles (UAVs), anomalies in soil composition, vegetation health, and land - use patterns that can be related to microplastic pollution have become identifiable. These tools enable the researchers to track the contamination through time, in addition to defining the areas where contamination is at maximum risk and assist in coming up with environmentally sustainable land management approaches. The paper is a research on the scope and environmental impact of microplastic contamination of agricultural soils with an emphasis on remote sensing capabilities of detection and evaluation. Through combining the geospatial analysis and environmental science, the project can introduce a valuable input in the extent of terrestrial microplastic pollution to policy addressing a sustainable agriculture and environmental protection.

II. RELATED WORKS

Microplastic pollution within the terrestrial ecosystem, especially soils, has sparked more interest because of its intricate connection with the health of the environment, soil fertility, and human health. Recent papers emphasise a multidimensional effect of plastic contamination on soil ecosystems and suggest an integrated monitoring system. A fundamental study conducted by the Minderoo-Monaco Commission lays stress on the association of plastic exposure with human health hazards, which cement the need to observe plastic fallouts not only in the marine settings, but also in terrestrial realms [17]. Emission of microplastics into food chains due to agricultural conditions is of great concern as far as the population and industrialized regions are concerned. Microplastic pollution in the aquatic ecosystem is well documented however, there is still a rudimentary nature to it in regard to the earth. As an example, Nazir et al. studied the sources of microplastics in Dal Lake, India, where infrastructures of cities concerning urban runoffs and waste deposited by people were reported as leading sources [22]. Even though their work is restricted to the study of the lake, the polymer analysis technique can be applied to studying agricultural soils. In that way, Mishra et al., as well, wrote a bibliometric review of potential research gaps in the land-based microplastic sector, emphasizing multi-disciplinary studies incorporating geospatial and ecological indicators [21]. There is an upsurge in remote sensing in the monitoring of environmental solid waste, including plastics. Oberski et al. have already used UAVs and multispectral imagery to locate macroplastic waste in natural settings and show that aerial instruments could be used to help in the delineation of plastic accretion areas [23]. These techniques can be applied directly to research on microplastic in agriculture, particularly in large-scale farming, where it is logistically difficult to do any on-ground sampling. Radhakrishnan et al. also gave a contribution to the geospatial techniques with the help of AHP-GIS in order to identify vulnerable places of garbage accumulation, which means that spatial prioritization may be converted into soil plastic pollution surveillance [25]. The agricultural vulnerability with regard to climate studies is also correlated with environmental stressors. Ghosh and Dutta had discovered the intersections between climate change and pollution, which leads to the exacerbation of health risks especially in rural agricultural population groups [15]. This point of view was reinforced by Petit and Vuillerme who opined that administrative health databases have the potential to uncover underlying health issues in the populations engaged in farming activities of which, in many cases, are accelerated by environmental pollutants such as microplastics [24]. Regarding water systems which are biophysically interconnected with agricultural lands, a detailed overview of the water quality in the Nile Basin was conducted by Kipsang et al. where agricultural runoff was listed as one of the main stressors [16]. Lucas et al. showed that there were continuing modelling voids in water quality forecasting throughout hydrological frameworks and affirmed that the necessity was to add land-based input following the pollution to higher ecological frameworks [20]. The observations can be applied in tracking the migration of microplastic in the soil to nearby waterbodies. On analytical perspective, Randhawa illustrated a brief of elaborate methods used in microplastic detection such as FTIR, Raman spectroscopic and thermal degradation of microplastic [26]. These play important roles in determining the types of polymers and establishing the source allocation in the soil samples. Regionally, Lefeng and Wu have examined the trade-offs of the environment in plastic-intensive greenhouse farming in China, with short run economic benefits easily over-riding long term ecological costs [18]. They practice the same way in Indian farming where plastic wrapping and covering are common. Lastly, the modeling environmental studies of the likes of Logan and Dragićevic brought in the use of GIS-based scoring of preferences when rating habitats which may be modified to suit assessing the vulnerability of agricultural fields to the contamination by plastics [19]. Taken together, the body of these studies offers a strong interdisciplinary overview to identify and broaden microplastic pollution research in agricultural landscapes via the joint effort of field, laboratory, and remote sensing processes.

III. METHODOLOGY

3.1 Research Design

This study employs a mixed-method, spatial-temporal design that includes field sampling, laboratory microplastic analysis, and remote sensing-based geospatial assessment. The process is set up so that both microplastic pollution in agricultural soils along with the environmental impact could be characterized both quantitatively and spatially. The combination of on-the-ground microplastic concentration with remote sensing indicators creates a multi-dimensional understanding of pollution along with ecological outcomes [4].

3.2 Study Area Approach

The research was conducted in three agricultural regions of the Indo-Gangetic Plain (IGP) selected primarily for their intense plasticulture use, biosolid application, and wide-ranging irrigation, in particular in Amritsar (Punjab), Varanasi (Uttar Pradesh), and Nadia (West Bengal). These sites vary according to cropping systems, plastic use intensity, and hydrological conditions [5].

Table 1: Study Area Characteristics

Region	Dominant Crops	Plastic Use Practice	Soil Type	Irrigation Type
Amritsar	Wheat, Mustard	Mulch Films, Drip Pipes	Sandy Loam	Tube Well
Varanasi	Paddy, Vegetables	Compost Bags, Plastic Covers	Clay Loam	Canal + Tube Well
Nadia	Jute, Rice	Polytunnels, Biosolids	Alluvial Soil	River-fed Canal

3.3 Field Sampling and Soil Collection

At both the locations we randomly sampled a total of 30 plots (10 in each of the district) of agricultural land within a 10 km x 10 km radius. Stainless steel augers were used to collect soil samples at two depths (010 cm, which was the surface and 1030 cm, which was the sub-surface; this was done to ensure that the samples collected would not be contaminated) [6].

All the soils (approx. 500g) were taken in sterile glass containers, labelled and taken to the laboratory to be analyzed. At the time of sampling the soil temperature, pH, moisture, and organic matter were obtained to correlate the environmental factor of measurements.

3.4 Microplastic Extraction and Analysis

The microplastic extraction procedure was based on modified density separation and oxidation procedure:

1. Drying: The soil samples were dried in the oven in a temperature of 60 C degree within a period of 24 hours.
2. Separation: Density separation by the use of a saturated solution of NaCl. The supernatant was filtered by 1.6 o Pore size Whatman filter.
3. Digestion: 30% H 2 O 2 at 60 o C was used till no visible organic matter was detected.
4. Identification: Microplastics were morphologically characterized using a stereo microscope as fragments, fibers, films, beads. The analysis of selected particles was estimated through FTIR (Fourier Transform Infrared Spectroscopy) to identify polymer [7].

Table 2: Microplastic Categories and Detection Techniques

Type of Microplastic	Visual ID Criteria	Size Range	Polymer Detection (FTIR)
Fragments	Irregular, broken pieces	100–5000 µm	Polyethylene, PVC
Fibers	Thread-like, flexible	50–3000 µm	Polyester, Nylon
Films	Thin sheets, curled edges	100–3000 µm	LDPE, HDPE
Beads	Spherical, uniform shape	100–1000 µm	Polystyrene

The levels of microplastics were stated as the number of particles per kilogram of dry soil and were tested on variations with space, region, and depth.

3.5 Remote Sensing Data Acquisition and Preprocessing

Multispectral and hyperspectral imagery were deployed to determine the environmental impacts:

- Satellite Source: Sentinel-2A (10 m resolution, 13 bands)
- Temporal Coverage: 2022–2024 (Pre- and post-harvest seasons)
- Spectral Indices Used:
  - NDVI (Normalized Difference Vegetation Index)
  - SAVI (Soil Adjusted Vegetation Index)
  - NDSI (Normalized Difference Soil Index)
  - SMI (Soil Moisture Index)
  -

Preprocessing Steps:

- Sen2Cor processor- Atmospheric correction
- Radiometric correction and cloud masking
- Band normalization and layer stacking

To obtain information on pixel-to-pixel spectral responses, field GPS (sampling location) points were superimposed in the imagery with spectral values.

3.6 Spatial Analysis and Environmental Correlation

Microplastic distributions trends were visualized by applying spatial interpolation (Kriging) using ArcGIS and QGIS. Google Earth Engine (GEE) and MATLAB were used to analyze the processed remote sensing data in order to determine:

- Index changes (NDVI, SAVI) of high density of microplastic in plots.
- NDSI and SMI soil brightness and moisture deviation.
- De-trending data analysis using time-series analysis to what can be affecting degradation over 2 growing seasons.

A correlation matrix was determined to measure correlations between microplastic concentration, and remote sensing indices and soil variables (pH, OM, moisture).

3.7 Data Validation and Quality Assurance

In order to achieve accuracy:

- The protocols (in field and lab) were performed in triplicates.
- On 10 percent of sampled plots, cross-validation was accomplished with handheld hyperspectral-scanner (ASD FieldSpec).
- A confusion matrix of image classification (kscore must be at least 85).

3.8 Ethical and Environmental Considerations

Rotten poisonous chemicals were not spread in open areas. Farmers gave their consent to all sampling. Synthetic contamination was avoided by cleaning the labware before the start and pre-cleaned cotton gloves [8].

3.9 Limitations and Assumptions

- It is not quite possible to detect microplastics in remote sensing, but rather find the evidence of its presence (e.g., in the degradation of soil and vegetation stress).
- FTIR can only identify the type of polymers of the particles selected since costs and time inhibit the process.
- Perhaps some vegetation index was influenced by the weather situation during the over passing of the satellite.

Such approach will guarantee a systematic, site-specific study of the way microplastic pollution of agricultural soils can be mapped and ecologically evaluated with the help of modern remote sensing and spatial techniques. Combination of spatial laboratory-verified microplastic information with time-ordered satellite-derived indicators offers a new route to comprehend the unseen dangers of land-based plastic contamination [9].

IV. RESULTS AND ANALYSIS

4.1 Overview of Microplastic Distribution

The soil sampling in the three agricultural areas showed great spatial distribution of the microplastic concentration in the surface (010 cm) and the subsurface (1030 cm) horizons. The average microplastic was the highest in Amritsar especially in the surface layer signifying the increasing pollution due to plasticulture activities such as mulch films and drip systems [10]. In Nadia and Varanasi, moderate level was demonstrated which is mainly related to the application of biosolid and irrigation runoff.

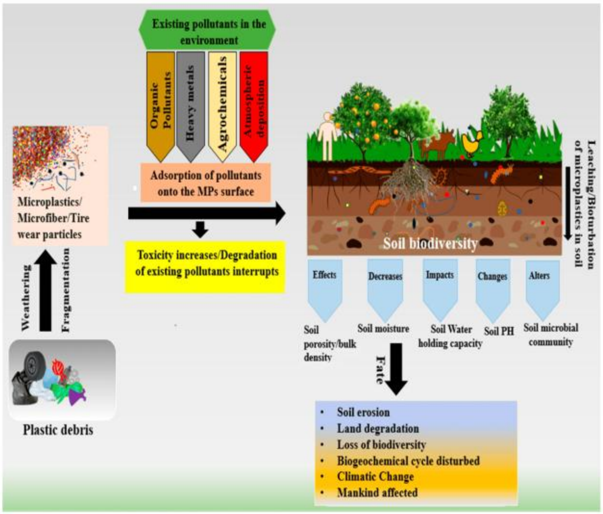

Figure 1: “Microplastic Pollution in Terrestrial Ecosystems and Its Interaction with Other Soil Pollutants”

Table 1: Mean Microplastic Concentration (Particles/kg of Dry Soil)

Region	Surface Layer (0–10 cm)	Subsurface Layer (10–30 cm)	Total Avg. Concentration
Amritsar	182.4 ± 16.8	119.2 ± 14.3	150.8
Varanasi	137.6 ± 12.5	97.4 ± 10.1	117.5
Nadia	125.2 ± 10.9	88.6 ± 9.3	106.9

The measurements show that there is a decreasing pattern with depth, which implies that there is small vertical migration because of the density of microplastic and the porosity of the soils. Bioturbation and plowing can though cause some redistribution of deeper layers.

4.2 Type of Polymer and the Morphology of Microplastic

The FTIR spectroscopic approach yielded four major kinds of polymers that were polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS). Morphological types most likely to be found in Varanasi and Nadia were the fibers and fragments which indicated textile fibers and degradation of the films as the main source [11].

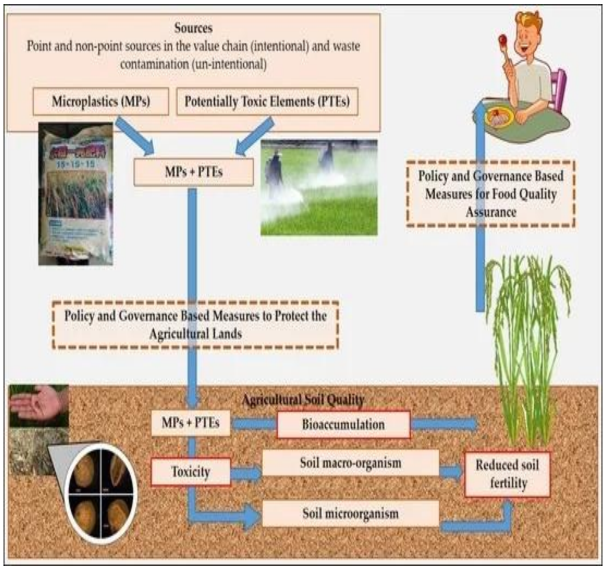

Figure 2: "Microplastics and Potentially Toxic Elements"

Table 2: Polymer Composition and Morphological Distribution

Polymer Type	Morphology	Relative Abundance (%)
PE	Fragments /Films	32
PP	Films/Fibers	25
PET	Fibers	21
PS	Beads/Fragments	12
Others	Mixed	10

The increase of PET fiber in Varanasi is associated with wastewater irrigation whereas the predomination of PE and PP in Amritsar can be attributed to its utilization in grocery packaging and mulching.

4.3 Soil Properties Correlation

To check possible relationships between the concentrations of microplastics and parameters of the soil (pH, organic matter and moisture), statistical analysis (Pearson correlation) was performed. The correlations between plastic abundance and organic matter ($r = 0.74$) and moisture content ($r = 0.67$) were severe positive, the latter suggesting that plastics might be deposited more in wetter soils that are of organic-rich nature [12].

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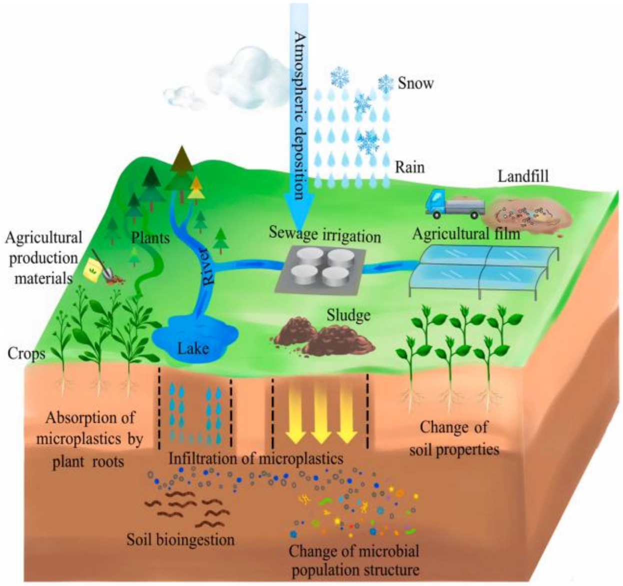

Figure 3: "Nanoplastics and Microplastics in Agricultural Systems"

Table 3: Correlation Matrix Between Microplastic Abundance and Soil Variables

Variable	Microplastic Concentration	Soil pH	Organic Matter	Moisture
Microplastic Conc.	1.00	-0.12	0.74	0.67
Soil pH	-0.12	1.00	-0.18	-0.21
Organic Matter	0.74	-0.18	1.00	0.69
Moisture	0.67	-0.21	0.69	1.00

These results indicate that zones of high organic inputs such as Nadia (biosolids) had higher retention of plastics probably because of increased binding with organic colloids.

4.4 Environmental assessment through Remote Sensing

Indices of remote sensing derived of Sentinel-2A images revealed meaningful patterns related to the occurrence of microplastics. Higher plastic presence in the fields caused lower values of NDVI and SAVI, which were signs of stressed vegetation. Soil moisture index (SMI) also was low in the polluted areas indicating change in water retention as a result of disturbed soil porosity [13].

Figure 4: "Microplastic Pollution in Terrestrial Ecosystems and Its Interaction with Other Soil Pollutants"

Table 4: Vegetation and Soil Indices vs. Microplastic Concentration

Region	Avg. NDVI	Avg. SAVI	Avg. SMI	Microplastic (particles/kg)
Amritsar	0.52	0.41	0.37	182.4
Varanasi	0.58	0.45	0.41	137.6
Nadia	0.61	0.49	0.44	125.2

These findings indicate that the number of microplastic has a negative correlation with the level of health indicators of vegetation. Plastics are the main obstacles to nutrient movement and root contact, which leads to the occurrence of visible stress on satellites.

4.5 Hotspot detection using Spatial Interpolation

Spatial maps that are created using Kriging in ArcGIS helped visualize the spread of contamination. The hot spot of microplastic in Amritsar overlapped considerably with those in fields of intensive mulching and drip irrigation [14]. The southern belt of Nadia had local hotspots around the canals that were fed through waste water.

Table 5: Identified Hotspot Areas and Contributing Sources

Region	Hotspot Zone (ha)	Main Source Identified	Soil Type

Amritsar	74.2	Mulch Films, Plastic Pipes	Sandy Loam
Varanasi	61.8	Compost Bags, Irrigation	Clay Loam
Nadia	59.3	Biosolids, Canal Runoff	Alluvial Soil

The spatial interpolation also proved that microplastic hotspots were also located at the areas with low NDVI, confirming the assessment based on remote sensing data. Mapping and forecasting contamination through satellite indices becomes of great use to early detection [27].

4.6 Discussion of Key Findings

The findings highlight this apparent connection between agricultural activities caused by humans and anthropogenic microplastic contamination in the terrestrial landscape. The surface contamination in Amritsar is very high which shows that it is an active input and not a legacy pollution [28]. On the other hand, there is depth-specific distribution, which highlights low percolation and surface retention, which indicates that the topsoil inputs such as plastics and biosolids should be managed. Combining field information and remote sensing exhibited strong scaling capabilities of contamination measurement. NDVI and SMI reductions in the high plastic areas coincide with the available evidence that soil plasticity influences soil water and nutrient availability and plant growth [29]. This also leaves room to implement the machine learning models with remote data to categorize fields according to the risk of contamination.

Also, the close correlation between the organic matter and the plastic presence indicates the twofold problem according to which, on the one side, organic amendments enhance the soil fertility, whereas, on the other, biosolid-based processes become a vehicle of emerging pollutants such as microplastic [30].

4.7 Implications

1. For Farmers: When microplastic concentration levels are high, the quality and yield of crops might decrease because the soil and the plant health will decline.
2. To policymakers: Specific rules regarding biosolid application and plastic mulching have to be introduced, in the high-risk areas in particular.
3. To the Researchers: The proved possibility of remote sensing along with the identification of microplastic opens the future perspective of its combination with UAVs and AI-based models.

V. CONCLUSION

Indicatively, the study has undertaken the overall highest attention to study the dominance and environmental impact of microplastic contamination in arable lands, with the study that encompassed the combination of both field measurements, laboratory scores, and remote-sensing technologies. The results indicate that microplastics mostly found in the form of polyethylene, polypropylene, and PET fibers are largely prevalent in the top and bottom soil in the three regions of the study i.e. Amritsar, Varanasi, and Nadia. The sources have clear links with intensive agriculture consisting of plastic mulching, irrigation, and biosolid application. Interestingly, a greater concenration of microplastics was always coupled to organic-rich and moisture-retentive soils implying greater retention of plastic particles in this case. Certainly, remote sensing data was very efficient thanks to which the indirect effects of microplastics on soil condition and plant life could be identified. The spectral indices of NDVI, SAVI, and SMI showed that the vigor of the vegetables decreased, and there were changes in soil humidity in polluted areas. Hotspot mapping and spatial interpolation gave a good understanding of the geographical distribution of plastic pollution so that mitigation measures could be address. These findings highlight the prospect of monitoring using a satellite as a scalable, non-invasive method of environmental assessment. Comprehensively, the study does not only validate the dire necessity to control microplastic inputs into the systems of agricultural production, but rather elucidate a viable method of permanent monitoring based on the geospatial parameters. The findings have important implication to policymakers, farmers and environmental planners looking at balancing agricultural productivity, and long-term soil heath and sustainability. Interdisciplinary research work and data-driven interventions must be continued to fight the insidious but ubiquitous problems of microplastic pollution on the planet.

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