Environ Monit Assess (2024) 196:66
https://doi.org/10.1007/s10661-023-12219-0

RESEARCH

Investigation of microplastics and microplastic communities in selected river and lake basin soils of Thiruvananthapuram District, Kerala, India

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Received: 2 September 2023 / Accepted: 5 December 2023

Abstract Riparian areas are highly dynamic biogeophysical settings with a surge of waste deposition predominantly including land-based plastic discards. These polymer discards are destined to be the prime constitution of marine "plastisphere." The polymer fate is determined by waterbodies, where the chances of plastic retention are higher, eventually mediating the formation of microplastics (MPs) in years or decades. Such formed MPs are a potential threat to the aqua bio-regime. A systematic investigation of three waterbody basin soils (Karamana River, Killiyar, and Akkulam-Veli Lake) showed the presence of MPs in all the samples analyzed with varying sizes, shapes, colors, and compositions. MPs of the shapes flakes, fragments, filaments, sheets, foams, and fibers were observed with dimensions 0.3–4.7 mm. Most of the particles were white in hue (WT), followed by colorless (CL), light yellow (L.Y), light brown (L.B), orange (OR), red (RD), and blue (BL), respectively. The polymer communities were identified as high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and nylon. The highest average MP density was identified in the basin of Killiyar (799 ± 0.09 pieces/kg) followed by Karamana River (671 ± 3.45 pieces/kg), indicating the closeness of the sampling station to the city center compared to Akkulam-Veli Lake (486 ± 58.55 pieces/kg). The majority of the sampling sites belonged to the slopy areas and came under the highly urbanized land category. A close association was observed between particle abundance and urban activity. The study foresees possible threats inflicted by MP abundance upon the area-wide hydro-biological system.

Keywords Microplastics · Riparian soils · Polymer community · Secondary microplastics · LULC · Slope categories

Introduction

Riparian environments are highly susceptible to waste disposal and have become the main source of riverine and marine plastic pollution (Kumar et al., 2023a). Land-based plastic waste found in these sensitive zones is an emerging environmental risk due to its potential to inflict ecological as well as human welfare. Macroplastics are directly a threat to various species of flora and fauna and damage vessels, fishing gears, and hydro-mechanical frameworks. It impacts the tourism industry, increases the efforts and cost of shoreline cleaning, triggers the risk of urban flood due to clogging (McIlgorm et al., 2011; van Emmerik & Schwarz, 2020), and causes the breakout of the longtime accumulated waste in bulk amounts

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during unfavorable climatic conditions (Prabhakaran., 2023). Macroplastic polymers undergo degradation physically, photo-chemically, and biologically resulting in the formation of micro-sized particles defined as "secondary microplastics (MPs)" (Waldman & Rillig, 2020) with dimensions less than 5 mm, implying even higher eco-toxicological impacts. Based on previous plastic pollution studies conducted within and through various waterbody catchment areas, it is evident that plastics and their degraded particles are retained in these regions causing serious impacts on various environmental compartments and human health (Ballerini et al., 2022; Campanale et al., 2020; Irfan et al., 2020a; Ryan & Perold, 2021; Srinivasalu et al., 2021; van Emmerik et al., 2019a). As per the global plastic quantification study conducted by Meijer et al. (2021), of all the plastic waste released into the environment, less than 2% of the discarded waste ends up in the marine ecosystem. For water bodies such as rivers with greater upstream population, increased number of dams, over bridges, and larger floodplains, the likelihood of oceanic plastic waste emission rates will be comparatively lesser due to the higher accumulation rates of the pollutant within and across the riverine system (Tasseron et al., 2020; van Emmerik et al., 2022). Exorheic lakes, which drain into the oceans, also show higher rates of macro-polymer stagnation on lake surfaces, burial in bottom sediments, and accumulation on lake shorelines/beaches (Egessa et al., 2020; Faure et al., 2015). The main sources of this plastic waste are urban drainage, wastewater runoff, littering, discarded fishing gear, or other drainage-ridden wastes (van Emmerik et al., 2022) which get concentrated into small temporary water whirlpools (Faure et al., 2015). Wind-induced surface currents, especially during storms, also transport and deposit substantial amounts of plastic on the shorelines of aquatic waterways (Zbyszewski et al., 2014). The sources of plastic pollution are depicted in the given illustrations (Fig. 1).

The prolonged detainment of the riparian zonal plastic litter is mediated predominantly by the vegetation type, distribution, and densities within the area (Bruge et al., 2018; Cesarini & Scalici, 2022; Martin et al., 2020). The freely floating aquatic vegetation such as water hyacinth, *Pistia*, and larger *Salvinia* trap and mobilize large amounts of plastic waste downstream under the influence of wind force and hydrodynamics (Schreyers et al., 2021). In other scenarios, these macro synthetic polymers shall either get transported, dispersed, discharged, and buried in the banks/shores/flood plains of waterbodies at low

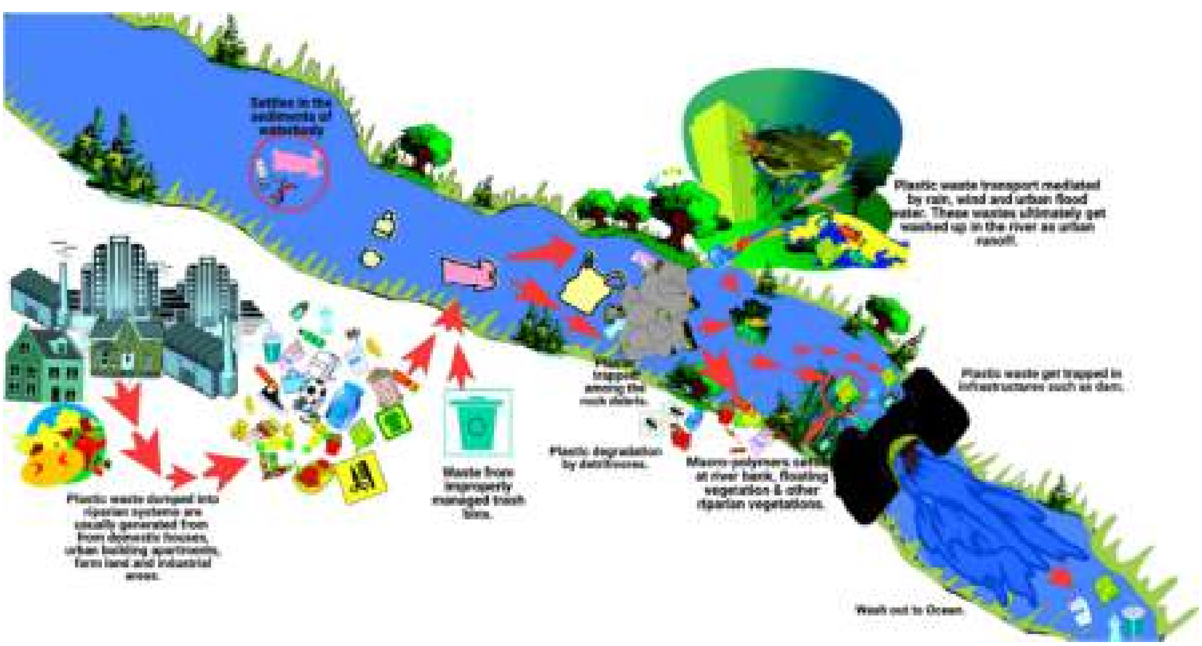


Fig. 1 Sources of plastic pollution in riparian zone

flow rates/lower channel slope or get settled within the downstream sediments based on the hydrodynamic and sedimentation characteristics of the waterbody basins (Egessa et al., 2020; Faure et al., 2015; Haberstroh et al., 2021; Lechthaler et al., 2020; van Emmerik & Schwarz, 2020). Wind-induced water currents, urban surface runoff, drainage waste discharge, and flood events also play equally important roles in the dispersion of low-density plastics toward the shoreward regions (Bruge et al., 2018; Egessa et al., 2020; Faure et al., 2015; Roebroek et al., 2021; van Emmerik et al., 2019b). High-density polymers (> 1000 kg/m^3) sink to the sediment beds in the absence of intense water currents. Low-density macro-polymer products like bottles and polythene bags lose their buoyancy on getting filled with water or wrapped by microbial biofilms (Al-Zawaidah et al., 2021; Gabbott et al., 2020; Lechthaler et al., 2020; van Emmerik et al., 2022). Once the water current–mediated buoyant plastic particles reach the embayment of marine interlinked water systems, the dual action of both these water currents shall determine the fate of polymer types (van Emmerik et al., 2022).

Most of the plastic wastes discarded at the banks or riparian zones disintegrate into smaller fragments due to physical, chemical, and biological processes (Delorme et al., 2021). Physical degradation of plastics involves wave actions, sediment-mediated abrasions, and/or digestive segregation by different organisms (Barnes et al., 2009; Dawson et al., 2018; Mateos-Cárdenas et al., 2020). Photo-degradation, thermal/thermo-oxidative degradation, hydrolysis, corrosive chemical or solvent-mediated deterioration, and bio-degradation bring about chemical degradation (van Emmerik et al., 2022). Prolonged exposure to direct ultraviolet (UV) radiations and wind-induced frictions further ease plastic degradation at considerable rates (Andrady, 2011). After the polymer degradation, the resultant MPs get either deposited in the bed sediment, transported in the water path, or devoured by aquatic biota (Leslie et al., 2017). The MPs entrapped within the sediments get remobilized during flood conditions and further carried away downstream, eventually reaching the ocean.

MPs with a density marginally greater than water and a size range greater than 0.2 mm are likely to be retained in soils (Kumar et al., 2023b; Nizzetto et al., 2016a), forming a direct interaction with soil aggregates, affecting their distribution and mobility within soils (Rillig & Lehmann, 2020). A thorough analysis of the flood-flushed MP fragments retrieved from oceans reveals that microsynthetic polymer dispersion is least affected by entrapment factors when compared to macroplastics (Hurley et al., 2018; Treilles et al., 2022). In earlier studies, the plastic fragment types reclaimed from riverine systems mostly included soft, hard, and foams (Castro-Jiménez et al., 2019; Tramoy et al., 2019; van Emmerik et al., 2020). White, transparent, black, and colored particles with varied shapes such as fibers, films, fragments, and pellets were reported in the water and sediments of Poyang Lake in China (Yuan et al., 2019). Samples from Vembanad Lake in Kerala showed MPs in shapes such as fibers, foams, films, sheets, and fragments with HDPE, LDPE, PP, and PS polymer compositions.

The effects imposed by MPs on the aquatic community have aroused global concerns over the past decades. The general impact of MPs on the biotic community includes physical harm, toxicity, and even death. MPs have the potential to accumulate in the food chains and get biomagnified, imposing possible threats to human health. In addition, they can change the physical and chemical nature of aquatic ecosystems, affecting nutrient cycling and altering the structure and function of these ecosystems. The eco-toxicological effects of MPs are influenced by polymer type, shape, and size (Rillig & Lehmann, 2020).

The use of catchment areas as dump yards is perceived as their limited accessibility and visibility, which prompt the local residents and industries to discard the generated waste. Moreover, the lack of accessibility to the banks, channels, and sediments bed of water bodies make reclamation difficult, eventually causing the extensive spread and piling up of pollutants, resulting in pollution disasters in riparian areas (Domínguez et al., 2016). The spatial distribution and portability of MP pollutants in catchment regions are controlled by the population density, precipitation patterns, and the slope of the area (Nizzetto et al., 2016a; Scheurer & Bigalke, 2018; Yonkos et al., 2014; Zhou et al., 2021). However, currently, sufficient data is unavailable on MP accumulation pattern, constitution, and factors influencing its distribution within the soil.

In this paper, various aspects of the riparian soil MPs retrieved from the banks of three water body basins including two rivers and a lake water system connected to a marine environment are discussed. The study area includes polluted downstream portions of the Karamana River, Killiyar (a tributary of the Karamana River), and Akkulam-Veli Lake within Thiruvananthapuram Corporation, near the immensely urbanized and populated city, infamous for its waste generation patterns over the years. Both Karamana River and Akkulam-Veli Lake are notorious for their pollution status. Akkulam-Veli Lake, in addition to being a tourist destination, is a wetland system with fertile land with agricultural practices. A total of 24 sampling sites were identified along the water body basins for the purpose of soil MP estimation. The paper focuses on MPs with dimensions greater than 250 µm for the convenience of the study. Furthermore, an investigation of the influence of slope and land use class on the intensity of MP contamination was also done. This study is the first of its kind to characterize the spatial distribution of MPs with contributing factors in riparian soils of Thiruvananthapuram Corporation on a vast scale.

Materials and methods

Study site and sampling scheme

The basins of three water bodies were considered for this study which include Karamana River, Killiyar, and Akkulam-Veli Lake of Kerala, India. The total area selected for the study includes 39 wards of Thiruvananthapuram Corporation, which is 68.3 km^2 lying in between the latitudes 9°34′48″ to 9°0′0″ N and longitudes of 70°18′14″ to 71°37′40.8″ E. The sampling sites were fixed equidistant after visualizing the area in the Google Earth Platform and by field investigation of basin dumpsites.

Akkulam-Veli Lake is the oldest tourist destination with a tourist village and several other tourist attractions. It is situated in the north-western outskirts of Thiruvananthapuram District along the south-west coast of India. The lake covers an area of 0.76 km^2, situated between 8°31′14″ and 8°31′52″ North latitudes and 76°53′12″ and 76°54′6″ East longitudes. Akkulam-Veli Lake is a combination of two lakes, Akkulam and Veli, separated partially by a bund running across its length. Of these, the Veli Lake opens to the Arabian Sea a few times a year (10–14 days repeated 6 to 8 times a year) depending upon the influx of land drainage received through inlet streams and canals. For the rest of the time, it remains closed by a 150-m sandbar. The opening of the Veli Lake into the marine system during the dynamic drainage influx period facilitates the settled pollutants within the lake to get drained into the ocean. Lately, the lake has been exposed to sewage and domestic waste as a consequence of population explosion and urban clustering.

Karamana River is the second longest river flowing through Thiruvananthapuram City with a length of 68 km. The coordinates of the river basin lie between latitudes 8°27′36″ N to 8°38′24″ N and longitudes 76°54′0″ to 77°15′0″ E. The river originates in the Chemmunji Peak and the Adurai Malai, located at the southern tip of the Western Ghats at Agastyar Koodam and is formed by the convergence of several small streams like the Vaiyapadi Aar, Attai Aar, Thodai Aar, and the Kavi Aar (Sukanya & Sabu, 2020). From the origins, the river flows westward and merges with the Arabian Sea at Panathura near Kovalam. The river is named after a locality in Thiruvananthapuram City, known as Karamana, through which it flows. The watershed basin is mostly forested and the mainland consists of mixed dry land crops such as coconut, plantain, rice, tapioca, areca nut, and pepper (keralapages.org). The river has several bridges and dams across its length. It is the main source of surface water which fulfills the water requirement of the city and plays an important role in groundwater replenishment. TS canal, otherwise known as Parvathy Puthanar, running parallel to the coast holds untreated sewage effluents that rush into the river, polluting its lower streams (Sukanya & Sabu, 2020).

The Killiyar (latitudes 8°40′30″ N, 8°27′0″ N and longitudes 76°57′ E, 77°2′0″ E) is a ground-fed or spring-fed rivulet forming the largest tributary of the Karamana, which covers a distance of 24 km (Jyothylakshmi and Abraham, 2020). Killiyar starts from Nedumangad, flows through Thiruvananthapuram City, and joins the Karmana River at Pallathukadavu. The tributary has five stream dams to regulate the water flow. A portion of the water deviates toward the Kochar channel and from there to the Padmatheertham pond. The ultimate destination of the river is the Arabian Sea through the Pozhikkara estuary. A part of the river runs parallel to the sea, known to be

Edayar. Like the Karamana River, Killiyar has also turned into a dumping site, where the waste materials from hospitals, factories, markets, households, city drainage, and garbage runoff are piled up. The major source of MP pollutants in the river is single-use plastics from households and the marketplaces. Several news reports have been published on the contamination of Akkulam-Veli Lake, Karamana River, and its tributary, Killiyar basins, with plastic waste. These factors necessitate the selection of this area for the current study.

The sampling scheme for the study involves soil sampling at 24 riparian sites along the basins of Karamana River, Killiyar, and Akkulam-Veli Lake during the month of March 2022. The sampling sites are given in Fig. 2. At each sampling site, a composite soil sample consisting of 15 soil cores (30 cm diameter and 10 cm depth) was collected from the areas that

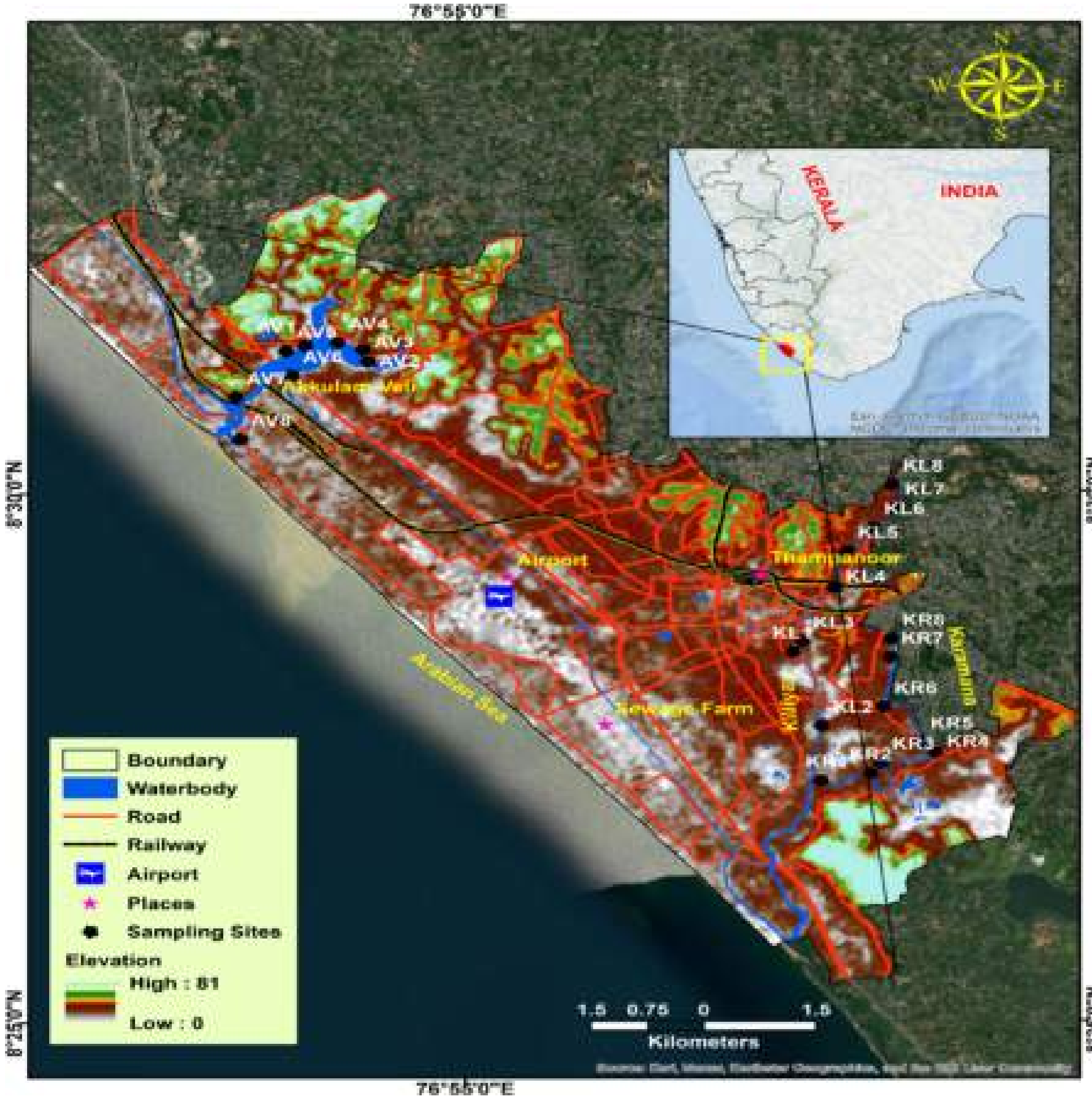


Fig. 2 Study area map with geographic position of sampling sites, important places, and features

were 0.5–1 m above the water level and at least 0.5 m away from the bank of the waterbody. The sampling method used was a modified version of the NOAA (National Oceanic and Atmospheric Administration) Technical Memorandum (Masura et al., 2015), with reference to Rafique et al. (2020) and Sruthy and Ramasamy (2017). A total of 24 basin soil samples were collected from the study area.

MP extraction from soil

The separation method for MP extraction from the soil is detailed in this section. Soil samples weighing 100 g were placed overnight in a hot air oven in the laboratory at about 60 °C to remove the excessive moisture content of the soil. The dry-weighed samples were then preserved in petri dishes and covered with aluminum foil to guard against aero-dynamic MP contamination. The dried samples were then transferred to a 500-mL beaker and stirred thoroughly with a previously prepared solution containing equal amounts of NaCl and $ZnCl_2$. The mixture was kept covered and undisturbed for 24 h. $ZnCl_2$ solution was used specifically for the separation of high-density polymers. Three sieves were used for the separation process with pore sizes 4.7, 1, and 0.3 mm. The floating debris in the supernatant was sieved through the sieve stack and the final fluid was collected for further filtration using a Whatman 0.45-μm-pore-size cellulose membrane filter with a vacuum pump–connected filtration unit. The other three levels of sieved debris including > 4.7, 1, and 0.3 mm were collected in glass petri dishes and covered properly. Larger particles like stones, plant roots, wood chips, degraded leaves, and plastic particles greater than 5 mm were removed manually from the sieves. Smaller particles were separated using fine-tipped brushes. The samples that remained after sieving were subjected to density separation, and the whole process was repeated three to four times to retrieve maximum plastic particles from the sample. Except for 0.3-mm-sized microparticles, all other filtered debris was dried in a hot-air oven at 50–60℃ for visually analyzing MPs. Particles with 0.3-mm size were subjected to organic matter digestion using 5 mL of 30% H_2O_2, 20 mL of ferrous sulfate solution, 6 g of NaCl (NOAA Technical Memorandum: Masura et al., 2015), and 30 mL of $ZnCl_2$ solution. The digested sample was then subjected to the density fraction method using a centrifugation unit at 4000 *g* for 5 min after manually shaking the solution. Finally, the supernatant with suspended MPs was collected and analyzed using a binocular microscope as per Klein et al. (2015) for morphological analysis. LabRAM HR Evolution Raman microscope was used to analyze the polymer composition of the identified plastic particles. A flow chart of the sampling scheme is given in Fig. 3.

Contamination reduction measures followed in the laboratory

In the laboratory, precautions were taken to avoid potential background contamination. Nitrile gloves and laboratory coats made of cotton fabric were worn during the whole process to avoid synthetic fiber contamination. Before usage, all the prepared solutions, the controls, and the distilled water collected were filtered through cellulose membrane filters with pore size 0.45 μm to avoid any means of cross-contamination. The results shown by the blank clearly indicated the absence of contamination while conducting the extraction procedure. The experiment was repeated to check the accuracy of the results. After filtration, filter membranes were placed in clean peri dishes for microscopic examination (Yaun et al., 2019).

MP categorization based on size shape, color, and polymer type

MPs were identified and categorized based on the visible characteristics, i.e., size, shape, and color. On the basis of shape, the particles were classified into flakes, fragments, filaments, fibers, sheets, and forms. The size-wise classification was done with dimensions > 4.75 mm, 4.75 mm, 1 mm, and 300 μm (0.3 mm). Classification based on color categorized the particles into white, colorless, red, blue, light yellow, and light brown colored. The hot-needle testing method was performed to confirm whether the identified particles were plastics or not and plastic particles showed a distinct melting while non-plastics burnt into ashes on heating (De Witte et al., 2014).

Calculations

Moisture content

To assess the moisture content of the samples, a specific quantity of the sample (100 g) was taken in terms of dry soil using the below formula (Rafique et al., 2020):

$$S_w = \frac{S_d}{M_c}$$

Fig. 3 Scheme of the study

where S_w = weight of wet sample taken for analysis in grams, S_d = weight of dry sample required in grams, and M_c = sample moisture content in percentage.

Concentration of MPs

The final concentrations of MPs were calculated in MPs per kilogram using another formula:

$$\text{MP concentration} = C_m \times 10$$

where C_m = number of confirmed MPs observed in the sample.

MP abundance

The abundance of MPs in the soil samples was calculated by Gray et al. (2018), Xiong et al. (2018), and Irfan et al. (2020b):

$$\text{Microplastic abundance} = \frac{\text{Number of MPs oberserved per sample}}{\text{Size of sample}}$$

Statistical analysis, spatial mapping, land use land cover mapping, and slope and buffer analysis

Descriptive statistical analysis and graphical representations (i.e., graphs and chart preparation) were done using MS Excel 2016. ArcGIS 10.4.1 was used for chart representations and for creating spatial distribution maps. Pearson correlation analysis was performed to analyze the relation between slope and MP abundance, where correlation coefficient (r), level of significance (p-value < 0.05), degrees of freedom (df), and t statistics (t) were estimated using RStudio statistical package (R 4.3.0 Console). Land use land cover classification was performed using Landsat OLI Imagery (9 bands) downloaded from USGS Earth Explorer during the month of March 2022. The data used had only less than 10% cloud cover. Erdas Imagine 2015 along with ArcGIS 10.4 and Google Earth Pro were used for the overall classification process.

K-Mean clustering algorithm was used as an unsupervised learning process as this method is the best applicable in visual data exploration. The total area was divided into six categories: (1) built-up; (2) farmland; (3) open scrub; (4) surplus land; (5) trees; (6) waterbody.

The slope (%) of the area was estimated from the SRTM 1 Arc-Second Global DEM with 30-m resolution (year of availability: 2014), acquired from the USGS Earth Explorer website. The voids within the data were removed using the DEM fill tool in the hydrology tool set to remove negative values. The slope calculator in the Surface toolset within Spatial Analyst tools was used for the generation of the slope layer. The slope was grouped into six classes including 0–0.5 (depression to level), 0.5–2 (very gently sloping), 2–5 (gently sloping), 5–9 (moderately sloping), 9–15 (strongly sloping), 15–30 (steeply sloping), and > 30 (very steeply sloping) (Soil Classification Working Group, 1998).

Result and discussion

MP pollution status in environmental compartments

The study showed that all the samples collected had MPs with an average concentration of 652 ± 54.25 items/kg, ranging from 310 to 1170 items/kg. There was a total of 15,650 MP particles with a size range of 0.3 to 4.7 mm (Table 1). The results are in consensus with studies conducted in Switzerland with an average amount of < 593 items/kg (Scheurer & Bigalke, 2018) and Germany, with an average amount of 1000–24,000 items/kg (Bläsing & Amelung, 2018). A study conducted in the agricultural soils of two different regions of China showed an average concentration of 18,760 items/kg (He et al., 2018) and 65.75 ± 13.92 items/kg in subsoils (Liu et al., 2018) and 84.75 ± 13.22 items/kg in top soils. Application of sewage sludge for fertilizer was observed as the reason for the higher concentrations, whereas a lower concentration of MPs in Loess plateau farmland soils of China (< 0.54 mg/kg) represented the reduced influence of urban communal activities at the vicinity of the region (Zhang et al., 2018).

In the study, despite significant anthropogenic activities and the potential for multiple MP sources, the observed concentration of MPs remained relatively low. This may be attributed to the insufficient maturation of plastic waste deposits in the area, not having aged sufficiently to transform into MPs as their degradation typically requires an extended period. The size range of the identified MPs in the study ranges from 0.3 mm (300 μm) to 4.75 mm. A comparison with previous studies on MP content within soil and sediment compartments is provided in Table 2. The highest MP concentration was recorded in KR_3 soil (1170 ± 2.89 MP/kg), followed by KL_2 (1120 ± 2.89 MP/kg), while the lowest concentration was found in the soil sample from AK_8 (310 ± 5.77 MP/kg) (Table 1, Fig. 4). A visual representation of MP concentrations across various sampling locations is illustrated in Fig. 5.

Sample sites exhibiting higher MP concentrations (specifically KR_3, KL_2, and KL_4 with MP concentration exceeding 1000 items/kg) were associated with the built-up land cover class as indicated by pixel value (Fig. 6). The LULC classification reflects the proximity of sampling points to the populated city areas (Table 3) and highlights the impact of human interventions on riparian soils.

Sampling stations KR_3, KL_2, and KL_4, characterized by higher MP contamination, were situated in areas with gentle slopes (2–5%) (see Table 4). In contrast, the AK_8 sampling station, exhibiting the lowest MP counts, is associated with the open scrub land cover class and features a moderate slope range (5–9%). Refer to Fig. 7 for the map illustrating the sampling locations and their respective slope ranges.

Killiyar soil samples exhibited the highest MP count among the three waterbody basins, registering 6390 items/kg, with an average abundance of 0.79875 ± 0.09 and a mean MP concentration of 81.25 items/kg (Table 5, Fig. 8). The observation is justified by its proximity to the city center, where the shore area is densely settled and fully urbanized. In contrast, the landscape pattern of the Karamana River shows a small tree-covered gap between the river and the adjacent urban area, providing a narrow buffer zone that shields the river bank from urban community interventions (Fig. 6).

Corradini et al. (2019) reported MP count in Chilean agricultural fields ranging from 0.6 to 10.4 items/g (equivalent to 600–10,400 items/kg). A similar MP count was exhibited by the KL_3 sample site (980 ± 3.46 MP/kg), located near Kerala Agricultural University's agricultural land. Intensive MP pollution at agricultural

Table 1 MP abundance, color type, polymer type, and sizes in basin soils of the study area

Sampling site	MPs/kg	MP abundance	MPs color type							MP polymer type							MP size		
			CL	WT	OR	RD	L.Y	L.B	BL	HDPE	LDPE	PET	PP	PS	Nylon	4.7 mm	1 mm	0.3 mm
KR_1	480 ± 4.62	0.48 ± 0.01	320	120	0	10	30	0	0	50	100	40	160	70	60	50	180	250
KR_2	890 ± 1.15	0.89 ± 0.003	170	520	20	0	180	0	0	30	290	140	330	80	20	80	230	580
KR_3	1170 ± 2.89	1.17 ± 0.01	450	320	120	30	90	140	20	60	470	240	190	170	40	120	360	690
KR_4	820 ± 1.73	0.82 ± 0.01	210	440	10	20	60	80	0	40	320	120	270	40	30	90	240	490
KR_5	670 ± 1.73	0.67 ± 0.003	0	370	80	40	140	0	40	0	250	160	200	60	0	100	200	370
KR_6	550 ± 4.04	0.55 ± 0.02	360	140	20	20	0	10	0	60	300	70	100	0	20	140	130	280
KR_7	320 ± 1.15	0.32 ± 0.01	120	100	10	20	40	20	10	30	150	40	70	20	10	120	80	120
KR_8	470 ± 1.15	0.47 ± 0.01	240	190	0	0	30	10	0	0	210	80	110	70	0	100	100	270
KL_1	580 ± 2.31	0.58 ± 0.003	80	260	0	20	50	160	10	20	130	120	220	50	40	30	210	340
KL_2	1120 ± 2.89	1.12 ± 0.01	140	610	40	50	130	120	30	80	450	150	170	180	90	160	310	650
KL_3	980 ± 3.46	0.98 ± 0.01	150	540	70	40	170	0	10	30	390	190	310	40	20	130	310	540
KL_4	1110 ± 0.58	1.11 ± 0.003	490	390	90	30	80	10	20	20	520	50	360	130	30	140	280	690
KL_5	840 ± 1.73	0.84 ± 0.01	580	140	20	0	60	30	10	50	300	130	220	90	50	80	250	510
KL_6	810 ± 5.77	0.81 ± 0.02	250	430	0	0	110	20	0	30	420	110	200	40	0	190	220	400
KL_7	550 ± 2.39	0.55 ± 0.01	190	240	50	20	0	30	20	40	190	70	240	0	10	190	150	210
KL_8	400 ± 2.31	0.4 ± 0.1	50	110	0	0	220	20	0	10	100	30	150	120	0	60	110	230
AV_1	780 ± 1.73	0.78 ± 0.01	70	610	0	20	80	0	0	20	330	80	260	90	0	40	250	490
AV_2	370 ± 0.58	0.37 ± 0.02	0	250	10	0	60	50	0	30	70	50	140	60	20	50	90	230
AV_3	570 ± 4.04	0.57 ± 0.01	200	320	0	20	0	10	20	10	260	20	190	70	20	30	200	340
AV_4	320 ± 2.89	0.32 ± 0.01	170	70	0	10	50	10	10	0	110	30	80	90	10	100	50	170
AV_5	440 ± 1.73	0.44 ± 0.003	220	60	40	0	100	0	20	20	80	50	150	120	30	30	60	350
AV_6	640 ± 2.31	0.64 ± 0.01	260	310	0	0	40	20	10	10	140	60	230	190	10	60	160	420
AV7	460 ± 1.15	0.46 ± 0.02	320	0	20	10	80	10	20	30	100	20	170	130	0	50	230	180
AV_8	310 ± 5.77	0.31 ± 0.01	150	70	10	20	50	10	0	10	30	10	80	170	10	20	80	210
Total	15,650	15.65 ± 0.34	519	661	61	38	185	76	25	68	571	206	460	208	52	216	448	901
%	–	–	33.2	42.2	3.9	2.4	11.8	4.9	1.6	4.4	36.5	13.2	29.4	13.3	3.3	13.8	28.6	57.6

KR Karamana, *KL* Killiyar, *AV* Akkulam-Veli, *CL* colorless, *WT* white, *OR* orange, *RD* red, *L.Y* light yellow, *L.B* light brown, *BL* blue, *HDPE* high-density polyethylene, *LDPE* low-density polyethylene, *PET* polyethylene terephthalate, *PP* polypropylene, *PS* polystyrene, % percentage

Table 2 A global comparison of MP abundance, polymer type, and particle shape in different soil and sediment compartments

Country	Sample type	MP abundance	Polymer type	Particle shape	Reference
India, Kerala	Lake and river basin soils	310–1170 MPs/kg	LDPE, HDPE, PET, PP, PS, nylon	Fragments, flakes, sheets, foams, filaments, and fibers	Present study
Switzerland	Floodplain soils	< 593 MPs/kg	PE, PS, PVC, SBR	Not identified	Vaughan et al. (2017)
Yangtze River Basin	Soil samples	3877 ± 2356 p kg^{-1}, subsoils (4005 ± 2472 p kg^{-1}), top soils (3748 ± 2301 p kg^{-1})	PP, PS, PE, PVC, PC, PET, polyacrylonitrile, polyvinyl fluoride, polyacrylates, polyurethanes, polyvinyl acetate, polyamide	Fragment, bead, fiber, pellet, foam, and film	Fischer et al. (2016)
Germany	Soil	1000–24,000 MPs/kg	PE, PVC, PP, PET	Fragment, film, sheet	Corradini et al. (2019)
China	Soil	7100–42,960 MPs/kg	PE, PP, PVC	Films, bead (others not mentioned)	Scheurer and Bigalke (2018)
Lahore district	Top soils	1750 to 12,200 MPs/kg	PS, PP, PE, polyester	Fragment, fiber, sheet, bead, and foam	Blasting and Amelung (2018)
China (Shanghai)	Farmland soils	78.00 ± 12.91 62.50 ± 12.97 item/kg	PP, PE, PES	Fiber, fragment, and film	Rodrigues et al. (2018)
China	Loess plateau farmland soil	< 0.54 mg/kg	PE	Not identified	Zhou et al. (2021)
Chile	Sludge-treated agricultural soil	0.6–10.4 MPs/g	PVC, nylon, LDPE, polyester, acrylic polymer	Fiber, film, pellets, fragment	Su et al. (2021)
Huangshui River and Dagu River basins, China	Basin soil and groundwater	3352 items in total	PE and PA	Fiber, films, and granules	He et al. (2018)
UK urban lake	Lake sediments	25–30 particles in 100 g of dry sediments	Not identified	Film and fiber	Xia et al. (2021)
Bolsena and Chuisi Lake, Central Italy	Lake sediments	112 (Lake Bolsena) to 234 particles/kg dry weight (Lake Chiusi)	Not identified	Fibers and fragments	Yaun et al. (2019)
Poyang Lake, China	Lake sediment	54–506 items/kg	PP and PE	Fibers, films, pellets, and fragments	Liu et al. (2018)
Rawal Lake Pakistan	Lake sediments	MP abundance 1.04 items/0.01 kg (104 items/kg)	PE, PP, polyesters, PET, PVC	Fibers and fragments	Zhang et al. (2018)
Veeranam Lake, Tamil Nadu	Lake sediments	92–604 items/kg	Nylon, polyethylene, PVC, PS, PP	Fibers, fragments, foam, pellets	Rafique et al. (2020)
Vembanad Lake, Kerala	Lake sediments	96–496 particles m^{-2}	LDPE, PE, and PS	Fragments, fibers, foams, and films	Irfan et al., (2020a, 2020b)

Table 2 (continued)

Country	Sample type	MP abundance	Polymer type	Particle shape	Reference
Antuã River (Portugal)	River sediments	100–629 items/kg in March, 18–514 items/kg in October	PE, PP, PS, PET, EVA, PVA, PTFE, PMMA, PEA, cellulose acetate, SBR	Foams and films	Sarkar et al. (2019)
Liangfeng River	River sediments	6950–149,350 MPs/kg	PE, PVC, PS, PP, and PA	Fragment, film, fiber, foam, pellet	Ram and Kumar (2020)
Ganga River (River Ganges)	River sediments	107.57–409.86 items/kg	PET, PE, PP, PS	Fibers, fragments, and films	Srinivasalu et al. (2021)
Sabarmati River, Ahmedabad	River sediments	47.1 mg (MP size from 75 to 212 µm) and 4 mg (212 µm to 4 mm)	Not identified	Fibers, films, and foams	Sruthy and Ramasamy (2016)

HDPE high-density polyethylene, *LDPE* low-density polyethylene, *PET* polyethylene terephthalate, *PP* polypropylene, *PS* polystyrene, *PVC* polyvinyl chloride, *PC* polycarbonate, *PE* polyethylene, *PES* polyethersulfone, *PA* polyamide, *EVA* ethylene vinyl acetate, *PVA* polyvinyl alcohol, *PTFE* polytetrafluoroethylene, *PMMA* polymethyl methacrylate, *PEA* polyethylene adipate, *SRB* styrene butadiene

lands is mostly attributed to plastic mulching; solid waste disposal; runoff from residential, commercial, and construction areas; use of sewage sludge as manure; and irrigation with water from contaminated urban water channels (Mahon et al., 2017; Majewsky et al., 2016; Nizzetto et al., 2016b; Willén et al., 2017; Li et al., 2018; Zhang and Liu, 2018).

Though there is only a limited reference available on MP contamination in riverine basin soils, a similar study was found to be conducted by Zhou et al. (2021) on the Yangtze River basin, revealing higher subsoil MP concentrations (4005 ± 2472 items/kg) than surface soil concentrations ((3748 ± 2301 items/kg). This suggests the submerging property of plastic particles within the soil. The study identified correlations between MP concentration and factors such as population density, precipitation, and elevation. Deeper soils exhibited higher MP concentrations due to the continuous deposition of washed-out soil over less mobile deposits, facilitating soil microbial, physico-chemical, and earth pressure factors in the degradation of inorganic polymer waste. Over time, macro-polymers become less flexible and gradually disintegrate into MPs in the topsoil too. Smaller particles are easily transferred to subsoils via soil pores (Hurley et al., 2018; Lazar et al., 2010). Su et al. (2021) found a total of 3352 MPs in the soil and groundwater samples of Huangshui and Dagu River basins in China. Most of the samples collected for their study were from agricultural lands and their MP contamination status reflects the human interventions in the area.

In the current study, most of the Killiyar basin sampling sites were dumping sites of relatively recent origin. Despite their age, these sites exhibited higher MP contamination due to the quantity and quality of dumped waste. Several smaller waste dumps of the city, found at junctions, roadsides, and unattended properties, contribute to MP formation, which reaches sewage drainage systems, rivers, and other water bodies. Shore-deposited macroplastics, along with MPs, undergo further degradation facilitated by detritivores in organic carbon-rich basin soils (Chae & An, 2018; Rillig et al., 2017; da Costa Araujo & Malafaia, 2021; Le Guen et al., 2020). Despite the higher MP concentrations in the Killiyar River basin (6390 ± 0.09 MP/kg), the values were comparatively lower than those reported in non-river basin soil studies by He et al. (2018) and Rafique et al. (2020).

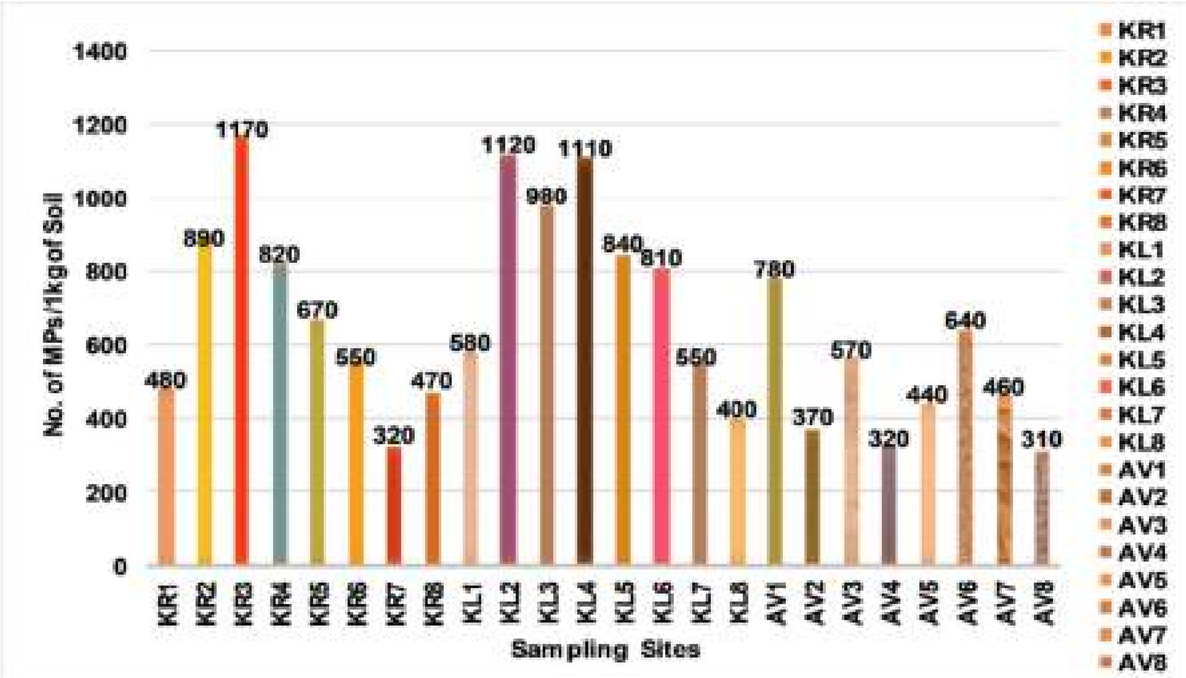


Fig. 4 MP abundance per kg of basin soil samples

Drains and roadsides receive urban sewage with significant MP quantities, including tire wear particles, wind-transferred MPs, and degraded/burned macroplastic litter (Knight et al., 2020; Rafique et al., 2020; Su et al., 2020; Wong et al., 2020). Water-flushed MPs reach the rivers and lakes, where they either settle in sediments or get transported to shores through water currents.

The lowest MP concentrations were found in Akkulam-Veli Lake basin soils, notably at station AV_8 (310 ± 5.77 MP/kg) near Veli parking grounds, emphasizing its cleanliness as a tourist destination. Despite this, on-shore regions reported higher macroplastic contamination. Rapid urbanization around the lake, marked by new constructions (apartments, restaurants, malls (Mall of Travancore and LULU mall), hospitals (PRS, Lords) tourist destinations, and commercial buildings), contributes to water quality issues. Plastic waste accumulates in the water hyacinth (*Pontederia crassipes*) population in the lake which gets transported to shores by wind or water flow, or gets submerged in sediments along with aquatic plant debris. The highest MP concentration in the Akkulam-Veli Lake basin was exhibited by the AV_1 site (780 ± 1.73 MP/kg), situated too close to the waterbody, with a steep slope at the lake entry point, promoting waste drainage into the lake from upper lands. Sloping terrain and rock particles increase friction-induced abrasions on the waste, generating more trapped MPs in drained soil particles.

Various reports highlighted the MP contamination in lake and riverine sediments (Fischer et al., 2016; Irfan et al., 2020b; Ram & Kumar, 2020; Rodrigues et al., 2018; Sarkar et al., 2019; Srinivasalu et al., 2021; Sruthy & Ramasamy, 2017; Vaughan et al., 2017; Yaun et al., 2019). For instance, the UK's Edgbaston Lake sediments showed a MP count of 25–30 items/100 g of dry sample (250–300 items/kg), while Bolsena and Chuisi Lake sediments in Italy reported a count of 112 and 234 items/kg, respectively (Fischer et al., 2016).). A study by Vaughan et al. (2017) highlights the biofouling properties of macro-polymers, which sinks the debris into deeper sediments and gradually break down into MPs. Lake characteristics, wind patterns, precipitation, tide range, and land-based effluent discharge can influence MP concentrations (Fischer et al., 2016). Rawal Lake sediments in Pakistan exhibited a concentration of 104 items/kg and showed the influence of population density, waste

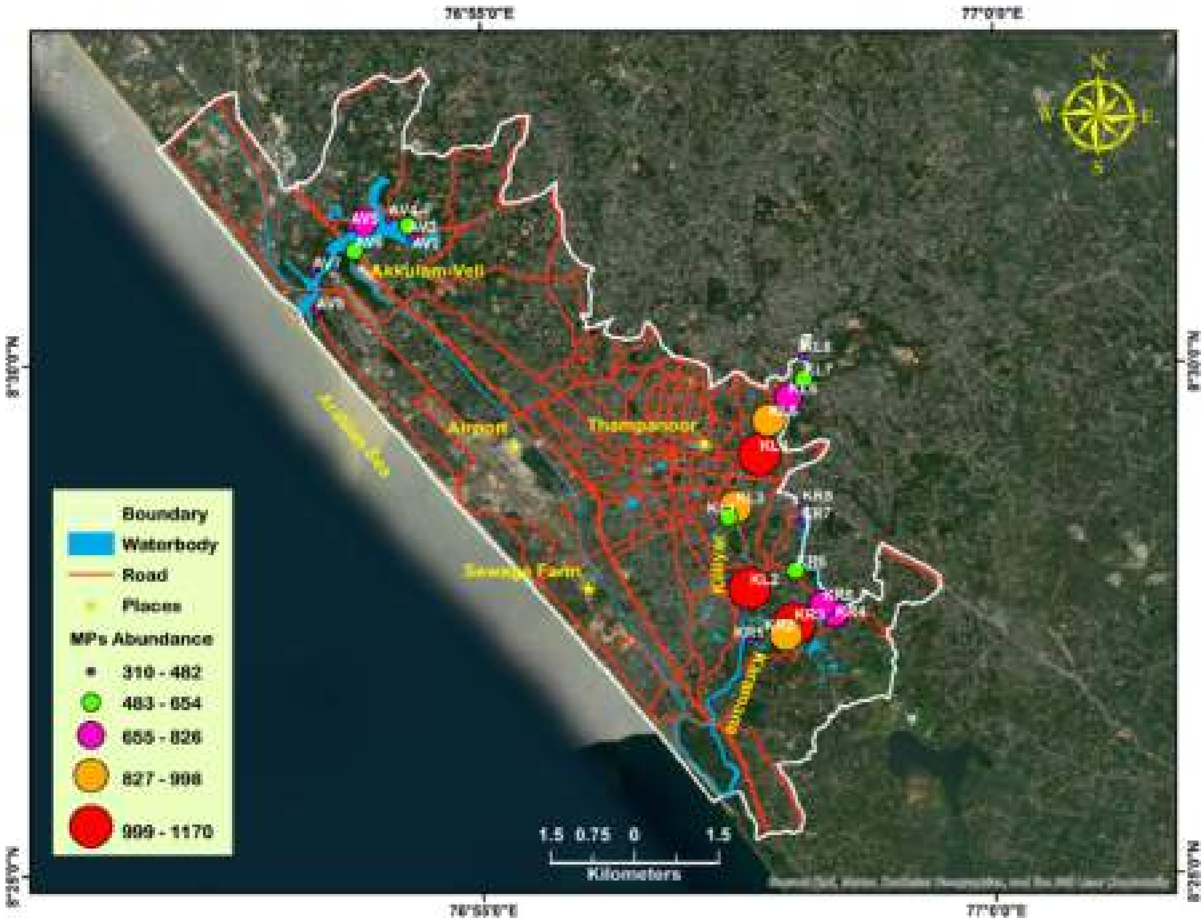


Fig. 5 MP abundance shown in the sampling sites

littering, recreation, and tourism (Fischer et al., 2016). Veeranam Lake (Tamil Nadu) and Vembanad Lake (Kerala) sediments analyzed for MP pollution that showed ranges of 92–604 items/kg of dry sediment sample and 96–496 particles/m^2, respectively (Srinivasalu et al., 2021; Sruthy & Ramasamy, 2017), are comparable to the present study.

Increased precipitation, flow rates, and drainage input from Kollidan and Vellar rivers contributed to Veeranam Lake's MP pollution (Srinivasalu et al., 2021). Vembanad Lake contamination was due to the discharges from urban bypassing rivers, streams, and canals (Mohan et al., 2014; Ramasamy et al., 2012; Sruthy & Ramasamy, 2017). This study represents one of the earliest MP analyses in Kerala. MP concentrations in lake sediments from the UK, Central Italy, Pakistan, Tamil Nadu, and Kerala aligned closely with the results of the current study (1170–310 items/kg) (Table 1 and 2). Similar results were also shown by the Antuã River in Portugal (100–629 MPs/kg), Liangfeng River in China (6950–149,350 MPs/kg), River Ganga in India (107.57 items/kg–409.86 items/kg), and Sabarmati River in Ahmedabad, India (47.1 mg—75 to 212 µm; 4 mg—212 µm to 4 mm) (Table 2). The high MP concentration in Liangfeng River was due to its contamination with effluent from the upstream wastewater treatment plant (Xia et al., 2021). River Ganga faces significant MP pollution from industrial cities and effluent points (Sarkar et al., 2019). MP content in the Sabarmati River results from human interventions, effluent emissions, water system stagnancy, and urban release (Ram & Kumar, 2020). Antuã River in Portugal exhibits spatial and temporal

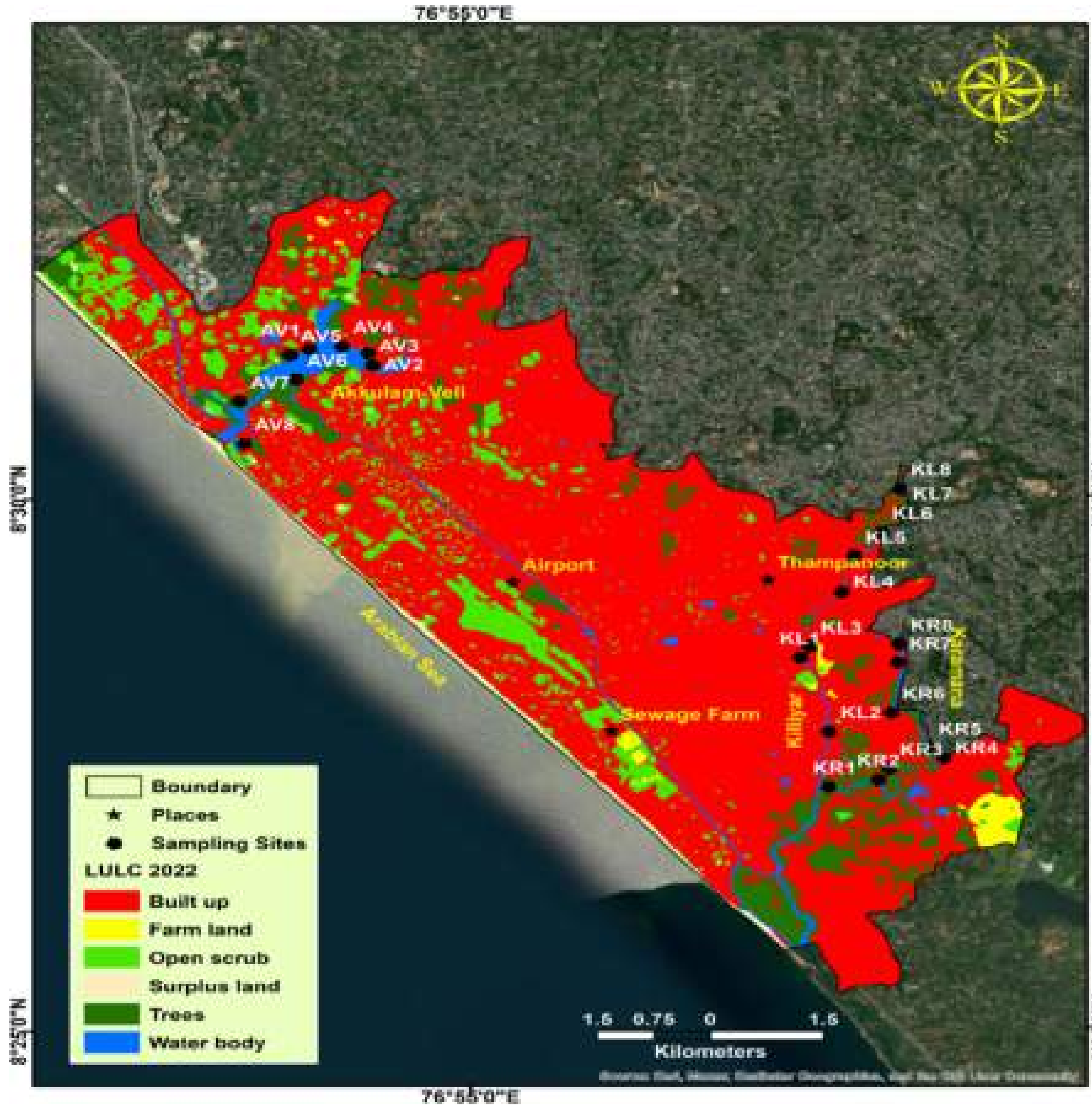


Fig. 6 Land use land cover classification of the study area for the year 2022

variations in MP concentrations, linked to precipitation patterns, river hydrodynamics, and proximity to urbanized areas (Rodrigues et al., 2018).

Micro-polymer color, shape, composition, and sizes

This study assessed three visual characteristics of the particles: color, shape, and size. The seven hues identified for the study were white, transparent, blue, orange, red, light yellow, and light brown. Shapes included fibers, fragments, and filaments (Table 5, Fig. 9). The distribution of MP shapes in the sample is depicted in the map (Fig. 10).

The sizes analyzed in the study were 0.3, 1, and 4.7 mm. The MP particles appeared as sharp, dull colored or transparent, either smoothened over the

Table 3 Area and sampling sites under each LULC class

SL no	LULC type	Area under each LU type (km^2)	Samples under the LU type
1	Built up	54.070862	KR_2, KR_3, KR_4, KR_5, KR_6, KR_7, KR_8, KL_2, KL_3, KL_4, KL_6, KL_7, KL_8, AV_3, AV_4, AV_6
2	Farmland	0.760322	–
3	Open scrub	5.822289	AV_8
4	Surplus land	0.792548	–
5	Trees	1.880003	KR_1, AV_5, AV_7
6	Waterbody	4.89936	KL_1, KL_5, AV_1, AV_2

LULC land use land cover, *LU* land use

Table 4 Slope range, slope type, area under slope, and sampling stations in each slope range of study area

SL no	Slope range (%)	Slope type	Area under slope (km^2)	Samples under the slope
1	0–0.5	Nearly level	0.412099	–
2	0.5–2	Very gently sloping	6.385728	KL_1, KL_5
3	2–5	Gently sloping	25.5606	KR_2, KR_3, KL4, KL2, KL_3, KL_4, KL_7, KL_8, AV_2, AV_3, AV_6
4	5–9	Moderately sloping	20.20988	KR_4, KR_5, KR_6, KR_7, KR_8, KL_6, AV_5, AV_8
5	9–15	Strongly sloping	10.17462	$KR_{1,}$ AV_1, AV_4, AV_7
6	15–30	Steeply sloping	4.964604	–
7	> 30	Very steeply sloping	0.320499	–

KR Karamana, *KL* Killiyar, *AV* Akkulam-Veli

edges or degrading, filmy, glossy, flat and thickened, elongated and fiber-like, spongy, filamentous, and mud stained. Among six shapes, fragments were most abundant (31.12%), followed by flakes (23.77%), sheets (17.76%), foams (14.63%), filaments (9.39%), and fibers (3.32%) within the basin soil samples (Table 5). Fragment percentage was highest in Killiyar (41.78%), followed by Karamana (32.77%). The order in abundance of shape was fragments > flakes > sheets > foams > filaments > fibers. Akkulam-Veli Lake basin showed a different order, with foam as the most abundant one (31.88%), followed by flakes (25.96%), sheets (20.31%), fragments (11.31%), filaments (7.97%), and fibers (2.57%). Fibers were the least found shape in all basins. The highest number of fibers (3.76%) were in the Killiyar basin soil and the least (2.57%) was in the Akkulam-Veli basin. KR_3 had the most fragments and AK_4 had the most foams. Macro-polymer type can influence the shape of MP particles formed during degradation and the size and shape of thus formed MPs can determine the intensity of impact imposed on the living system.

According to the 2016–2017 Extended Producer Responsibility (EPR) report jointly prepared by Thanal and Green Army for Thiruvananthapuram Corporation, the urban center with nearly 250,000 households generates 4242 tons of plastic waste annually (Kumar, 2018). Despite the 47 Resources Recovery Centers (RRCs), the city's waste management system faces challenges with improperly managed RRCs, potentially losing plastic litter during heavy rain or wind events (Jambeck et al., 2015). Commonly generated wastes include single- and double-layered single-use plastic products such as LDPE-graded curd and milk covers, ready-made batter packages, disposable glasses, plastic plates, oil covers, snacks and food packages, cosmetic, sanitary, and healthcare products, tubes and bottles, sachets; polypropene-graded laminated sheets, wire meshes, medicine strips, and HDPE-graded bottles, containers, and boxes. River contamination is aggravated due to the proximity to urban settlements, driven by a lack of awareness or non-compliance with authorities' mandates and rules, leading residential and industrial communities to improperly discard plastic waste.

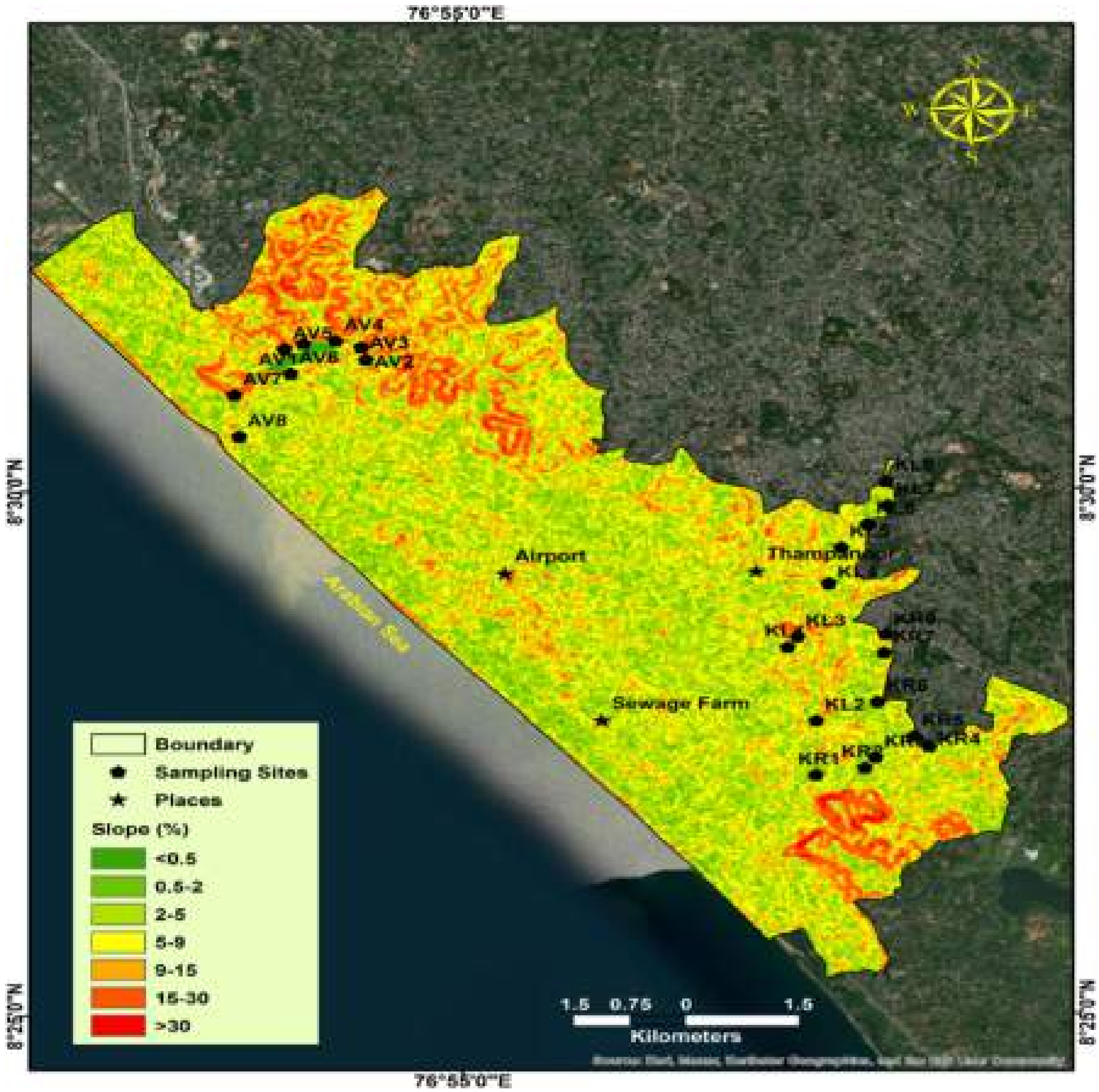


Fig. 7 Slope ranges of the study area

This study identifies micro-fragments as the predominant shape type in the area, consistent with findings in previous studies (Mehdinia et al., 2020; Urban-Malinga et al., 2020; Wang et al., 2018a, 2018b; Zhou et al., 2021), reflecting their high frequency in various environments. The spatial distribution of MP shapes is influenced by local activities, industrial processes, runoff from streets and drains, wind action, and distance from sources (Ogonowski et al., 2018). Micro-fragments, primarily resulting from the degradation of macro and meso plastics, are categorized as "secondary microplastics" (secondary MPs) (Wang et al., 2018b). Fragmentation or degradation reduces MP size, increasing its bioavailability to organisms and potential biomagnification (Cole et al., 2011; Sruthy & Ramasamy, 2017). Micro-fragments originate from rigid plastic items like bottles, containers, toothbrushes, bottle caps, buckets, and

Table 5 Average abundance and shape of MPs in Karamana, Killiyar, and Akkulam-Veli

Sampling area	Total MPs/kg	Mean MPs	Avg. abun	Particle shape					
				Flakes	Fragments	Filaments	Sheets	Foams	Fibers
KR	537	65.75	0.67125	1280	1760	600	1180	370	180
KL	639	81.25	0.79875	1430	2670	560	810	680	240
AV	389	48.625	0.48625	1010	440	310	790	1240	100
Total				3720	4870	1470	2780	2290	520
Percentage (%)				234.7	311.2	93.9	177.6	146.3	33.2

Avg. abun. average abundance

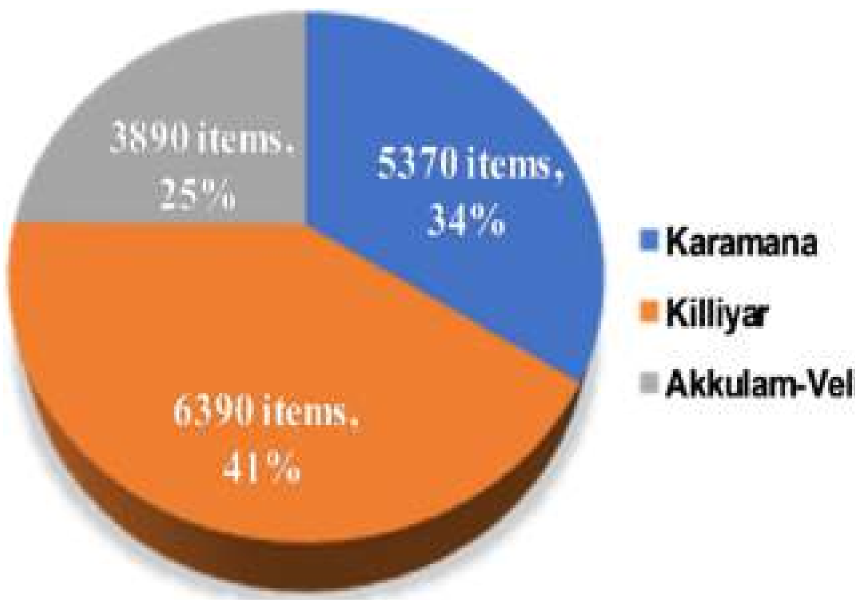


Fig. 8 Abundance proportion of MPs in Karamana, Killiyar, and Akkulam-Veli

plastic utensils. Machado de Souza et al., 2018) noted higher persistence of micro-fragments within soil aggregates, particularly in sub-surface soils.

Reports indicate synthetic microfibers as a significant MP type, following micro-fragments (Lots et al., 2017; Mahon et al., 2017). Mostly composed of polyester, nylon, and polyethylene, microfibers originate from clothing, household items, sewage sludge, and industrial activities (Zhou et al., 2021; Brahney et al., 2020; Li et al., 2019; Liu et al., 2019). Sources of these MPs comprise laundry wastewater, municipal sewages, tire wear particles, and suspended air particles (Anthony et al., 2011; Hernandez et al., 2017; Wang et al., 2018a; Leads & Weinstein, 2019; Liu et al., 2019). This study found microfibers to be the least abundant shape (Table 5), possibly due to their low density allowing easy wind or water transport or methodological challenges owing to their imperceptibility to the naked eye (Lots et al., 2017; Mahon et al., 2017).

Flakes, the second most prevalent MP form in the study area (Table 5), were mainly transparent or colorless. Turner et al. (2022) noted paint flakes as the most abundant MP type in marine ecosystems, often mistaken by marine organisms as food source. The observed flakes likely originated from the deterioration of traditional Kerala snack packages (Achappam and Murukku packages), grain packages, polypropylene grocery and ration store bags, plastic labels, PE tarpaulins, and stressed or burned cosmetic plastic tubes or containers.

Micro sheets, the fourth most abundant type in the study area (Table 5), are primarily colored and rarely transparent. They result from the degradation of

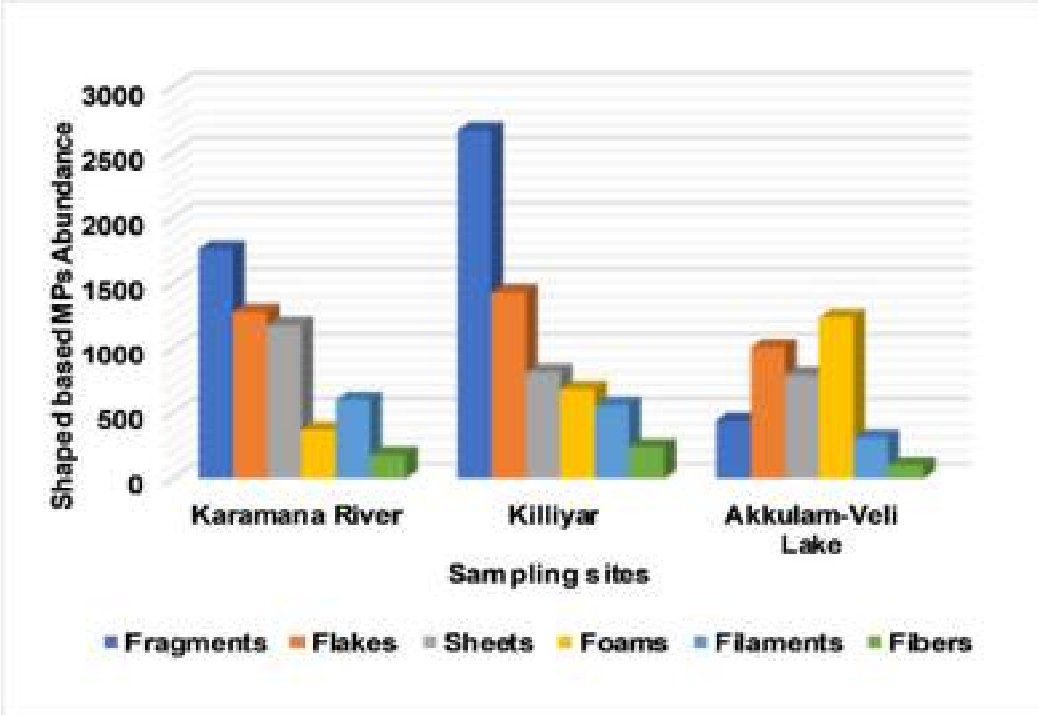


Fig. 9 Abundance of various shapes of MPs in Karamana, Killiyar, and Akkulam-Veli

macro particles, likely from sheet-type plastics (PP, PE) or discarded plastic bags (Gomiero et al., 2019; Su et al., 2021; Wang et al., 2020; Zheng et al., 2019). The study also identified micro-filament particles derived from various plastic materials such as ropes (nylon, polypropylene, polyester), fishing nets, school bags, handbags, laptop bags (nylon, PET), and plastic sacks (HDPE, PP).

Micro-foams, which result from progressive macroplastic degradation, appear as irregular or round-shaped particles smaller than other MP shapes (Li et al., 2021). These are widely used as insulators in various production industries, including construction equipment, electronics, automobiles, and by packaging companies (Egessa et al., 2020; Wen et al., 2018). Foams are primarily thermocol made of polystyrene (PS) or expanded polystyrene (EPS); LDPE foams, commonly used for electronic gadget protection, were also detected. Magnified images of MPs with different shapes are provided in Fig. 11. MP beads were not found in the study area, clearly indicating the predominance of secondary MPs (Sruthy & Ramasamy, 2017; Wessel et al., 2016; Yonkos et al., 2014), consistent with findings in the sediments of Vembanad Lake (Sruthy & Ramasamy, 2017).

White was the most abundant particle color (661 particles, 42.24%), followed by colorless (519 particles, 33.16%), light yellow (185 particles, 11.82%), light brown (76 particles, 4.86%), orange (61 particles items, 3.90%), red (38, 2.43%), and blue (25, 1.60%) (Table 1, Fig. 12).

The majority of white particles were found the site Killiyar (272, 42.57% of colored particles) followed by Karamana (220, 40.97% of colored particles) and Akkulam-Veli (169, 43.44% of the total colored particles). Overall, 96% of MPs were white, 92% were colorless, 87.5% were light yellow, and a few were blue (58.33%). KL_2 and AV_1 reported the highest number of white particles. Color diversity in MPs indicates the diversity of pollution sources (Qu et al., 2018; Li et al., 2021). The possibility of particle intake by aquatic organisms is higher due to its resemblance to prey in color and shape (Shaw & Day, 1994), especially the white particles are highly mistaken for *C. auratus*, a plankton species (Yuan et al., 2019). In the study, the majority of the samples

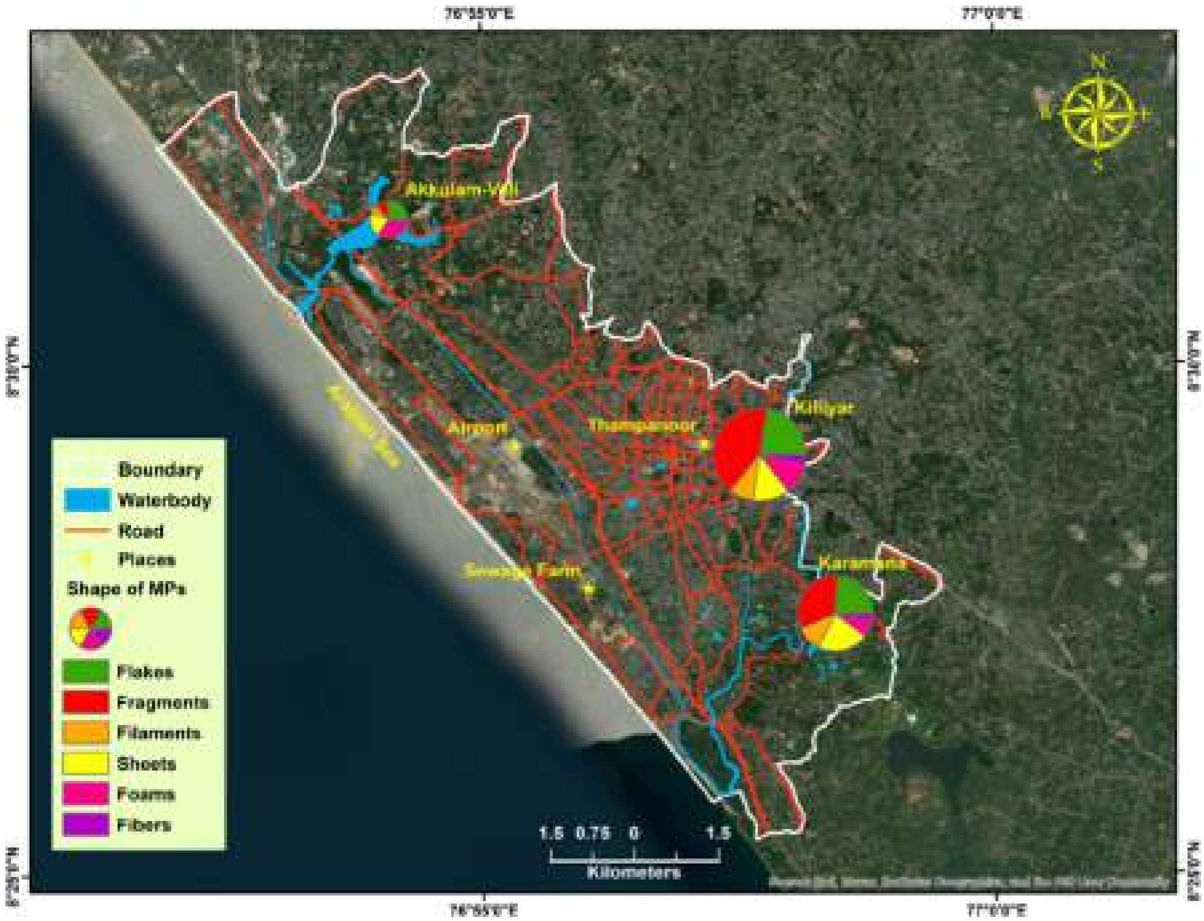


Fig. 10 Shape proportion of MPs in the study area

were identified with white, colorless, and colored particles with no polychromatic or black-hued ones. Li et al. (2021) reported an abundance of white and transparent MPs in their study. The main sources of white MPs could be white plastic carry bags and discolored polychromatic particles exposed to weathering, heat, light, and bio-activity (Galafassi et al., 2019; Liu et al., 2020; Waldschlaeger et al., 2020; Zhu et al., 2019b). Plastic sheets used for packaging food, snacks, and sweets (mostly PP and PE) may contribute to transparent particles. The abundance of MPs by hue is white (WT) > colorless (CL) > light yellow (L.Y) > light brown (L.B) > orange (OR) > red (RD) > blue (BL). The color type distribution of MPs is shown in Fig. 13.

Six polymer types were identified in the study (Table 1 and Fig. 14), with LDPE being the most prevalent (571 particles, 36.49% of the total). In the Karamana basin, 209 LDPE particles were found (38.92% of the total in Karamana), 250 particles in Killiyar (39.12% of the total in Killiyar), and 112 LDPE particles were in Akkulam-Veli basin (28.79% of the total in Akkulam-Veli). KL_4 recorded the highest LDPE count (52 items, 9.11%), while AK_8 had the least (3 particles, 0.53%). The overall abundance order was LDPE > PP > PS > PET > PES > HDPE > PES. The second most common polymer type was PP (460 items, 29.39%), followed by PS (208 items, 13.29%), PET (206 items, 13.16%), and HDPE (68 items, 3.32%). Almost all sites had LDPE, PP, and PET microparticles, 92% had PES, 87.5% had HDPE, and only 75% had polyester particles. Previous studies also reported PE and PP abundance in similar areas (Sruthy & Ramasamy, 2017; Pan et al., 2019; Hamid Shahul et al., 2018; Liu et al., 2018; Yaun et al., 2019; Irfan et al., 2020b). Irfan et al. (2020a)

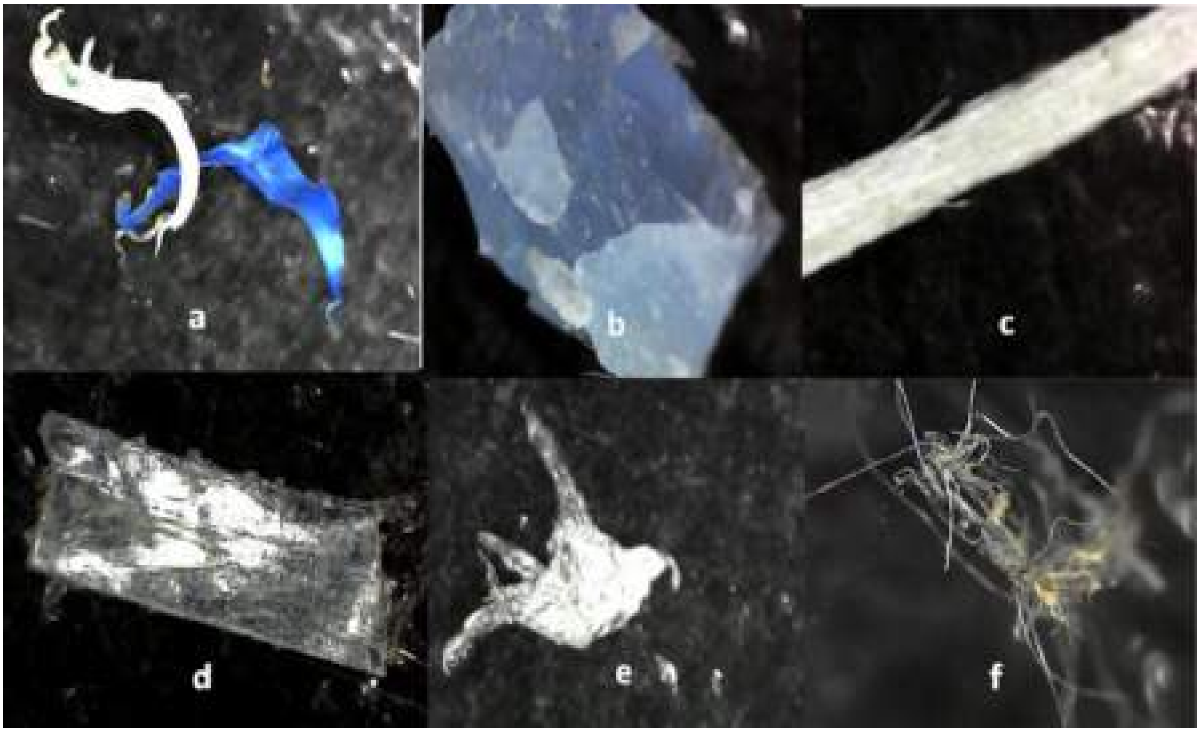


Fig. 11 Binocular microscopic images of MPs in basin soil samples of the study area. **a** Flake, **b** fragment, **c** filament, **d** sheet, **e** foam, **f** fiber

identified a correlation between MP type and potential plastic products.

The distribution of MPs coming under various polymer types depicted in the map is shown in Fig. 15.

Sruthy and Ramasamy (2017) found results similar to Vembanad Lake sediments, where LDPE was the most abundant polymer (26–91%), followed by PS and PP. Polyethylene (PE) is widely used due to its versatile applications (Noik et al., 2015; Ballent et al., 2016). PS serves various purposes, including thermal insulation and packaging appliances, while PP is used for items like carpets, fishing nets, plastic bags, containers, lids, and wrappers (Allahvaisi, 2012; Vianello et al., 2013). A study in the Chishui River basin, in China, reported polymer types such as PE, PP, PS, and PVC, reflecting the widespread use of low-quality, affordable, and daily-use plastic products (Köfteci et al., 2014; Li et al., 2021).

Regarding the size range observed in the current study, approximately 58% (901 MPs) of identified micro-polymers are of the size 300 µm, while 28.63% (448 MPs) were of size 1 mm and 13.80% (216 MPs) were of 4.7 mm in dimension (Table 1 and Fig. 16). The proportion of particles of varying sizes are represented in the map is shown in Fig. 17.

Killiyar River basin had the highest count of 300-µm-sized MPs (357 MPS, 55.87% of the total in Killiyar), notably at sites KL_3 and KL_4. Following this, the Karamana basin reported 305 MPs (300 µm) and Akkulam-Veli had 239 MPs (300 µm). Mesoplastics (> 5 mm to < 2 cm) were observed mostly within the Karamana basin (40 particles), tailed by Killiyar (36 particles) and Akkulam-Veli (32 particles). MPs pose a significant risk to aquatic and terrestrial life due to their larger surface area, facilitating the absorption of toxic pollutants (Devriese et al., 2017). Their small sizes, resembling zooplankton, increase their likelihood of being mistaken as prey by aquatic organisms (Cole et al., 2011). Numerous studies have explored MPs with size ranging both less than and greater than 100 µm (Zhang et al., 2016; Liu et al., 2018; Scheurer & Bigalke, 2018; Zhang et al., 2018; Zhang & Liu, 2018; Zhou et al., 2021).

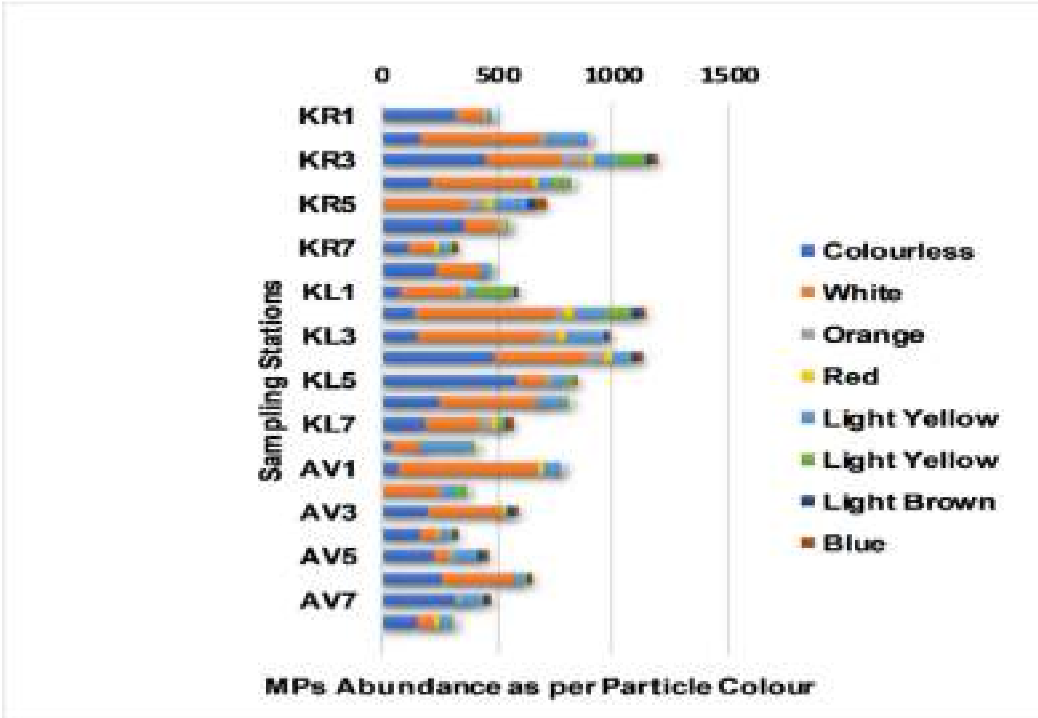


Fig. 12 Abundance of various colored MPs in soil of sampling sites

Statistical findings

The Pearson correlation (Sedgwick, 2012) analysis performed between the variables, slope and particle abundance, exhibited a statistically irrelevant weak negative correlation, where the values were estimated as *r* (correlation coefficient) $= -0.3724274$, $t = -1.8822$, *df* (degrees of freedom) $= 22$, and *p*-value (level of Significance) $= 0.0731$. Here the *p*-value was greater than 0.05, hence the correlation is statistically insignificant. The correlation plot between slope percent and MP concentration is represented in Fig. 18.

LULC classification for the year 2022

A LULC map of the study area was prepared for the year 2022. The land use classes and the estimated area under different classes were as follows: built-up, 54.07 km^2 (79.25%); open scrub, 5.82 km^2 (8.53%); waterbody, 4.98 km^2 (7.18%); trees, 1.88 km^2 (2.76%); surplus land, 0.79 km^2 (1.16%); farm land, 0.76 km^2 (1.11%) (Table 3, Figs. 6 and 19).

The study area, covering 68.3 km^2, is predominantly characterized by built-up land, reflecting urbanization and increased human activities. The built-up class includes settlements, roads, and man-made structures. Urban highlands contribute to surface runoff and non-segregated waste disposal, influencing plastic pollution in basin areas. With only 2.76% tree coverage, the area indicates intensive urban development, leading to soil erosion and increased mobilization of MPs. Farmlands (1.11% of the total area) may also contribute to plastic pollution, as observed by Liu et al. (2018) in suburban vegetable fields. The proximity of site KL_3 to farmland suggests its potential MP pollution (Liu et al., 2018).

Slope ranges

The slope of an area describes the relief of the land, where the rate of surface runoff is directly proportional to the steepness of the slope, thus mediating higher rates of soil erosion. In this study, the area estimated under each slope percentage category were 0–0.5: 0.61

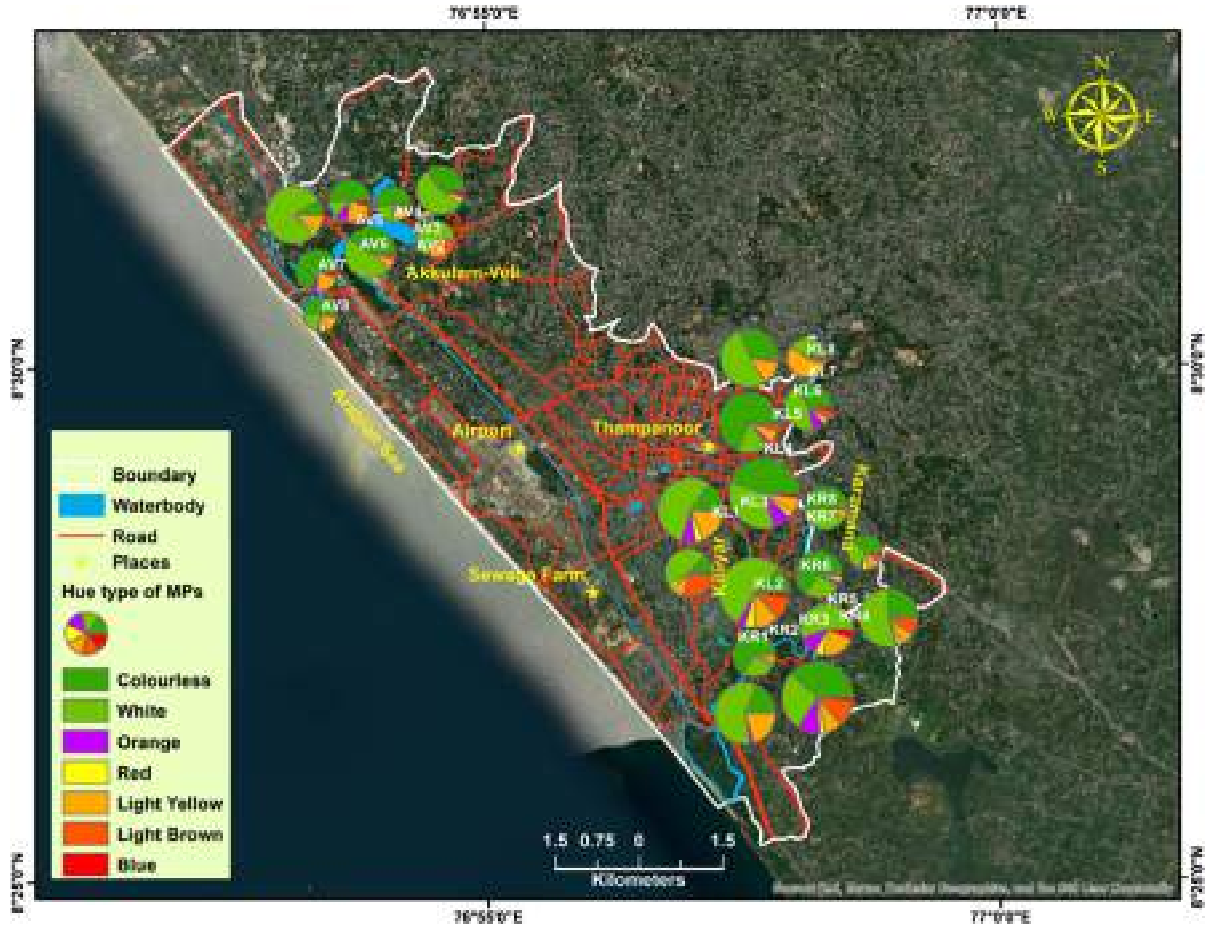
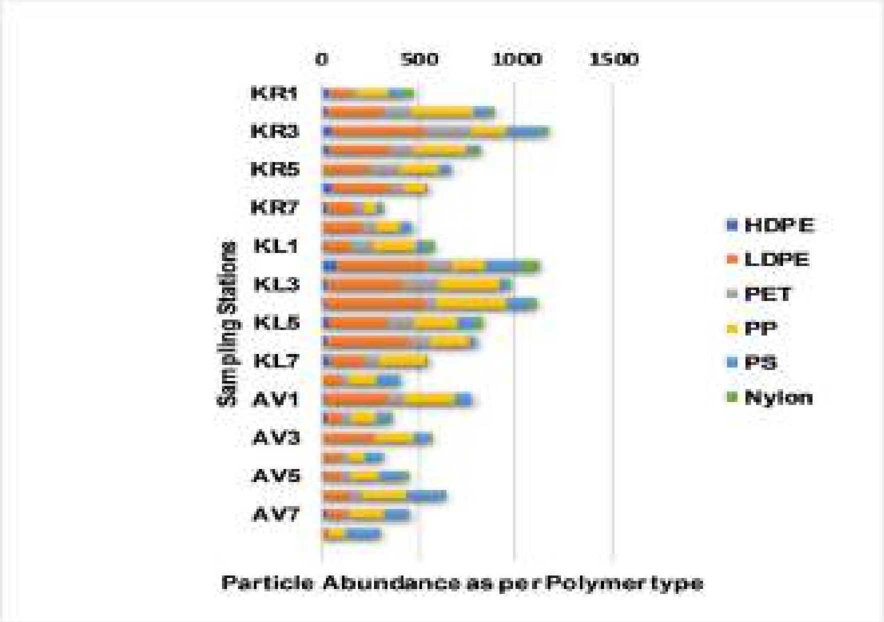


Fig. 13 Color proportion of MPs shown in sampling sites

km^2 (0.89%); 0.5–2: 6.40 km^2 (9.37); 2–5: 25.56 km^2 (37.42%); 5–9: 20.21 km^2 (29.59%); 9–15: 10.24 km^2 (14.99%); 15–30: 4.96 km^2 (7.26%); and > 30: 0.32 km^2 (0.47%). The slope ranges, area, and sampling points under each slope class are given in Table 4, Fig. 7, and Fig. 20. Slope promotes the transportation of pollutants from higher-elevation terrains to low-lying elevations, especially to the water body basins. Kerala has a prominent monsoon season and the amount of storm runoff along with other factors determines the pollutant transport. This flow is mostly influenced by the terrain features, where slope is one of them. Slope range 5–9 (moderate slope) covers most of the study area (20.21 km^2) and slope class > 30 (very steep slope) covers the least area (0.32 km^2). Most of the sampling sites belonged to the 2–5 range, which is gently sloping areas. Sampling sites KR_1, AV_1, AV_4, and AV_7 belong to strongly sloping areas, whereas KL_1 and KL_5 belong to very gently sloping areas.

To know the impacts posed by MPs, it is essential to understand its transport mechanisms. From soil compartments, MPs are transferred to other environments such as water and air, through various transmission mechanisms (Guo et al., 2020). Other than the percolation and infiltration mechanisms (less effective transport of MPs), the alternative wet and dry cycles (due to evapotranspiration) of soil mediate the MP penetration (O'Connor et al., 2019). The horizontal and vertical movement (through soil pores) of these MPs can lead to their distribution in groundwater and freshwater resources at alarming rates (Rillig, 2012; Silva et al., 2018).

Fig. 14 Polymer types of MPs in the basin soil of sampling sites



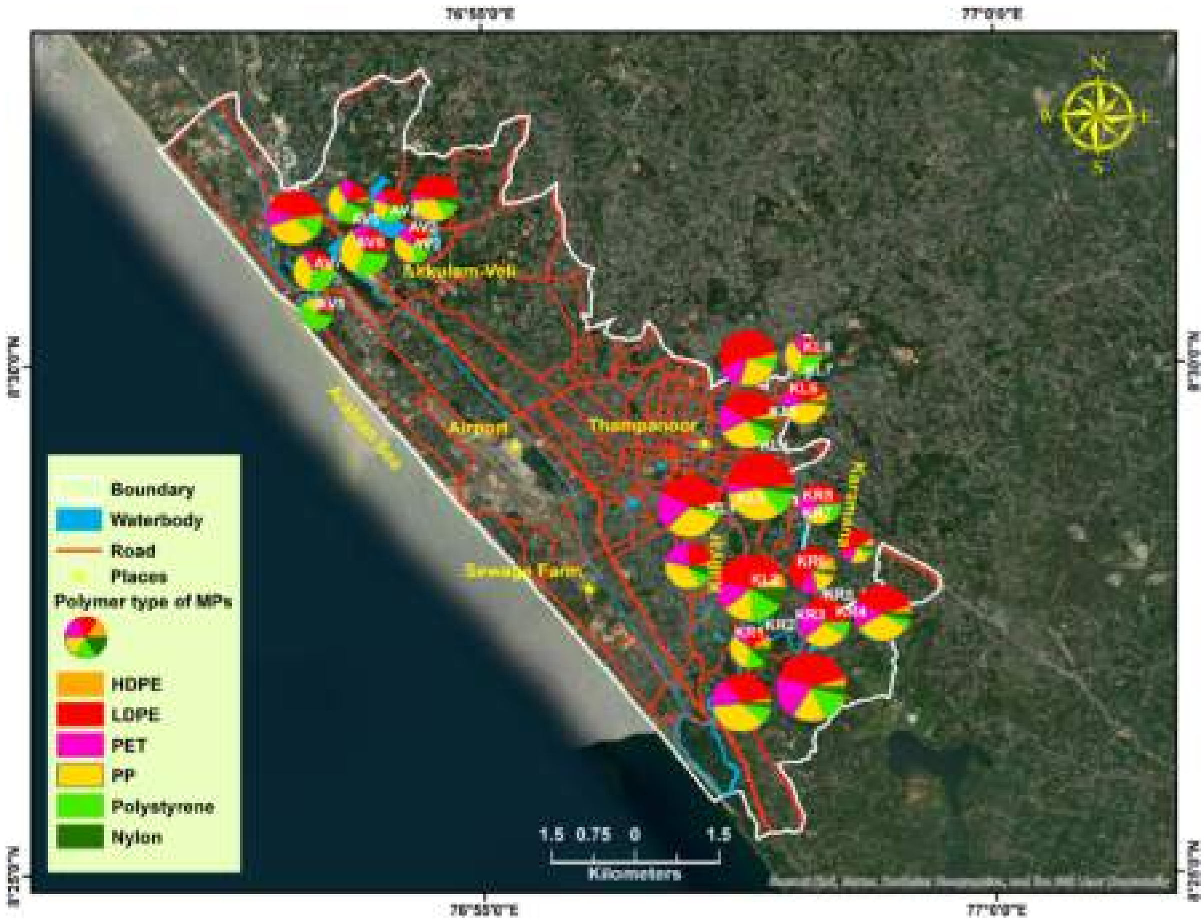


Fig. 15 Polymer-type proportion of MPs in sampling sites

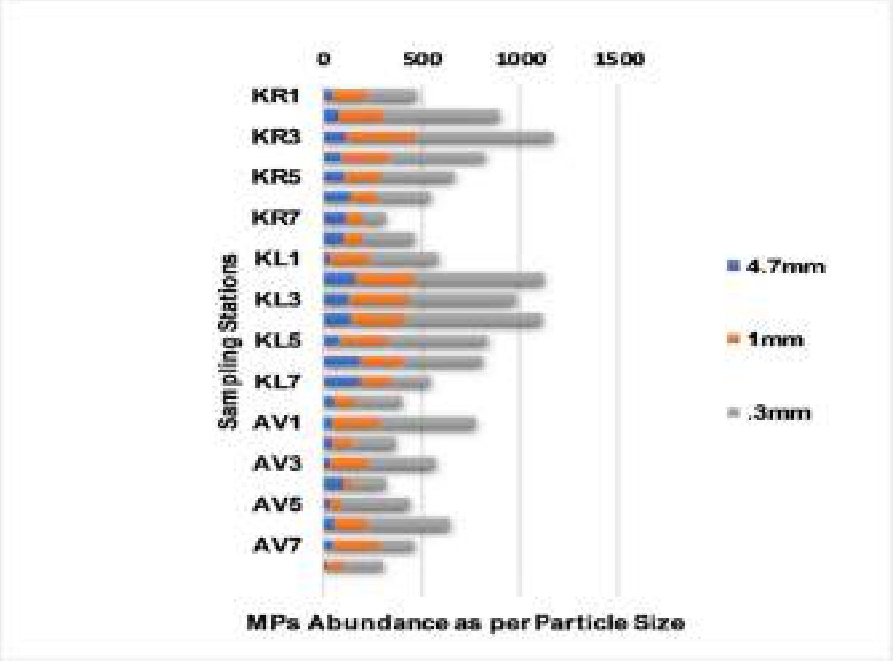


Fig. 16 Size-based abundance of MPs in the basin soil of sampling sites

MPs act as a framework to form soil aggregates enhancing water-holding capacities but reducing microbial activities (Machado de Souza et al., 2018). Once they get into the environment, micro-polymers become bioavailable, thus entering the food chain (Rillig, 2012; Silva et al., 2018). Ingested by organisms, MPs can accumulate in the gut, causing inflammation, weakening, and even death (He et al., 2018). Higher MP concentrations elevate earthworm mortality rates (Horton et al., 2017; Lwanga et al., 2017). Qi et al. (2018) found that modern biodegradable plastics showed more negative impacts on wheat plants than polyethylene MPs. Polystyrene particles can easily accumulate in edible plants (Zhu et al., 2019a). Rapid degradation of biodegradable plastics increases soil toxicity risk (Raza, 2019). These plastics absorb organic pollutants, posing a bioavailability threat to higher trophic levels (Hüffer et al., 2019).

Proper knowledge of the frequently used disposable plastics is essential to control MP pollution (Addamo et al., 2017; Ferreira, 2014). Without strict regulations and lifestyle changes, current plastic consumption rates may cause irreversible environmental damage (Rafique et al., 2020). The present levels of soil MPs in the study area can be harmful to terrestrial and aquatic biota, but the intensity of harm is unknown because no risk assessment was performed here. Robust legislation and regular monitoring are essential to curb plastic waste production and its impacts. This study presents initial evidence of MP pollution in the basins of three key water bodies in Thiruvananthapuram, the capital city of Kerala, influenced by anthropogenic activities. Further in-depth studies are recommended to explore MP sources, spatio-temporal variations, distribution influencing factors, and its eco-toxicological impacts in the region.

Conclusion

Karamana, Killiyar, and Akkulam-Veli are three significant aquatic ecosystems of Thiruvananthapuram City, Kerala, India, which are confronting the immense risk of pollution due to frequently evolving urban practices, landscape, and population expansion. Thiruvananthapuram City, one of the fastest growing and urbanizing cities of Kerala, has undergone a major transformation in recent years due to projects such as Vizhinjam International Transshipment Seaport, Rail and Road projects, IT-based solution projects, and Digital Science Parks. Notably, the city's transformation has intensified plastic deposition and pollution rates in the basin areas, with multiple establishments and sources contributing significantly to the

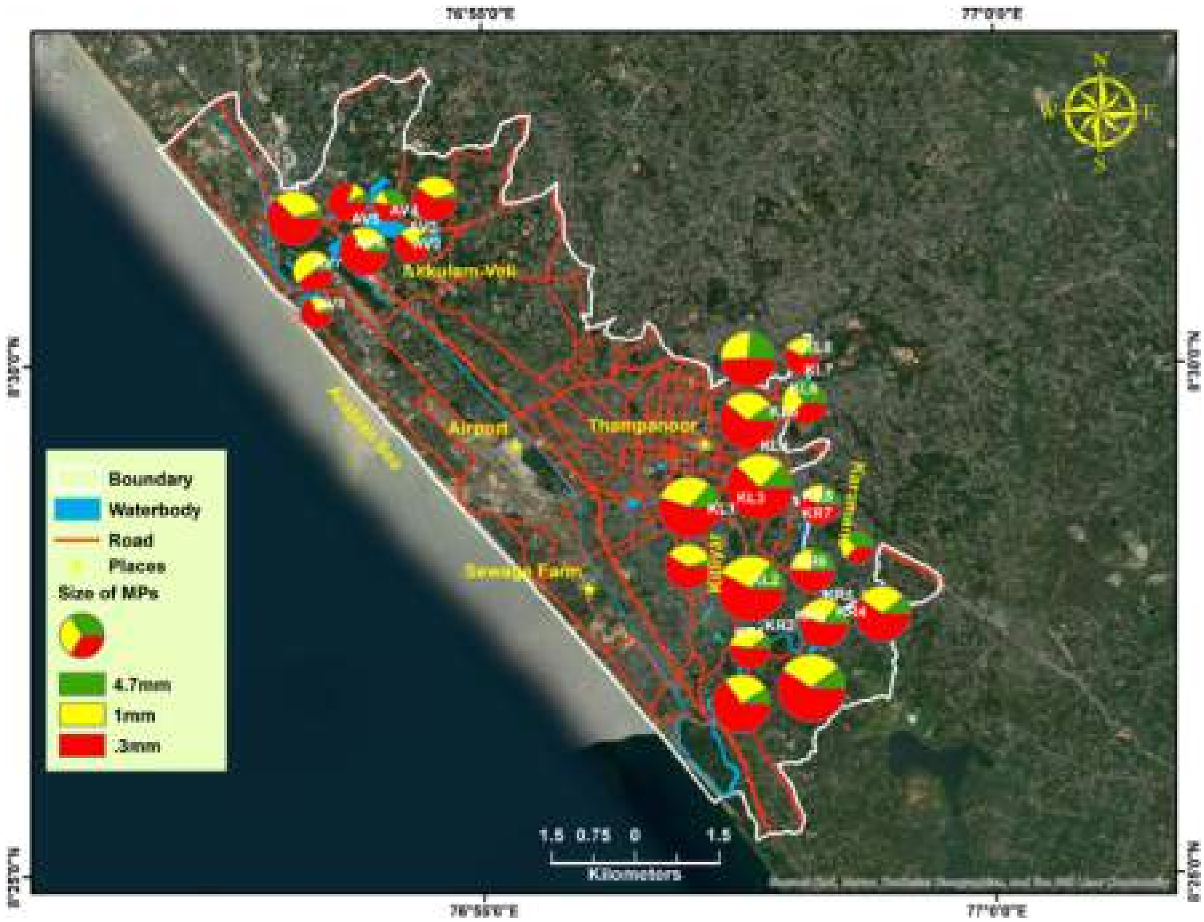
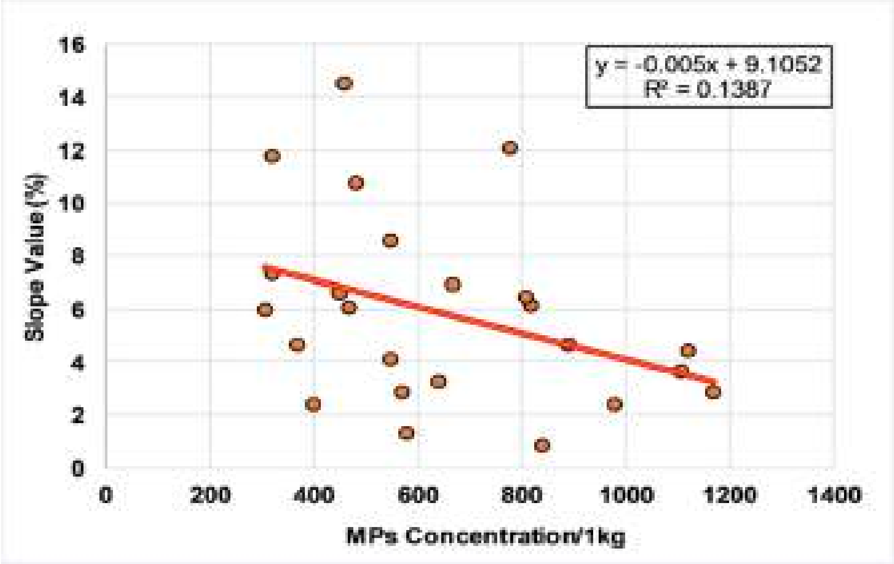


Fig. 17 Size proportion of MPs in sampling sites in accordance with particle abundance

Fig. 18 Correlation between slope (%) and MP concentrations/kg of soil



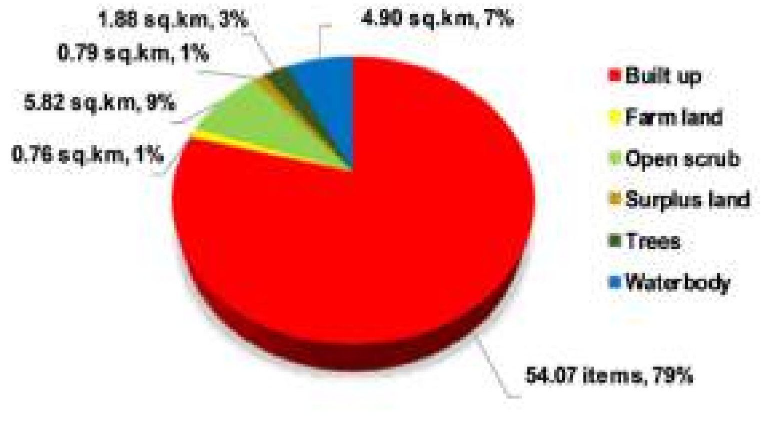


Fig. 19 Area proportion of land use land cover classes in the study area (year 2022)

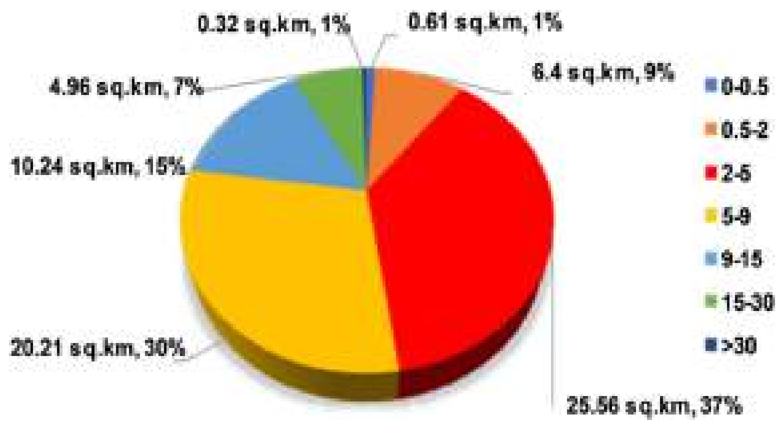


Fig. 20 Area proportion of slope classes in the study area

addition of easily perishable single-use plastics. With subsequent exposures to various environmental stressors, these synthetic macro-polymers can degrade into smaller MPs. The current study unveils the concentration of MPs in the three waterbody basins of Thiruvananthapuram Corporation, Kerala, India, revealing a range from 310 ± 5.77 to 1170 ± 2.89 items/kg. Further investigation exposes variation among the MP concentrations of Karamana, Killiyar, and Akkulam-Veli basin soils. Remarkably, the majority of MPs, characterized by a size of ~ 300 µm, can cause a higher risk of bioaccumulation as well as groundwater contamination through vertical transport. Diversity and abundance among the shape, color, and polymer type of MPs is an indication of the various anthropogenic sources of soil MP pollution. Overall, in the study, the abundant MP shape, color, and polymer type identified were fragments, white, and LDPE, respectively. Rainy seasons are expected to worsen contamination, although it is hectic and tedious, emphasizing the need for temporal variation assessment of MP distributions in soils. This research emphasizes the importance of discerning and eliminating frequently used plastics as an initial step of MP mitigation measures. Comprehensive measures, including national or state action plans, stringent laws, eco-friendly alternatives, awareness initiatives, and robust recycling practices are essential to mitigate plastic production, usage, and disposal, safeguarding ecosystems from MP pollution's detrimental effects.

Acknowledgements The authors thank the Library of All Saints' College, Thiruvananthapuram and the Kerala University Library, Palayam for providing the necessary information which aroused the motivation to initiate and conduct this study and to prepare this manuscript. The authors also thank the Environmental Chemistry Laboratory of All Saints' College and the Laboratory of the Department of Physics, Karyavattom Campus, University of Kerala for providing the required facilities for the work. The authors also thank all the pioneers whose research works have been refereed while preparing this manuscript.

Author contribution ABSK and MM: exhibited equal contribution in the execution; methodology and sampling scheme setting; data collection; data analysis and validation; investigation; resources utilization; graphs, tables, and spatial distribution map generation; handling GIS and statistical software and writing of draft manuscript. AJ: conceptualization, planning of methodology and workflow design, supervision, data validation and visualization, error correction, editing and proofreading.

Funding The work was done using the grants provided by the Department of Minority Welfare Kerala as the ASPIRE Scholarship Research Award and the Research Grants provided by the University of Kerala, which provided financial assistance for the smooth conduct of the study.

Data availability Some of the datasets used in the current study were retrieved from the open sources mentioned in the methodology, while the administrative boundary file was attained from the Inter-University Center for Geo-information Science and Technology (IUCGIST), University of Kerala. Data such as tables, charts, and maps are not publicly available due to data security reasons but shall be provided by the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval All authors of the study have thoroughly read, understood, and met the conditions applicable as per the declaration "Ethical responsibilities of authors" and are well informed that once the paper has been submitted, with minor exceptions, changes cannot be made to the authorship.

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