detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

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HEAVY METAL ACCUMULATION ON MICROPLASTICS IN COMPOST - THE ROLE OF BIOFILM

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Article Info:
Received:
7 September 2023
Revised:
21 February 2024
Accepted:
22 March 2024
Available online:
31 March 2024

Keywords:
Microplastics
Heavy metals
Compost
Bio-film

ABSTRACT

Microplastics, small plastic pieces (<5mm), are emerging contaminants in water, terrestrial, and air environments. This study investigated the possibility that microplastics act as carriers of heavy metals (Cu, Zn, Pb, Mn, Cd) in the municipal solid waste (MSW) compost samples, which were obtained from municipal composting yards at Kozhikode and Kochi, in Kerala, India. The heavy metal accumulation was expected in the biofilm that formed on microplastics during composting. Therefore, five samples were analysed: (i) compost after microplastic separation, (ii) untreated microplastics, (iii) microplastics washed with distilled water, (iv) chemically separated microplastics, and (v) new macro-plastics for comparison. Total Organic Carbon (TOC) and SEM analyses were used to assess the biofilm formation over microplastics. The study showed high microplastic abundance in the compost of both locations, with Kochi having nearly double the count as that of Kozhikode (1600 vs. 840/kg dry compost). Microplastics collected from Kochi exhibited higher biofilm formation, leading to greater heavy metal accumulation and higher concentrations compared to the compost. Heavy metal concentrations generally varied in the following order at both locations: handpicked microplastics > microplastics washed with distilled water > compost free from microplastics > chemically separated microplastic > new macro-plastic, with some exceptions. Heavy metal concentrations were significantly higher in samples from Kochi, due to a larger bio-film formation on the plastics as determined by TOC and SEM analyses. The findings of the study highlight the importance of source segregation and prevention of mixing of organic waste with plastic waste in MSW, to avoid heavy metal transport in terrestrial environment through microplastics.

1. INTRODUCTION

Plastic pollution serves as a prominent reminder of the unsustainable nature of the plastic-dominated era in human civilization. It is estimated that by the year 2030, as much as 53,000,000 metric tons of plastic will be released into the environment (Borrelle et al., 2020; Geyer et al., 2017). These plastics could degrade to microplastics due to physical, chemical and biological factors. Microplastics are generally defined by National Oceanic and Atmospheric Administration (NOAA) as small plastic particles that are having sizes of 5 mm to 1 nm (Masura et al., 2015). They can be formed from primary and secondary sources (Auta et al., 2017). Microplastics are found widely in terrestrial and aquatic environments (Rillig & Lehmann, 2020). In terrestrial environment, compost is considered as a major route for the entry of microplastics to the environment (Vithanage et al., 2021). The presence of microplastics in Municipal Solid Waste (MSW) compost and its role as a carrier of heavy metals were topics of many researches. These studies have reported Lead (Pb), Copper (Cu), Zinc (Zn), Manganese (Mn), and Cadmium (Cd) as the heavy metals of major concern in MSW compost with concentrations varying with the place of study (Bożym, 2017; Fan et al., 2021; Vithanage et al., 2021).

The adsorptions of heavy metals on microplastics can be related to the biofilms which are present on its surfaces (Wang et al., 2020). Biofilms are comprised of a combination of microorganisms, including algae, fungi, and bacteria, along with extracellular polymeric substances (EPS). These EPS play a crucial role in the structure and function of the biofilm (Carson et al., 2013; Shabbir et al., 2020). The biofilms present in microplastics are known to carry toxic metals to different environments and cause adverse impacts (Guan et al., 2020). In this research, microplastics, separated from the compost samples, were collected from the municipal composting yards of Kochi and Kozhikode,

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https://doi.org/10.31025/2611-4135/2024.18362

Kerala (India), and analysed for the presence of heavy metals. The objective of the study was to examine how biofilms contribute to the accumulation of heavy metals on microplastics in the MSW compost. The concentration of heavy metals like Pb, Cu, Zn, Mn, and Cd was analysed in different samples: compost free of microplastics, microplastics handpicked from the compost, handpicked microplastics washed with distilled water, chemically separated microplastics, and new macro-plastic samples.

2. MATERIALS AND METHOD

The overall methodology followed in this work is shown in Figure 1.

Compost samples were collected from the composting yards following a standard procedure (Figure 1). Microplastics (1-5mm) were separated from the compost manually by handpicking after sieving. The separated microplastics were divided in three portions and prepared differently for analyses. Analyses were performed to quantify the heavy metals accumulation in the microplastics. Total Organic Carbon (TOC) analysis and Scanning Electron Microscopy (SEM) were employed to understand the biofilm accumulation on the microplastic samples. Finally, the heavy metal concentrations were correlated with the extent of biofilm formation to evaluate the role of biofilm in heavy metal accumulation by microplastics.

2.1 Sampling

The study was carried out on the compost samples collected from the Kozhikode Municipal Corporation's compost plant situated at Njeliyamparamb (11.203257° N, 75.816797° E) and Kochi Corporation's compost plant situated at Brahmapuram (9.99517° N, 76.37163° E). The compost plant owned by the corporations handles the biodegradable waste collected from city's markets and other public places. The map showing the sampling locations is given in Figure 2.

The sampling was made according to the Australian Standard AS4454-2012 for composts, mulches, and soil conditioners. The sample was collected using a shovel, a stainless steel mesh and polyethylene covers. The compost heap was thoroughly mixed with the shovel and 1 kg of compost samples were taken from the top, bottom and middle part of the heave. The samples were stored in the polyethylene covers (Vithanage et al., 2021). The samples

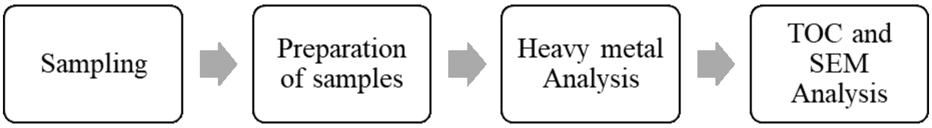

FIGURE 1: Methodology.

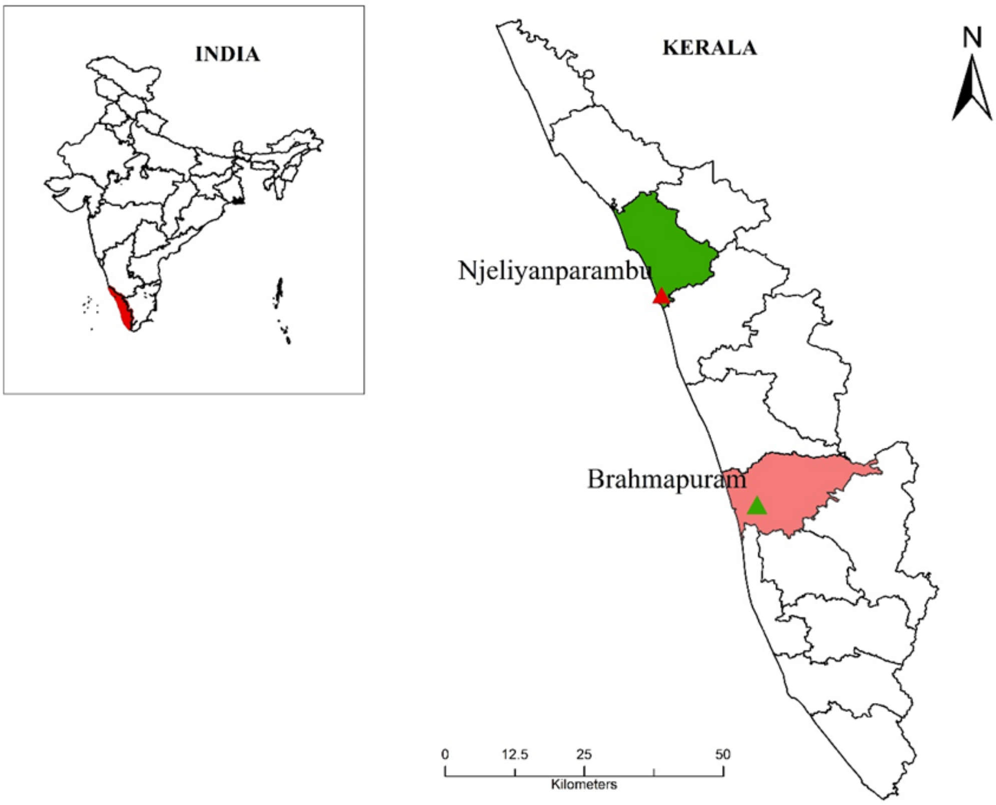

FIGURE 2: Sampling locations.

were brought to the lab and were air dried at 70°C and preserved for further analysis.

2.2 Preparation of Samples

Samples were prepared for the analyses from the composts collected from the two locations. For the analysis of the heavy metal content in biofilms, microplastics subsamples were chosen from the whole sample that matched the morphology (fibre, film or fragment) and polymer types (as determined by FTIR spectroscopy) in both locations. By this procedure it was possible to compare the differences in the heavy metal content in the biofilms on plastics between both locations.

The sample preparation was as follows. The air-dried samples were sieved through 5 mm sieve followed by 1 mm sieve. The portion of compost retained on 1mm sieve was used for the study. The compost, after removing the microplastics (1-5 mm) manually was preserved for analysis (Sample 1). The removed microplastics were quantified. The microplastics hand-picked from both locations with matching morphology and resin type were divided into three portions. The first portion of the handpicked microplastics was preserved for further analysis as hand-picked samples (Sample 2). The second portion of the hand-picked samples was washed with distilled water and was preserved for analysis (Sample 3). The remaining portion of the hand-picked microplastics was subjected to the chemical separation procedure. Chemical separation procedure included the oxidation of the organic matter using Fenton's reagent as the first step. For every 0.1 g of solid Matrix (dry mass), 0.1 ml of a 0.002 mol $FeSO_4$ (Fe (II)) and 1 ml of a 30% H_2O_2 solution were added to provide the necessary iron ions and hydrogen peroxide (Tagg et al., 2016). The samples were digested, filtered, and washed with distilled water. These samples were dried and preserved for analysis as chemically separated microplastics (Sample 4). Also, macro-plastics that were potentially matching the microplastics found in the compost were collected (in both locations) and categorized by morphology and polymer matching criterion, which included morphology (fibre, film, or fragment), colour and polymer type. The best fitting macroplastics according to the morphology, colour and polymer matching criterion were then cut into manageable pieces and were preserved for analysis (Sample 5).

2.3 Heavy Metal Analysis

Heavy metal analysis was conducted to determine the concentrations of Lead, Copper, Zinc, Cadmium and Manganese in the five samples. The samples were digested using Aqua Regia (HCl: HNO_3 = 3:1) at a rate of 15 mL/g of the sample (Bożym, 2017). The standard solutions of heavy metals were prepared by diluting the stock solutions and analysed in flame AAS (PerkinElmer piNacle900F). The limit of detection for the analysed metals were, Cu-10 µg/L, Zn- 20 µg/L, Pb- 10 µg/L, Mn- 20 µg/L and Cd- 10 µg/L. The digested sample solutions were filtered using Whatman filter paper (42) and were diluted again. Both samples and standards were stored in the refrigerator for 24 hours. All chemicals used in the analyses were research-grade.

2.4 TOC and SEM analysis

The biofilm present on the microplastic surface was characterized quantitatively based on the Total Organic Carbon (TOC) (%) and qualitatively using SEM imaging. These analyses were made for the three microplastic samples, that is., hand-picked, distilled water washed and chemically separated ones.

The hand-picked samples and the samples washed with distilled water were subjected to Fenton's reagent and Potassium Hydroxide (KOH) treatment. Subsequently, they were heated at 50°C to extract the biofilms. The samples that were previously separated using Fenton's reagent underwent further heating at 50°C in the presence of HNO_3 and KOH (Prata et al., 2019). The resulting mixture was then filtered using Whatman (42) filter paper and subsequently diluted for TOC analysis. The TOC analysis was carried out using the Shimadzu TOC-L analyzer, following the methodology outlined in method 5310 C (APHA 23rd Edition, 2017 ; P. Li et al., 2022; Zheng et al., 2023).

To corroborate the findings related to the concentration of heavy metals in the microplastic samples and the TOC results, SEM analysis was also performed on the microplastic samples. This analysis encompassed the examination of the hand-picked samples, chemically separated microplastics, and microplastic samples that were washed with distilled water. By employing SEM, the surfaces of these plastic samples were thoroughly investigated, allowing for a comprehensive evaluation of the removal of the biofilms from the samples. Therefore, the SEM analyses served as an additional information to complement the results that were obtained from the heavy metals analyses, providing valuable visual evidence and insights into the microplastic samples under scrutiny.

3. RESULTS AND DISCUSSIONS

The quantification done by manual counting revealed that the number of microplastics (1mm-5mm) per kg of dry weight of compost is 840 items in Kozhikode and 1600 items in Kochi. These values were much higher than what was reported from Germany for microplastics of same size range, which was 39 to 102 items per kilogram of dry weight on a study conducted by Schwinghammer et al. (2020) and between 40 and 60 to 100 and 120 items per kilogram of dry weight on a study conducted by Weithman et al. (2018). This may be due to the higher waste recycling rate of 46% in Germany (Conversio, 2018) that prevents the entry of plastic wastes to MSW, as against the 30% recycling rate in India. Another study conducted on Austrian compost samples shows a count of between 0 - 49 particles per kg of dry waste (size range 2-6.3 mm) (C. Zafiu et al.,2023). The higher recycling rates in Europe reflect also a higher degree of separate collection of plastics and therefore a lower fraction of plastics in MSW. In addition, the composting of MSW is not practiced in many European Countries anymore. Therefore, the lower recycling results in higher presence of plastic in MSW compost in India (Loizia et al., 2021; Pal & Bhatia, 2022; Shah et al., 2023). However, a study from another European country, Netherland, has reported the presence of PLA microplastic fibers in green waste compost as high as 82,800 items/kg. However, PLA is a different case, as it is a biodegradable polymer, which is (in certain cases) allowed to be disposed of with biowaste. However, when present in compost they are not effectively recycled (Gross & Kalra, 2002; Huerta-Lwanga et al., 2021; Karamanlioglu et al., 2017). In this study, the microplastics encountered were mainly non-biodegradable single use plastics.

3.1 Heavy metal concentrations

The heavy metal concentration of dry compost was analysed, and the results are given in Table 1.

The results in Table 1 show that the concentrations of heavy metals in and on microplastics in both locations followed an order: Hand-picked microplastics > Microplastics washed with distilled water > Microplastics separated using chemicals > matching macro plastic samples. The concentration of heavy metals in compost exceeded that of the chemically separated microplastic samples for all investigated heavy metals in the case of Kozhikode. However, in the samples from Kochi, for Manganese, Zinc, and Copper, chemically separated microplastics had higher concentrations than the compost. In all cases, the concentrations of heavy metals in macro-plastic samples analysed as control was much lower than microplastic samples, indicating accumulation of heavy metals from compost to microplastic. The highest concentration noticed for any heavy metal in the compost and microplastic samples was for Zinc in the samples of Kochi. Zn in MSW generally comes from paper, cardboards wood, plastics, concrete wastes, leather, paints, leaching of batteries, and tire rubber particles (Jones et al., 2014; Rotter et al., 2004). There were instances of much higher occurrence of Zn in composts than our study in other cities of India, for example 10616 mg/kg in the compost of Mumbai and 6693 mg/kg in Delhi (Khare et al., 2023). Zn is a micronutrient for plants and as such, its presence in compost is desirable. At the same time, its excess, like its deficiency in soil, can cause stunted plant growth and decreased photosynthetic activity, inducing chlorosis and necrosis of the leaf (Andresen et al., 2018; Dobrikova et al., 2021). Due to the impacts, US EPA has set 7500 mg/kg as the ceiling concentration of Zn in biosolids, including composts, intended for land application. The concentration limit for exceptional quality biosolids, that can be applied without any restrictions, is 2800 mg/kg (USEPA, 1994). The compost from Kochi had Zn concentrations close to this limit.

After Zn, the next abundant heavy-metals in the compost were Cd and Cu. Kitchen waste, plastics, cinder and lamps are the main sources of copper in MSW (Aendo et al., 2022; Long et al., 2011). Plastics, pigments, soil and food containers may be the possible sources of Cd in MSW (Aendo et al., 2022; Tang et al., 2019; Valadez-Vega et al., 2011). Cd is not essential to plant growth. In the contrary, even low concentrations of Cd in soil can adversely affect plant growth and metabolism (Qadir et al., 2014). US EPA has set 85 mg/kg as the ceiling concentration of Cd in biosolids for land application (USEPA, 1994). Thus, the composts of both Kochi and Kozhikode, with Cd concentrations of more than ten times the threshold concentration, are unsuitable for land application. The current practice of sale of compost in bags at these places should, therefore be discontinued, or measures for reducing the source of Cd should be taken.

Pb and Mn were the two heavy metals that had higher concentration in the compost of Kozhikode than in Kochi. Glass wastes, textiles, and plastics are the sources of Pb in MSW. Manganese sources are predominantly attributed to the improper disposal of bottle caps, blades, and pharmaceuticals, pigments, insecticides and cosmetics (Kanmani & Gandhimathi, 2013; Tang et al., 2019). Irrespective of the higher concentrations of some heavy metals in the compost of Kozhikode, the concentrations of heavy metals in the handpicked microplastics in all cases were higher for the samples from Kochi. The higher organic matter found attached to the microplastics handpicked from the compost of Kochi explains this observation.

In order to compare the adsorption of heavy metals on microplastics with concentration in composts, the ratios of heavy metal concentrations of both sample types were calculated and are shown in Table 2. The ratio of heavy metal concentration in microplastic to that in matching unpolluted macro-plastics was calculated to understand the addi-

TABLE 1: Heavy metal concentrations in Kozhikode (in mg/kg of dry compost).

Sample	Heavy metal concentration (mg/kg of dry weight)									
	Lead (Pb)		Manganese (Mn)		Copper (Cu)		Zinc (Zn)		Cadmium (Cd)	
	Kochi	Kozhikode	Kochi	Kozhikode	Kochi	Kozhikode	Kochi	Kozhikode	Kochi	Kozhikode
Microplastics separated using chemicals	417	315	878	469	873	442	2987	1796	709	445
Microplastics washed with distilled water	878	765	1078	596	914	504	5147	3017	793	697
Handpicked microplastics	912	809	1312	741	1036	798	6980	3960	927	866
Compost free of microplastics	401	594	400	582	856	541	2715	1955	863	851
Matching macro-plastic samples	117		259		209		374		91	

TABLE 2: Ratio of heavy metal concentrations in microplastic samples, compost and matching macro-plastics.

Ratio	Lead		Manganese		Copper		Zinc		Cadmium	
	Kozhikode	Kochi	Kozhikode	Kochi	Kozhikode	Kochi	Kozhikode	Kochi	Kozhikode	Kochi
Handpicked micro-plastics/compost	1.37	2.27	1.28	3.28	1.47	1.21	2.02	2.57	1.02	1.07
Distilled water washed microplastics/ compost	1.29	2.18	1.02	2.70	0.93	1.07	1.54	1.90	0.82	0.92
Chemically separated microplastics/ Compost	0.53	1.04	0.80	2.12	0.82	1.02	0.92	1.10	0.52	0.82
Handpicked microplastics/ macro-plastic	6.91	7.80	2.86	5.06	3.81	4.95	10.58	18.66	9.51	10.18
Distilled water washed microplastics/ macro-plastic	6.53	7.50	2.30	4.16	2.41	4.50	8.06	13.76	7.65	8.71
Chemically separated microplastics/macro-plastic	2.70	3.56	1.81	3.39	2.11	4.17	4.82	7.99	4.89	7.80

tion of heavy metals to microplastic from compost. These ratios are also shown in Table 2.

The ratios in Table 2 reveal an accumulation of all heavy metals in the handpicked microplastics from Kochi and Kozhikode, indicated by a concentration ratio (concentration in microplastic/concentration in compost) higher than 1.0. Samples from Kochi exhibited a greater adsorption for all metals than the samples from Kozhikode, except for Copper. The highest proportional adsorption on microplastic was found for Mn, with a concentration ratio (microplastic to compost) of 3.28 in the handpicked samples from Kochi. The second highest was found for Zn with a ratio 2.57, closely followed by Pb. Pani et al. (2017) found that Zn and Mn are two heavy metals that are highly adsorbed by biofilms on microplastics. Pani et al., reported that even chemical washing could not remove these metals entirely from microplastics. Cu was also reported to be a heavy metal that has strong affinity towards biofilms (Wang et al., 2021). Cd, on the other hand, was shown to exhibit a lesser affinity towards adsorption by biofilms when compared to Copper, Lead and Zinc (Dong et al., 2003), which was also found in this study. Cd had the lowest concentration ratio (microplastic to compost) of 1.07 for the bio-film-rich handpicked samples compared to other heavy metals.

The ratio of heavy metals in microplastic samples to that in matching unpolluted macro-plastic samples analysed as control, showed that there was strong adsorption of heavy metals to microplastics from compost. There was more than 1800% increase in Zn concentration in the handpicked microplastic collected from Kochi and 1058% in Kozhikode compared to unpolluted plastic. The next highest increase (1018%) in concentration was noticed for Cd in the samples from Kochi in spite of the metal's lower affinity to adsorb to biofilms. The lower concentration of Cd in unpolluted plastics resulted in such a high increase. The ratio (chemically separate microplastic/macro-plastic) for all metals being larger than 1.0 indicates that, even after digestion with Fenton's reagent for the removal of the biofilm, heavy metals were still adsorbed to microplastics. The TOC analysis (described in a subsequent section) showed that there was a remaining biofilm, even after digestion with Fenton's reagent. This indicated that the heavy metals remaining on the plastics after the chemical treatment could originate from the biofilm residues, or that adsorbed directly to the microplastics, or a combination of both.

3.2 TOC results

The TOC of the collected microplastic samples were determined and the results are given in Table 3.

Table 3 shows the results from the TOC analyses that indicate that samples from Kochi exhibited much larger attached biofilms than samples from Kozhikode. There could be multiple reasons for this observation. The waste generation in Kochi is higher than in Kozhikode and consequently there is a higher chance of organic matter to adhere to plastics within the wastes of Kochi. Further, the MSW dumped in the Kochi corporation's yards are processed with larger delay than in Kozhikode due to the smaller capacity of the plant, which allows the formation of larger biofilms. The richer biofilm can explain the higher heavy metal concentrations observed in the microplastic samples from Kochi. Many studies have shown that biofilms formed over microplastics represent adsorption sites for various contaminants including heavy metals (J. Wang et al., 2021; Q. Wang et al., 2023), organic pollutants (Huang et al., 2021) and microorganisms (Hernández-Sánchez et al., 2023).

TABLE 3: TOC results.

Samples	Hand- Picked Samples		Distilled Water Washed Samples		Chemically Separated Samples	
	Kozhikode	Kochi	Kozhikode	Kochi	Kozhikode	Kochi
%TOC	1.97	2.82	0.83	1.54	0.07	0.37

The decrease in TOC percentage across the three samples implies the removal of biofilms adhered to the microplastics by distilled water and chemical treatments. This reduction in biofilm indicates a decrease in adsorption sites and functional groups on the microplastics. The reduction in heavy metal concentrations and the reduction in TOC suggests that the biofilms on the microplastics play a significant role in the adsorption of heavy metals, and their removal leads to a reduction in heavy metal concentrations (Guan et al., 2020). This highlights the importance of separating plastic wastes at source itself, before these get mixed with organic waste. In addition, the microplastic impurities act only as a scavenger for the heavy metal pollution in the MSW, which should be reduced in any way. Good waste management practices can prevent the entry of microplastics and heavy metals to the compost. The quantification results of microplastic in German composts implies that a better segregation and recycling of municipal solid waste is an efficient way of tackling the entry of microplastics to compost (Schwinghammer et al., 2020; Shah et al., 2023). By implementing better waste management strategies, the microplastics presence can be prevented, which in turn controls the transfer of heavy metals through the biofilms attached in them, to different environments.

In order to quantitatively understand the influence of biofilm on the adsorption of heavy metals, graphs were plotted between TOC (%) and heavy metal concentrations (mg/kg) in microplastics. Graphs were plotted separately for Kochi and Kozhikode, as the concentrations of the heavy metals in the compost matrix were different for the two places.

The variation in heavy metal concentrations for the hand-picked samples, distilled water washed samples and chemically separated samples at different TOC (%) are given in Figure 3 (Kochi) and Figure 4 (Kozhikode).

The graphs show that the heavy metal adsorption on the samples is directly proportional to the amount of biofilms adhered to the microplastic surface. The linear relationships between the heavy metal concentrations and TOC are generally strong, except for lead (R^2 = 0.7196 for Kozhikode and 0.7802 for Kochi) which is relatively weak. Zn showed the highest incremental affinity to biofilms, as

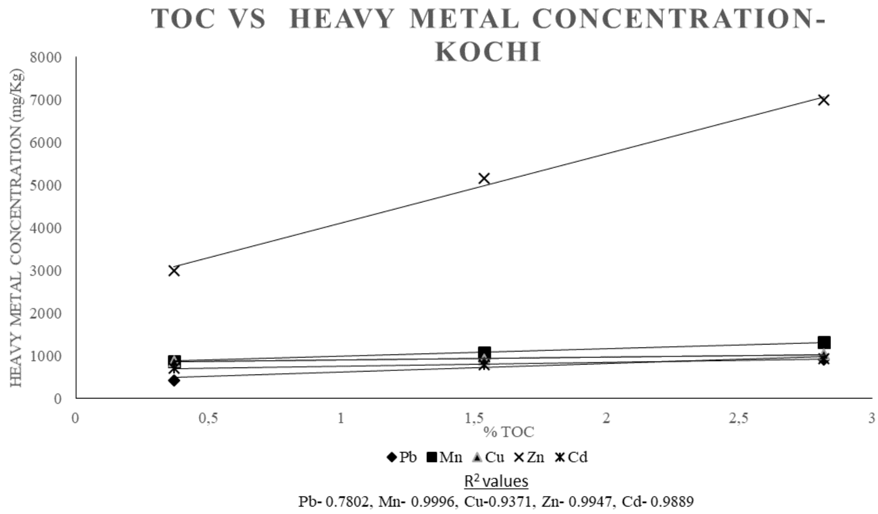

FIGURE 3: Variation of TOC with heavy metal concentration of Kochi samples.

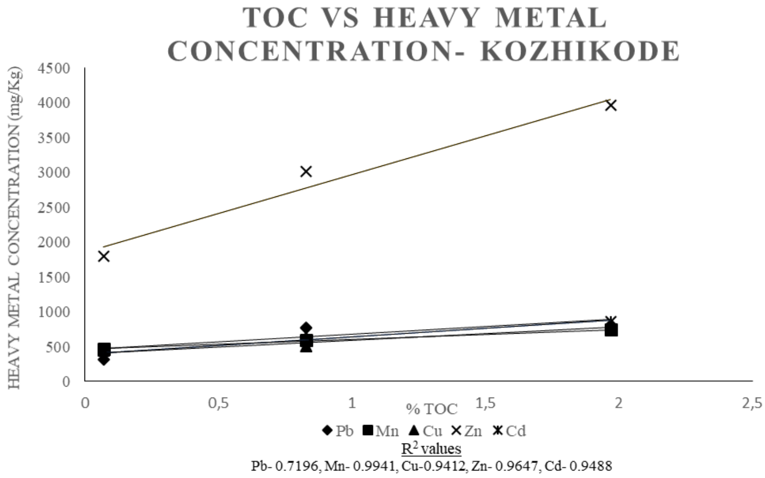

FIGURE 4: Variation of TOC with heavy metal concentration of Kozhikode samples.

indicated by a steeper graph. The intercepts of the graphs are given in Table 4.

The Y-intercept represent the theoretical concentration of heavy metals that adheres to the microplastics from the compost without biofilms (TOC=0%). The comparison of the heavy metal concentrations and the new unpolluted macro-plastics to the Y intercept values indicates that the adsorption of heavy metals onto the microplastics occurred via alternative mechanisms, rather than being solely adsorbed to biofilms. In the samples from Kochi, more than 80% of Cd and Cu remained directly adsorbed on the microplastic surface. The heavy metal adsorption on microplastics can depend on the polymer type, crystallinity, surface area, and also on the pH and temperature of the environment (Gao et al., 2021).

3.3 SEM results

The removal of biofilms adhered to the microplastic surfaces were visualized by the SEM images. The images obtained from the SEM analyses are shown as Figure 5.

The SEM analyses performed on the three microplastic samples revealed a noticeable decrease in the presence of biofilms adhered to the microplastic surfaces, progressing from Figure 5a to Figure 5c. The initial handpicked samples (Figure 5a) showed to have a thick layer of organic matter or biofilms. However, through subsequent treatments including thorough washing with distilled water (Figure 5b) and Fenton's reagent digestion (Figure 5c), the organic impurities were significantly reduced, as also shown by other authors (Pfohl et al., 2021). As a result, the surfaces of the microplastic samples appeared cleaner and less contaminated. The reduction in biofilm adherence can be correlated with a decrease in adsorption sites and functional groups present on the microplastics. These adsorption sites and functional groups have the potential to bind heavy metals to the microplastics. Therefore, the diminishing presence of organic matter suggests a corresponding reduction in the availability of sites that can facilitate the adsorption of heavy metals onto the microplastic surfaces. This observation reinforces the understanding that bio-films play a crucial role in the adsorption and retention of heavy metals by microplastics (Y. Li et al., 2022; Zheng et al., 2023).

TABLE 4: Y intercepts from the graphs.

Heavy Metal	Y intercept (mg/kg)	
	Kochi	Kozhikode
Lead	240.6	135.6
Manganese	655.3	330.0
Copper	778.0	225.3
Zinc	1045.0	760.3
Cadmium	591.6	248.3

4. CONCLUSIONS

The study showed that there is significant concentration of microplastics in the compost generated in MSW compost plants of Kochi and Kozhikode. It was also found that the concentration in the compost of some heavy metals exceeded the limits set by the US EPA for land application. Further, it was found that microplastic can act as vectors of heavy metals from compost to other environments. The biofilm formed on the microplastic surface was found to be the most influential factor for the heavy metal accumulation, although, the microplastic surface also adsorbs lower quantities of heavy metals directly. This finding highlights the importance of source segregated collection of MSW, where organic matter is not allowed to mix with plastic waste. Analyses showed that the heavy metal concentration adsorbed on microplastics is directly proportional to the amount of biofilm present over the microplastic, for a given concentration of heavy metal in the environmental matrix. The normal methods adopted for separation of microplastics from an environmental matrix influence the heavy metal analysis results. Analysis after chemical separation results in the underestimation of heavy metals concentrations in microplastics and consequent impacts.

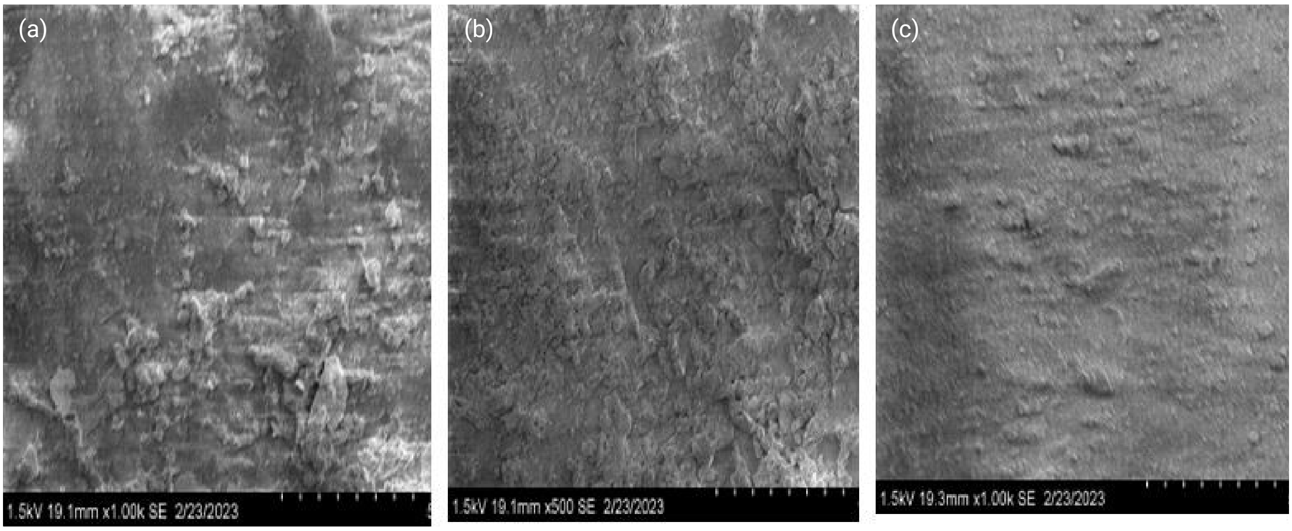

FIGURE 5: SEM images of Hand-picked samples, Distilled water washed samples and chemically separated microplastics.

Nevertheless, plastics act only as vectors (that may transport the pollution to other, more fragile environments) for the heavy metals that are anyways present in the waste. Therefore, a reduction of the heavy metal inflow is also an important measure that has to be taken into account.

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