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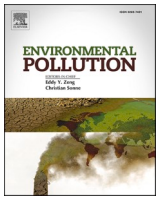

A screening of metal(loid) content in conventional and compostable plastic polymers: understanding the sources and the connected environmental implications☆

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ABSTRACT

Plastic pollution is a well-known environmental issue, yet the ecotoxicological implications are still underexplored. In this context, attention towards the characterization of chemical additives in plastics and their potential risks to both human health and ecosystems is now increasing. While significant research has been conducted on organic chemicals, data on inorganic additives (e.g., metallic compounds) remain limited. In this study, we analyzed the metal(loid) content in different types of plastics to better understand the presence of inorganic additives in these materials, their distribution across different polymer types, and their potential impacts. We investigated pristine plastic pellets, single-use plastic materials and recycled plastic pellets made from both conventional and compostable polymers. We observed a notable enrichment of metal(loid)s (particularly Ti, Al, and Zn) across a range of plastic types, especially when comparing pre-production pellets with final consumer materials, suggesting that these additives are incorporated during the final stages of production. Samples of polyethylene terephthalate displayed elevated levels of Sb, while compostable plastics exhibited specific trends related to Sn and In: they are abundant in the pellets, since they are used as catalyst in polymer production. This study provides a comprehensive comparison of metal additives in different plastic polymers and across different production phases. It highlights the need for characterizing metal(loid) content in plastic to understand the potential connected risks. Additionally, the findings underscore the role of compostable plastics as potential carriers of metal(loid)s to terrestrial and aquatic environments, raising concerns about their degradation and impact.

1. Introduction

Plastic pollution is a known environmental threat. However, the potential ecotoxicological implications and negative effects to ecosystems are still far from being sufficiently understood. In this context, the chemical additives included in plastic and their potential risks to human health and the environment have recently attracted interest: the array of additives and other chemicals that can be included in plastic compounds is extremely wide, and can vary on plasticizers, slip agents, catalysts, dyes, fillers and more (Geueke et al., 2023; Hahladakis et al., 2018; Turner and Filella, 2021). These chemicals are in fact abundantly present in plastic consumer materials. Gaining knowledge on the composition and abundance of chemical additives in commercial plastic has become a key need, as several knowledge gaps have been highlighted, especially towards a green policymaking process (Maes et al., 2023; Mitrano and Wohlleben, 2020; Wiesinger et al., 2021).

The dispersal of plastic in the environment may favor the release of these additives, enhancing the biota exposure to these chemicals. This is due to several aging processes which alter the features of plastic in the environment: these processes are known to decrease the hydrophobicity

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of polymers, increase the specific surface area and induce fragmentation of plastic particles. These alterations of plastic properties can also favor the sorption of other chemicals from the surrounding environment, further complicating the understanding of additive leaching when monitoring environmental plastic (Binda et al., 2024; Catrouillet et al., 2021; Ge et al., 2023; Luo et al., 2022; Zhang et al., 2025). This process may be even more problematic considering the increasingly abundant use of compostable polymers to produce plastic materials. Their potentially faster degradation rates under environmental conditions may foster a more rapid dispersion of (potentially toxic) additives from the polymer formulations, as well as an increased reactivity towards other chemicals (Cao et al., 2023; Peng et al., 2023; Torres et al., 2021).

Several inorganic chemicals are added along plastic production process, such as functional additives and pigments (Turner and Filella, 2021). Other inorganic compounds are instead added as catalysts in the first phases of polymerization and may remain in the polymer matrix. This process is strictly polymer specific: a known example is the use of Sb in polyethylene terephthalate (PET) to favor the polycondensation of this polymer (Filella, 2020). As a further complication, several metal (loid)s are known to be potentially present in plastic materials as non-intentionally added substances, such as impurities of inorganic fillers or incorporated during fragmentation of recycled plastic (Horodytska et al., 2020; Núñez et al., 2022). However, researchers are mostly focusing on several organic chemicals present in plastic as additives (Hahladakis et al., 2018; Sørensen et al., 2023), while the research on concentration ranges and variability of inorganic additives is notably more limited (Cao et al., 2023; Klöckner et al., 2021; Turner and Filella, 2021). This is not in line with the known toxicological properties of several metal(loid)s, as well as with the persistence of these compounds in the environmental matrices (Ali et al., 2019; de Paiva Magalhães et al., 2015). This class of additives has only recently attracted the interests of researchers and there are still important knowledge gaps regarding the frequency of detection and concentration ranges of metal(loid)s in plastic materials, comparing different polymer types and plastics at different production stages, such as the pre-production pellets and the end-use plastic materials.

Expanding knowledge in this direction may provide guidance for the potential use of some metal(loid)s as chemical markers of specific polymers in environmental media (Klöckner et al., 2021; Pořízka et al., 2023; Rodrigues et al., 2023) and may help in understanding other indirect side-effects of plastic (e.g., inorganic additive leaching), both in simplified ecotoxicological studies and in broad environmental risk assessment process (Catrouillet et al., 2021; Peng et al., 2023; Turner et al., 2020; Turner and Filella, 2021), in order to understand the environmental relevance of plastic as a new source of metal(loid)s in the natural environment (Walsh et al., 2025). The toxic effects of several metal(loid)s are in fact well-known, and environmental plastic may become a new source of exposure to these chemicals in the environment (Binda et al., 2021b). Understanding the amount of metal(loid)s potentially present in plastic become also fundamental for the comprehension of the potential sorption of these compounds by plastic from the environment: several studies are in fact focusing on the comparison of pristine (i.e., commercial-grade and newly produced) and environmentally collected plastic samples (Binda et al., 2021b; Klöckner et al., 2021; Rodrigues et al., 2023).

In this study, we analyze the metal(loid) content in different types of plastics. We analyzed pristine pellets, single-use plastic materials of several types and some samples of recycled pellets. These objects were composed of different conventional and compostable polymers which are frequently reported in environmental compartments. This screening aims to gain knowledge on the amount of plastic inorganic additives, their presence in specific polymers and their eventual enrichment during the production process of end-use plastic materials. While this approach limitedly enhances the information relative to the environmental risk induced by the leaching of these compounds from plastics, the survey of these chemical features is needed, as extremely limited information is available in the current literature about concentration ranges and detection frequency of these chemicals in plastic (Klöckner et al., 2021; Walsh et al., 2025). This knowledge gap is even more dramatic for compostable plastics, which presents even more fragmented and limited evidence for their metal(loid) content (Carnati et al., 2024). This investigation can give guidance in the evaluation of indirect side-effects related to plastic in the environmental risk assessment process, in the production of representative reference materials and in the probing of specific chemical markers to detect plastic polymers in environmental matrices.

2. Materials and methods

2.1. Plastic samples selection, preparation and characterization

The plastic samples (n = 65 in total) were selected to cover a variety of single-use objects composed of both conventional (i.e., polyethylene - PE, polypropylene - PP, polystyrene - PS and PET) and compostable polymers (i.e., polylactic acid – PLA and polybutylene adipate terephthalate – PBAT). This selection was made to cover the more abundantly used and environmentally detected polymers from mismanaged single use products (Geyer et al., 2017). We integrated the two compostable polymers in this screening as they are currently used to substitute conventional polymers in single use items. However, while their use is notably increasing in the market, the chemical composition of their additives is much less well known in comparison to conventional polymers (Cao et al., 2023; Qin et al., 2021).

We selected different categories of plastic to also observe the potential change in additive concentration along the production phases. These include.

- 51 samples composed of end-use materials covering different market sectors (e.g., food industry, disposable labware and agriculture). These also include five samples of fragmented plastic waste obtained from mixed end-use materials in a recycling facility. These are referred to as “material” in the following text;
- 11 samples of pristine pellets composed by the same polymers analyzed in the end-use materials were investigated to evaluate the initial metal(loid) content already in the pre-production phases (referred to as “pristine pellet” in the following text);
- Three samples of pellets obtained from a recycling plastic facility composed by PET and PS (referred to as “recycled pellet” in the following text). This helped us to evaluate potential contamination with inorganic additives due to plastic grinding in the recycling process. This issue is also of increasing interest to understand the improvement of circularity in plastic recycling, as metals may also negatively affect the production of material from recycled plastic (Eriksen et al., 2018). While this category presents a notably lower sample size, it was introduced to explore potential differences of recycled plastics with other end-use materials.

Details on the specific plastic samples are listed in Table S1.

Once in the laboratory, the plastic samples from end-use plastic were first cut using a ceramic knife down to a size of approximately 5 mm and homogenously mixed. Plastic in the shape of pellets and grinded recycled plastic were instead analyzed as they were. All plastic samples were analyzed using a Fourier-transform infrared (FTIR) spectrometer (Nicolet™ iS™ 10 ATR-FTIR, Thermo Scientific™, USA) to evaluate or confirm their polymeric composition. Sixteen scans were collected for every sample in the 4000 - 650 cm^{-1} spectral range and with a resolution of 0.67 cm^{-1}. A background spectrum was recorded in between the measurements of every sample.

2.2. Plastic digestion and analysis of metal(loid) content

The digestion protocol used in this study is a specific method we set

up to digest and analyze the metal(loid) content in plastic polymers, and it is thoroughly described in Carnati et al. (2024). This digestion protocol in fact highlighted reliable measures within accuracy and precision for the analysis of metals in plastic samples and it was validated with the use of a certified reference material (ERM®-EC681m). Dissolution of the plastic materials was obtained through microwave-assisted digestions in a closed system (ETHOS One, Milestone MLS, USA) equipped with 10 polytetrafluoroethylene (PTFE) vessels. Briefly, approximately 100 mg was accurately weighed and inserted into each pre-cleaned vessel, together with 4 ml of 65 % v/v HNO_3 and 1 ml of 95 % v/v H_2SO_4. The materials were then digested by applying a temperature ramp reaching 200 °C for 45 min.

Afterwards, a further digestion at room temperature was performed by adding H_2O_2: 0.1 ml of H_2O_2 was added to each vessel and, following a gentle stirring, the reaction was allowed to continue for 30 min at room temperature, after which another H_2O_2 addition of 0.1 ml was made. This further oxidation step was applied to ensure a complete dissolution of the recalcitrant or partially digested polymer matrix. Solutions were then left at room temperature to cool inside the vessels. Then they were transferred to pre-cleaned low-density polyethylene (LDPE) bottles and diluted to reach a final weight of about 20 g with ultrapure water. The obtained solutions were then filtered (0.45 μm PTFE filter), further 20-fold diluted and spiked with two internal standards (Rh and Re, respectively). These diluted solutions were finally analyzed via ICP-MS (Thermo Scientific ICAP Q, USA) and metal(loid) quantification was obtained by external calibration. 51 metal(loid)s were analyzed in total, including: Ag, Al, As, Ba, Be, Bi, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Hf, Ho, In, Ir, K, La, Li, Lu, Mg, Mn, Mo, Na, Nd, Ni, Pb, Pr, Rb, Sb, Sc, Se, Sn, Sr, Ta, Tb, Ti, Tl, Tm, U, V, Y, Yb, Zn and Zr. This wide list of metal(loid)s can show also uncommon metal (loid)s potentially (both intentionally and unintentionally) added to plastic, which has been observed to be unexpectedly present in plastic polymers (Cuthbertson et al., 2024; Turner et al., 2021; Walsh et al., 2025).

2.3. Reagents and QA/QC protocols

Sample handling and solution preparations were carried out under a laminar flow hood to avoid airborne contamination (aura HZ72T BIO-AIR, Italy). Analytical grade reagents and ultrapure water (Milli-Q from Sartorius Arium® mini, Germany; resistivity: 18.8 MΩ cm; TOC: <5 ppb) were used. Ultrapure HNO_3 was produced by sub-boiling distillation from commercial HNO_3 (Carlo Erba, 65 % v/v) using a Milestone (USA) DuoPur system (Monticelli et al., 2019). Commercial H_2SO_4 (Analytika, 95 % v/v pure) and H_2O_2 (Fisher Chemical, 30 % v/v for trace analysis) were used as purchased. All LDPE containers employed for laboratory and analytical solutions underwent a two-step cleaning procedure with ultrapure water, NALGENE® solution and a 2 % v/v HNO_3 solution (Binda et al., 2018). PTFE digestion vessels were pre-cleaned before each digestion cycle following a two-step procedure: they were first cleaned through a heating cycle with 65 % HNO_3 and rinsed three-times with ultrapure water. Then, they were conditioned through another heating cycle with the same acid mixture used in the digestion and again rinsed three times with ultrapure water (Carnati et al., 2024).

The precision and accuracy of the method were assessed after five digestion replicates of the certified reference material ERM®-EC681m for the certified metal(loid)s (i.e., As, Cd, Cr, Pb, Sb, Sn, Zn). Results are reported in Table S2. Limits of detection (LODs) were obtained after the analysis of five procedural blank samples (i.e., acid solutions underwent digestion and dilution without the addition of plastic sample), and were calculated as three times the standard deviation of the blanks (Rødland et al., 2024). These are listed in Table S3.

2.4. Data analysis

Metal(loid) concentration data from ICP-MS analyses after digestion were expressed as the average after three replicates in mg/kg of digested plastic in every plastic sample. Then, for samples presenting concentrations < LOD, a replacement was made by dividing the LOD value for that metal(loid) by 10.

All datasets of metal(loid) concentrations were evaluated for normality using a Shapiro-Wilk test prior to further analysis. Since assumptions of normality and homogeneity of variance were violated, the non-parametric Kruskal-Wallis ANOVA was used to validate differences among different polymer types, as well as between pellets and end-use plastic samples. Dunn's post-hoc test was also applied to observe significant differences (as $p < 0.05$) among different categories. The relationships between different metal(loid) concentrations in different plastic samples were explored using principal component analysis (PCA). Data handling, descriptive statistics, non-parametric tests and PCA were computed using Microsoft Excel and Origin 2024 pro software.

3. Results and discussion

3.1. Features of the plastic samples

The plastic samples, after FTIR analysis, were composed of 6 polymers in total (Fig. 1). Regarding the conventional polymers, 17 samples were composed of PE (14 materials and 3 pristine pellets), 11 of PP (10 materials and 1 pristine pellet), 8 of PS (5 materials, 1 pristine pellet and 2 recycled pellets) and 8 of PET (5 materials, 2 pristine pellets and 1 recycled pellet). This proportional composition corresponds well with both the current market and the environmental detection of these polymers (Bellasi et al., 2020), reinforcing the selection of materials included in this study. We would highlight that the sample size of recycled pellets is limited as these samples were not readily accessible. They were included in the study as they still provide valuable information. However, this limitation affects the ability to make statistically robust comparisons with other categories. Concerning the compostable polymers, 15 samples were composed of PBAT (12 materials and 3 pristine pellets) and 6 of PLA (5 materials and 1 pristine pellet). These

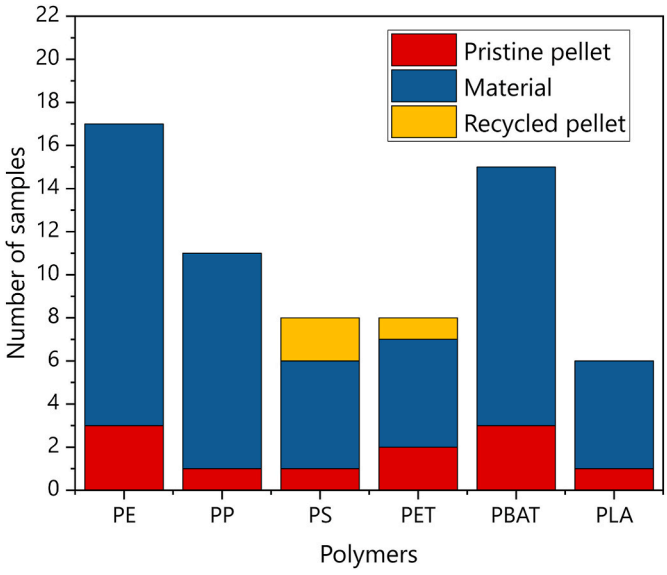

Fig. 1. Stacked bar plot of the number of samples analyzed in this study composed of different polymers. Bar colors indicate the categories of samples analyzed for each polymer (pristine pellets, end-use materials and recycled pellets). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

two polymers represent more than 25 % of the current production of compostable polymers (Haider et al., 2019). Overall, the analysis of polymeric composition confirmed all the composition labels marked on the commercially available samples.

3.2. Metal(loid) content and comparison with threshold values

Plastic samples analyzed in this study showed extremely variable concentrations of metal(loid)s: their total content is in fact variable by up to 2-3 orders of magnitude in concentration among the different samples (Table S3), with most of the analytes showing a skewed distribution in concentration. This trend was already observed in previous studies on pristine and environmentally collected plastic samples (Binda et al., 2021a; Carbery et al., 2020; Carnati et al., 2023; Klöckner et al., 2021). In this study, the most abundant metals detected in the samples were Ti, Al, Mg, Na, Fe, K and Zn with median concentrations ranging from about 3 to 70 mg/kg in the plastic samples. The use of these metals in plastic materials is generally established. Ti, for example, is extensively used in plastic objects for several reasons, including pigmentation (white), thermal insulation and to enhance the structural integrity of plastics (Allen and Edge, 2021; Day, 1990; Turner and Filella, 2023).

Several other metal(loid)s (such as Ba, Mn, Ni, Sn, Sb, Sr and Zr) showed a broader difference among the different samples with concentrations ranging from below the LODs up to above 10 or 100 mg/kg. Among the 51 elements analyzed, a total of 24 presented results where >50 % of the samples had values below the LOD. These metal(loid)s were therefore excluded from further statistical analyses and are also excluded from the following discussions on the trends observed in the analyzed plastic samples, given their lower relevance confirmed through low detection in common polymeric materials (sections 3.3 and 3.4).

To understand potential concentrations of concern for toxic metal (loid)s in the plastic samples, a comparison of the maximum values observed in investigated samples with the legislation values for specific metals and metalloids presenting interest for environmental and human exposure was performed. These values are derived from different legislations with varying threshold values related to the different exposure scenarios and the plastic type. They include, for example, the "restriction of hazardous substances" and the "contact with foodstuffs" from the European Parliament (Commission Directive, 2002; European Parliament and Council, 2003), as well as the UNI EN14995 threshold limits for the biodegradation of plastics. These have also been recently used as a comparison of the total metal(loid) content in plastic samples (Klöckner et al., 2021; Turner and Filella, 2021). All the samples showed concentrations within the reference values for Cd, Cr and Pb of the restriction of hazardous substances values (Turner and Filella, 2021). Similarly, the values of 9 metal(loid)s selected for the compostable plastic samples were within the ranges of the thresholds relative to the biodegradation and potential toxicity of compostable plastics during and after their biodegradation. There are, instead, some values beyond the threshold limits for the objects used as food containers in comparison to the levels of "contact with foodstuff" thresholds, considering only the samples of plastic objects used in the food market: Cr is higher than the threshold of 1 mg/kg, Zn is above the threshold of 100 mg/kg and Cu is two orders of magnitudes higher than its value (101 mg/kg, with a threshold value of 5 mg/kg). The other metal(loid)s listed in this legislation are instead below the reference values (Table 1). It is, however, worth mentioning that the legislation still presents a limited suite of metal(loid)s to be considered in these compounds, as the knowledge on inorganic additives in plastic has only recently attracted the interests of policymakers (Maes et al., 2023; UNEP, 2023). This investigation, in fact, highlighted other metal(loid)s with relatively high concentrations and high detection frequency (e.g., Ba, Sn and Zr), which are not considered in the current legislation, highlighting the necessity to implement the evaluation of more metal(loid)s in the evaluation of the threshold values.

3.3. Comparison with other available data on metal(loid) concentrations

A comparison with the available data showed on metal(loid) in plastic materials collected in grocery stores and in environmental samples highlighting the most commonly detected metals (Fig. 2) indicate a variable amount in the different studies (Abbasi et al., 2024; Battulga et al., 2023; Klöckner et al., 2021; Walsh et al., 2025).

The metal(loid)s analyzed in these studies also showed a markedly skewed distribution. Some metals we analyzed (such as Ba, Co, Cu and Zn) have comparable ranges with the ones observed in other studies (Abbasi et al., 2024; Battulga et al., 2023; Klöckner et al., 2021; Walsh et al., 2025). It is however worth considering how these values can widely range of more than 3 orders of magnitude in concentration. Comparing instead the median data observed in our study to other ones, most of the metal(loid)s show a lower concentration in the plastic samples analyzed in our study. This could indicate a likely increase in concentration of some metals (such as Cr, Fe, Mn, Pb and Zn) in plastic samples collected in the environment, in comparison with pristine plastic collected in production areas or grocery stores. This process is already highlighted in the current literature and potentially ascribable to the aging plastic polymers and the colonization by biofilms in the environment, likely to increase the sorption of several meta(loid)s (Binda et al., 2023; Carnati et al., 2023; Liu et al., 2022; Rodrigues et al., 2023).

We would finally highlight that another process which can affect the final concentrations observed may be the different pre-treatments (i.e., sample digestions) performed in the different studies. This is known to potentially alter the concentrations observed in the different analyses (Carnati et al., 2024).

3.4. Factors affecting the concentration of metal(loid)s in plastic

We performed a PCA using the different concentration values obtained by acid digestion as inputs, in order to preliminary explore the

Table 1
Comparison of maximum values detected in the dataset with legislative thresholds, depending on the use of the samples selected (data are expressed as mg/kg of plastic). The threshold values for all samples are obtained from Restriction of Hazardous Substances, the threshold for compostable plastic is obtained from UNI EN 14995 and the threshold for food is obtained from contact with foodstuffs (Turner and Filella, 2021). Values above the threshold are highlighted in bold and italics.

Element	All samples		Compostable polymers		Food market	
	Maximum values	Threshold	Maximum values	Threshold	Maximum values	Threshold
As	1.88	–	0.24	5	0.16	1
Cd	9.04	100	<LOD	0.5	0.05	–
Cr	45.2	1000	0.9	50	***2.7***	1
Cu	365	–	10.6	50	***101***	5
Mo	2.01	–	<LOD	1	1.3	–
Ni	30.1	–	<LOD	25	<LOD	–
Pb	6.88	1000	0.43	50	1.24	2
Se	2.18	–	<LOD	0.75	0.3	–
Zn	169	–	44.5	150	***151***	100

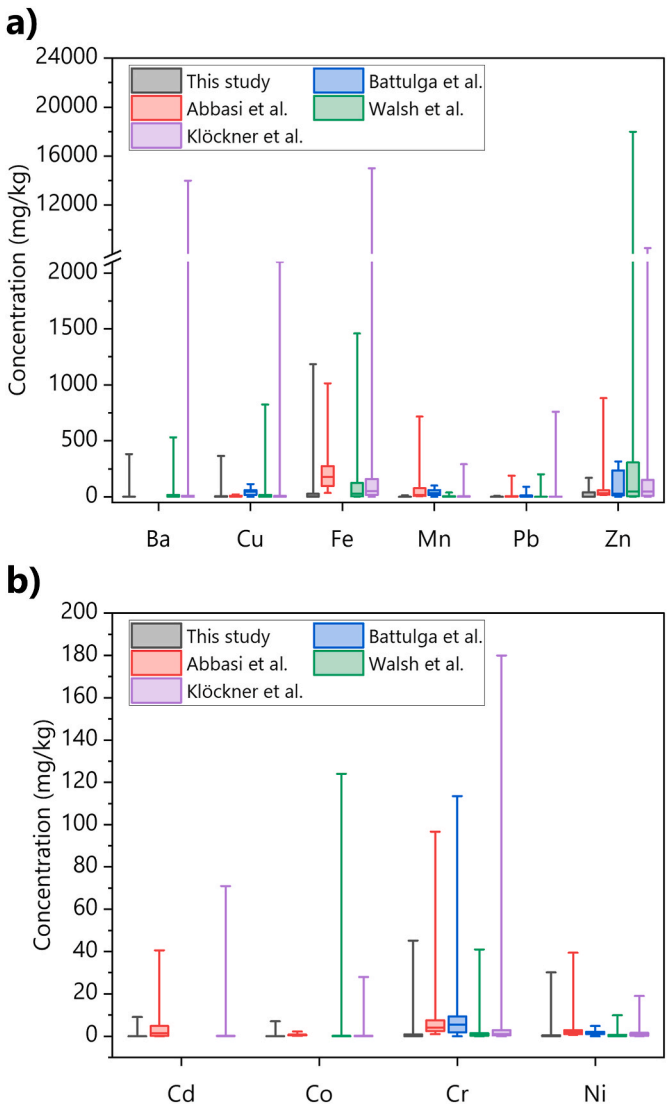

Fig. 2. Comparison of the range in concentration of the most frequently detected metal(loid)s in this study and other research investigating the content of plastic (Abbasi et al., 2024; Battulga et al., 2023; Klöckner et al., 2021; Walsh et al., 2025). Panel a shows metal(loid)s with concentrations ranges above 200 mg/kg, while panel b shows values below this concentration. Lines indicate the median value, boxes the 25th-75th percentile range and whiskers the minimum-maximum range.

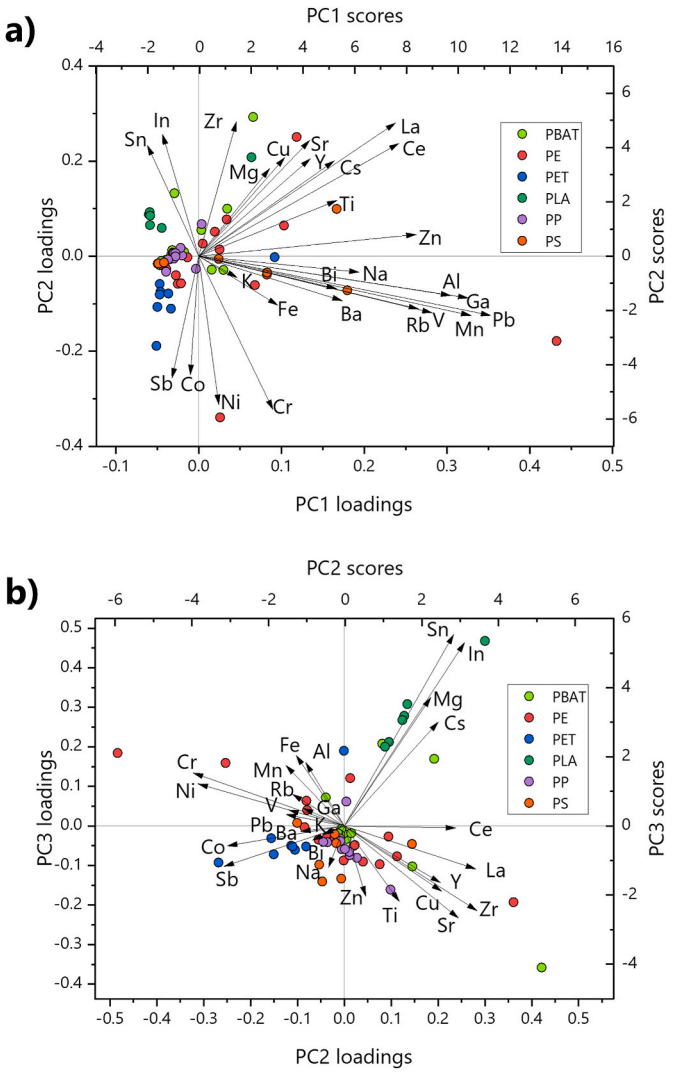

Fig. 3. PCA biplot including all acid digestions for PC 1 and 2 (panel a) and PC 2 and 3 (panel b). Samples are marked based on the composing polymer using different colors. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

effect of different variables on metal(loid) concentration in plastic pristine pellets and end-use materials. We selected the first three PCs, as they explained the 40.8 % of the total variance (with 22.47 % explained by PC1, 9.52 % by PC2 and 8.32 % by PC3).

The biplot of scores and loadings obtained from the PCA is depicted in Fig. 3, with the scores of different samples categorized by polymer type. A clear variance among different samples is observable on both PC 1 and 2, regardless of the polymeric composition (see for example PE, in red): this effect is more evident for end-use plastic materials, which showed higher concentration of several metallic elements in comparison to the pristine pellets, as evident by the high score values on PC 1 (see also Fig. S1a and c, showing the PCA outputs colored by sample category). The only exception for this trend is a pristine pellet sample composed of PET, which is reported by the producer as enriched in talc, possibly explaining this shift in concentration (Sample "PET_PEL_1" in Table S1).

Other polymers showed instead a more marked clustering observing the scores of PC 1, 2 and 3. Polyethylene terephthalate and PLA samples, for example, are mostly well clustered. In addition, these polymers showed clustered samples even when considering both end use materials and pristine pellets, indicating that there are specific trends in metal (loid) concentrations regardless of the additives added in the final compounds. Inorganic additives (e.g., Sb_2O_3 catalysts in PET and Sn- and In-based catalysts in PLA) for these polymers are therefore likely used in the polymerization phase and are already present before the production of end-use materials.

3.4.1. *Mechanisms of metal(loid) enrichment in the plastic production phases*

Several metal(loid)s can be added in plastic both as functional additives (e.g., slip agents, UV stabilizers, biocides), pigments and fillers. Also, other metal(loid)s may be integrated unintentionally during the plastic production process (e.g., as filler impurities). The enrichment in some metal(loid)s was therefore expectable in end-use plastic materials, especially in comparison to pristine pellets.

This enrichment is in fact clearly visible in the PCA analysis, with increasing PC 1 values for several metal(loid)s (Fig. 3 and Fig. S1). Several end-use materials show higher scores of PC 1 in comparison with the pristine pellets, regardless of the polymeric composition. This was more evident for polymers such as PE and PS, but also other ones (e.g.,

PBAT, PLA and PP) and indicates an enrichment in metallic concentration due to the final suite of additives included in the end-use materials. We decided therefore to analyze this effect in more detail: Fig. 4 depicts the trends of 6 abundant metals in the samples analyzed (namely, Ti, Al, Zr, Zn, Mn and Pb), in the different categories of plastic samples we collected (pristine pellets, materials and recycled pellets). While the high variation among different samples still highlights a wide concentration range, with a marked negatively skewed distribution, a trend is evident especially comparing the concentrations in pristine pellets and end-use materials. There are significantly higher concentrations in the final materials and/or in the recycled pellets for all these metal(loid)s in comparison to the pristine pellets. This trend, in addition, is remarked also for other metals (e.g., Cr, Cu, Sr and V), as well as for other less environmentally relevant (and less toxic) ones such as Mg, Ca,

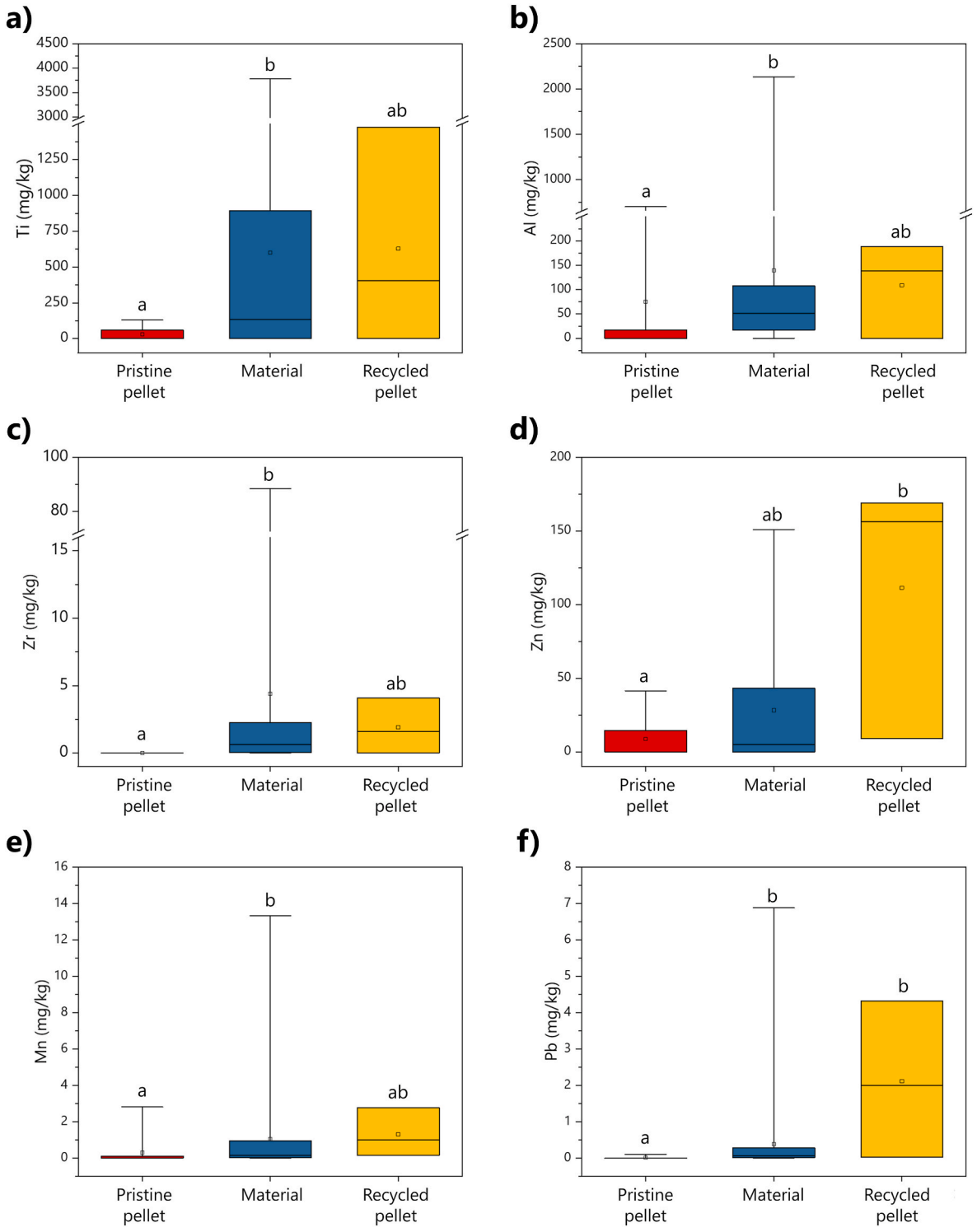

Fig. 4. Box plots of metal concentration in different samples categorized as pristine pellets (n = 11, in red), end-use materials (n = 51, in blue), and recycled pellets (n = 3, in yellow). Letters indicate the significantly different datasets after Kruskal-Wallis ANOVA and Dunn's post-hoc test. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Na and K (Table S4). These results were expected considering the abundant use of these additives in the polymer market (Hahladakis et al., 2018; Turner and Filella, 2021).

Inorganic fillers are in fact commonly used in the processing of plastic materials. For example, Ti, which is the most abundant metal in the end-use materials, is used frequently in polymers and other materials both as a white dye as well as a UV filter (Zhang et al., 2025). Aluminum, Mg, Zr, K and Fe are also abundantly present in the fillers, which are often talc-based or carbonate-based. Similarly, zirconia-based fillers are also frequent, as evidenced by the higher Zr concentration in end-use materials in comparison to pristine pellets (Turner and Filella, 2023; Zhou et al., 2022). Inorganic fillers and catalysts may also include impurities of other metal(loid)s, justifying significantly higher concentrations in end-use materials for metal(loid)s which are not commonly used as additives (such as Y, La, Ce and Bi, Table S3). The presence of these elements in trace amount is already observed in commercial plastic samples used for research purposes, representing anyway concentrations not significantly higher than in other natural compartments (Cuthbertson et al., 2024; Walsh et al., 2025).

Metal-containing additives are also commonly used in plastic industry as pigments (Carnati et al., 2023; Hennebert, 2023; Luo et al., 2019). This process is observable from the PCA analysis too: transparent objects and pristine pellets, in fact, present generally lower values of PC 1 in comparison to colored ones (including both white, black and others, Fig. S1b and Table S3).

Comparing pristine and recycled pellets in more detail, a less marked trend was observed. Some metal(loid)s in fact show non-statistically significant differences in concentrations, while others (such as Zn) showed higher concentrations than the end-use materials instead. This may be due to the enrichment in some metal(loid)s in the grinding process before the generation of new recycled pellets, as well as to the presence of notably high concentrations in some metal(loid)s in the plastic waste (Daggubati et al., 2025; Eriksen et al., 2018), as also already highlighted in this study. However, we would remark that the limited number of samples composed of recycled plastic pellets (n = 3) still hamper a systematic comparison. More in-depth investigations are needed to confirm these speculations.

3.4.2. *Specific trends of metal(loid) content in different polymers*

Beside a notable difference observed between consumer materials and pristine pellets, many metal(loid)s also showed specific polymer-related trends in the PCA analysis. PET samples, for example, showed an overall clustering, especially observing the scores of components 2 and 3 (Fig. 3). This behavior is due to the high concentration of Sb observed in comparison to other plastic samples: a direct comparison of concentration values with other polymers highlights a markedly higher concentration in PET samples (Fig. 5). The presence of Sb in PET is a known issue: the potential risk and release has been extensively analyzed especially in bottles and containers for food and beverage, to assess potential risks for human consumption (Filella, 2020; López et al., 2024). This concern, however, has been limitedly investigated so far considering the long-term environmental implications of dispersed single use plastics in the environment (Walsh et al., 2025). Also other plastic polymers beside PET contain relatively high concentrations of Sb: PS samples in this study show a median Sb concentration of 45.06 mg/kg. This is because Sb is also used in plastic as a flame retardant,

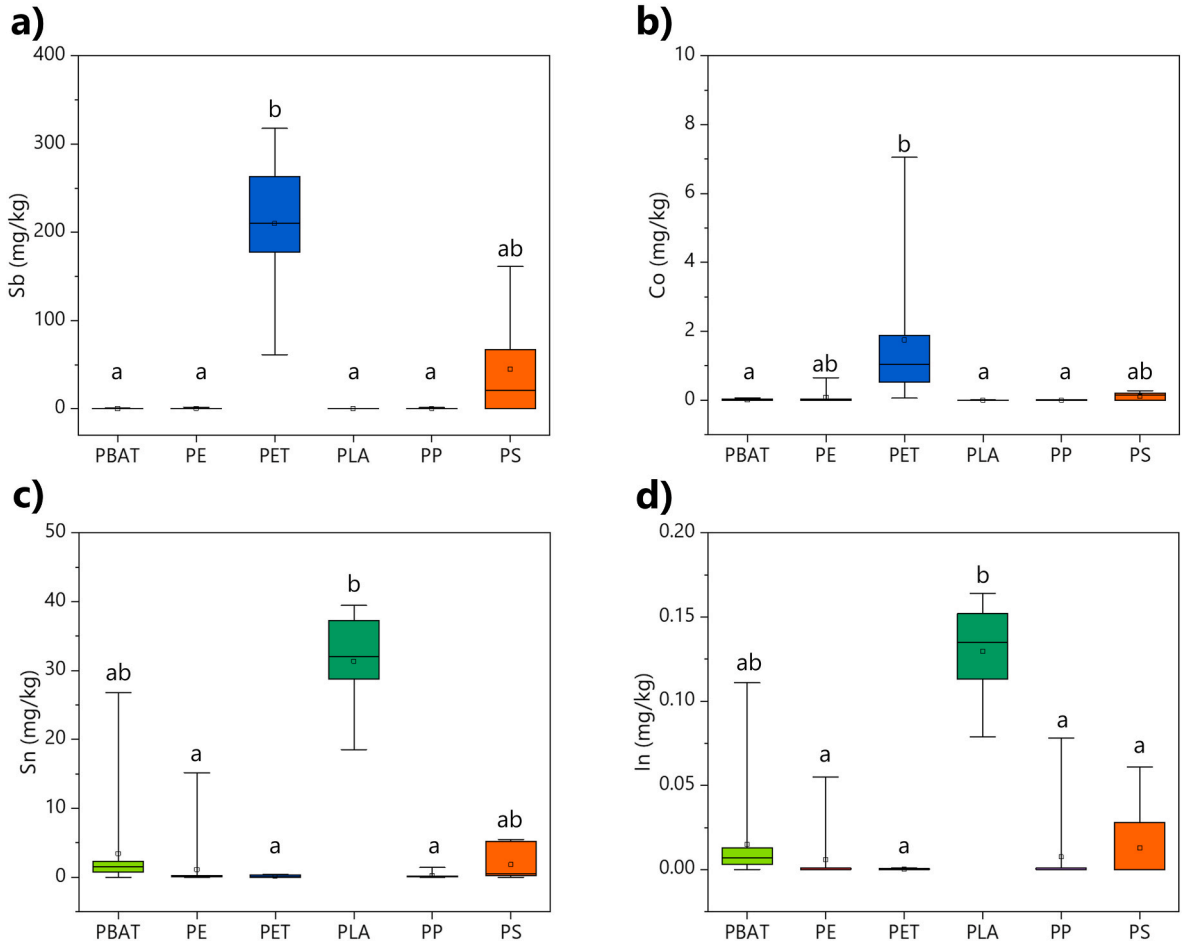

Fig. 5. Box plots of metal(loid) concentration (Sb in panel a, Co in panel b, Sn in panel c and In in panel d) of all samples categorized by the composing polymer. Letters indicate the significantly different groups after Kruskal-Wallis ANOVA and Dunn's post-hoc test.

with concentrations reaching up to several percent by weight, particularly in the plastic casings of electronic devices (Menger et al., 2024). These concentrations should warn about potential environmental implications for polluted sites: an accumulation of plastic materials containing this amount of Sb may lead to notable accumulation in soils and sediments as their natural concentrations of this element are generally below 1 mg/kg (Bolan et al., 2022).

Another relatively abundant metal in PET, especially in comparison with other polymers, is Co, with median concentration of 1.05 mg/kg. This metal is commonly added as a catalyst in PET polymerization: it serves both as an initiator to produce radicals favoring polymer cross-linking and as a coloring agent to reduce the yellowing during polymerization and the lifetime of the plastic object (MacDonald, 2002; Weatherhead, 1980). The residual concentration in the end-use materials is however limitedly considered in the current literature. This study sets a primer on the presence of Co in end-use plastic materials. The values of this metal in PET are, however, comparable to the natural concentrations of this element in soils (Liu et al., 2024), posing a limited issue of plastic in comparison as a specific source in comparison to other anthropic activities.

Other metals showed instead a specific enrichment in compostable polymers, and especially in PLA. These are Sn and In. Tin is a common stabilizer used in the production of PLA (Kricheldorf and Weidner, 2022), but also used to promote the polycondensation reaction of PBAT (Burford et al., 2023). The use of this metal (both as salt and as organotin compound) is highlighted by a significantly higher concentration in PLA and some anomalously high values in PBAT samples (Fig. 5d). Also In concentrations in the plastic samples, while generally being lower than the other metal(loid)s discussed so far (with concentrations in the order of 0.1 mg/kg), present a marked trend concerning PLA samples. Indium based catalysts, in fact, are increasingly used for the polymerization processes of lactides (Kremer and Mehrkhodavandi, 2019). While generally presenting lower content than the other metal(loid)s discussed in this work, the concentrations of In in our PLA samples are at least double of the average values in agricultural soils (Ladenberger et al., 2015). The specific concentration of this metal in comparison to natural compartments raises questions about the potential environmental risks it may pose. Additionally, it suggests the possibility of using In as a marker for identifying PLA in environmental samples.

3.5. *Warnings for environmental risk assessment and monitoring of plastic*

The data observed in this study highlight a diverse and complex array of inorganic additives present in plastic samples, indicating also some specific trends in metal(loid)s enrichment during the production process, as well as the marked concentration of specific metal(loid)s in some polymers. These chemicals, while being less commonly considered in the suite of plastic additives, require a careful evaluation when considering the environmental implications of plastic pollution. This is due to their known potential toxicity and persistence in the natural environment (Fairbrother et al., 2007). The outcomes of this survey, therefore, give guidance for the inclusion of metal(loid) analysis within plastic environmental risk assessment and monitoring in future research.

Concerning the use of plastics for ecotoxicity testing and environmental behavior (e.g., fate and additive leaching), the total content of metal(loid)s should be assessed when preparing the experimental batches of (micro)plastic materials (Hurley et al., 2024). Similarly, the trend observed for several metal(loid)s, showing markedly higher concentrations in end-use materials in comparison to pristine pre-production pellets, warns about potential side effects related, for example, to their leaching when assessing the toxicology of plastic fragments to biota, regardless of their polymeric composition. This indicates a cautious selection of experimental materials for ecotoxicity testing, as possibly more relevant negative responses can be expected for (micro)plastics obtained from end-use materials in comparison to industrial pellets (Rozman and Kalčíková, 2022). We also encourage the comparison of plastic composed by the same polymer to observe the specific side-effects related to the additive suites. It is also worth considering that the load of inorganic additives in plastic fragments is potentially capable of affecting its environmental fate and physical properties (i.e., density). This further calls for the integration of these parameters when characterizing (micro)plastics (Turner and Filella, 2020).

There is a potential to use some specific metal(loid)s as markers for plastic in environmental and biological media (Mitrano et al., 2019; Pořízka et al., 2023), as some metal(loid)s are known to be present at notably high concentrations in specific plastics (such as Zn for tires, Rødland et al., 2024). This potential use, however, still present several hindrances for the application in the real environment due to: 1) natural concentrations in other environmental matrices which are comparable to the ones observed in plastics, hampering a specific detection (Klöckner et al., 2021) and to 2) different use of these metal(loid)s in different plastic objects, hampering a specific marker for polymers (as an example, Sb is commonly used in PET but Sb compounds are also used as flame retardants in other polymers). In this study we observed specific trends for polymers (i.e., Sb and Co for PET and Sn and In in PLA) which can be potentially tested as markers for specific polymers. Indium, in more detail, can be a potential specific marker of compostable plastics in environmental matrices as it shows generally higher concentration than the natural background and a specific enrichment in PLA and in PBAT.

Finally, regarding the environmental implications associated with metal(loid)s in plastics, this study provides important insights in the total amount of metal(loid)s which can be transported by a new source in the environment, that is plastic. Plastics have been subject to uncontrolled discharge to the environment since their manufacture began several decades ago, leading to up to 4900 million metric tons potentially released in the environment (Geyer et al., 2017). Considering transport and residence times for terminal or temporary environmental receptors of many products (e.g. sediments and soils), plastic may become an important source of these chemicals in environmental compartments. Recent research, for example, suggest that some metal(loid)s abundant in plastic, such as Zn and Sb, may compose up to the 3 % and the 1 % of riverine inputs of these elements, respectively (Walsh et al., 2025). This issue may be even more problematic in the case of compostable plastics. Although the actual concentration of these metal(loid)s in compostable plastics is not extremely higher than in the environmental compartments, the enrichment of these metal(loid)s in compostable plastics should raise concerns given the theoretically shorter persistence of these polymers in the natural environment. This shorter lifespan may lead to the progressive accumulation of these metal(loid)s, some of them potentially toxic, in solid environmental compartments, such as soils and sediments. The calls for the integration of metal(loid) analyses in plastic characterization, and for the monitoring of the likely environmental sinks of plastic fragments and metal(loid)s (e.g., Chouchene et al., 2021) to assess wheter plastic should be considered as a potential carrier and a new source of metal(loid)s in the environment (Bradney et al., 2019; Peng et al., 2023; Turner and Filella, 2021).

We would finally mention that this preliminary screening only highlights the total content of metal(loid)s in plastic, which is a required measure for the understanding of potential transport and effects for the biogeochemical cycling of metal(loid)s (Walsh et al., 2025). The understanding of relative environmental risk, especially related to the leaching of these additives and their potential exposure to the biota requires more specific characterization concerning both the aging processes of plastic and the leaching potential of these metal(loid)s through specific extractions (Binda et al., 2023; Catrouillet et al., 2021).

4. Conclusions

In this study we underpinned the concentrations of metal(loid)s in various conventional and compostable plastic samples, and tracked

these concentrations across different production phases. The findings reveal significant variability in their concentrations among different plastic samples, reflecting the broad spectrum of chemicals that can be incorporated during plastic production. A key observation from this study is the enrichment of certain metals (such as Mg, K, Ti, Mn, Zn and Zr) in the final steps of plastic processing, ascribable to the use of metallic additives for several functions. Furthermore, the trends in metal (loid) concentrations appear to be associated with specific plastic polymers (such as Sb and Co with PET), suggesting the use of polymer-specific metallic catalysts for production of some polymers.

Given the persistence of metal(loid)s in the environment, it is crucial to investigate the long-term processes and potential environmental implications associated with their potential release from plastics. Understanding these dynamics will be essential for assessing the environmental risks posed by both conventional and (especially) compostable plastics. This study gives guidance for the understanding of potential risk related to plastic, also linked to the role of plastic as a carrier of metal(loid)s and the importance of specific monitoring to understand the likelihood of this process in the real environment.

CRediT authorship contribution statement

Gilberto Binda: Writing – original draft, Data curation, Conceptualization. **Stefano Carnati:** Writing – original draft, Formal analysis. **Noemi Passignani:** Investigation, Formal analysis. **Rachel Hurley:** Writing – review & editing, Investigation. **Luca Nizzetto:** Writing – review & editing, Supervision. **Davide Spanu:** Writing – review & editing, Formal analysis. **Gabriela Kalčíková:** Writing – review & editing, Formal analysis. **Andrea Pozzi:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2025.126364.

Data availability

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