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Alpine temporary ponds as overlooked sinks of anthropogenic macrolitter

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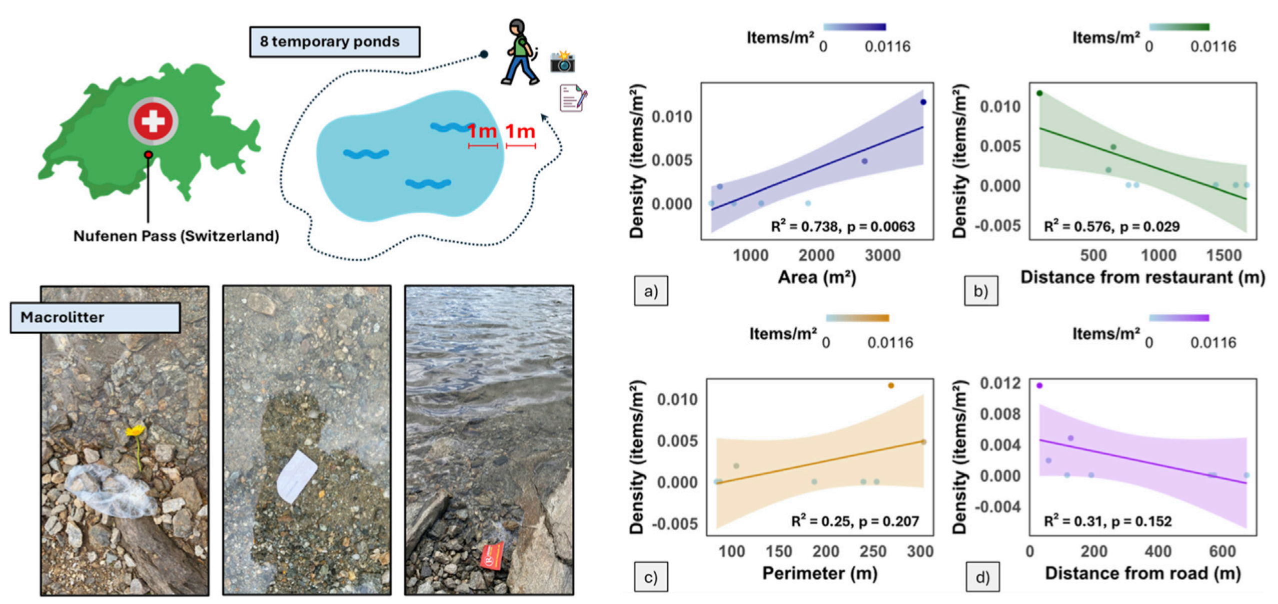
Temporary ponds represent fragile habitats that host species of high ecological and conservation interest. High-altitude ponds, although often considered pristine environments, may instead act as important sinks for anthropogenic macrolitter. This study, conducted in eight temporary ponds at Nufenen Pass (Switzerland, 2478 m a.s.l.), aimed to assess the abundance and characteristics of anthropogenic macrolitter in these habitats, focusing on key aspects such as polymer type, origin, shape, size, and color. A total of 56 macrolitter items were recorded, with an average of 7.0 ± 14.8 items per pond, corresponding to 0.002 ± 0.004 items/m^2. Among macrolitter items, most plastics (82%) consisted of food-related packaging (50%), artificial plants (15%), bottle labels (11%), and shotgun cartridges (4%), with smaller numbers of twist ties, clothing labels, cables, fruit boxes, and plastic rings. Non-plastic litter (18%) included bolts, cans, can tabs, aluminum packaging, and paper food packaging. The size of macrolitter was highly variable, with a total length of 695.5 cm and an average of 12.4 ± 15.4 cm per item. The most common polymers for plastics were PO hard (n = 26) and PO soft (n = 16). Macrolitter density increased significantly with pond area (R^2 = 0.73, p = 0.006), while a negative effect of distance from the restaurant present *in situ* was observed, with density decreasing as distance increased (R^2 = 0.58, p = 0.03). We reported for the first time the presence of macrolitter accumulated in alpine temporary ponds, showing alarming density of items and calling for immediate management actions.

KEYWORDS
alpine ecosystems, ephemeral pool, freshwater, high-elevation pond, macroplastic sinks, mountain pollution, plastic pollution

1 Introduction

Plastic pollution has become a major concern for environmental conservation and ecosystem protection (Chowdhury et al., 2022; Gündoğdu et al., 2026). Since 2004, global plastic production has surged, with output in the past 2 decades exceeding that of the previous 50 years (Rhodes, 2018). Within just a few years, plastic have contaminated every environmental compartment: soils (Bläsing and Amelung, 2018), the atmosphere (Taurozzi et al., 2024), oceans (Cressey, 2016), and freshwater systems (Dris et al., 2015). The main sources of pollution are urban centres, both large and small, where plastic waste management is often inadequate (Mihai et al., 2021). From cities, plastics are typically transported to the oceans through inland waters such as rivers, lakes, and ponds, with atmospheric events such as rainfall, hail, and wind often facilitating their dispersal (Belioka and Achilias, 2024; Ma et al., 2024; Wei et al., 2023). Plastics can also fragment into smaller



GRAPHICAL ABSTRACT

particles such as micro- (0.1 μm–5 mm) and nanoplastics (<0.1 μm), further increasing their pervasiveness in natural ecosystems (Al-Thawadi, 2020). These particles, whether produced directly during manufacturing or formed secondarily through the degradation of larger plastics, can cause both mechanical and chemical damage when ingested by organisms (Mishra et al., 2025; Rakib et al., 2023).

Over recent decades, the scientific literature on micro- and nanoplastics has increased exponentially, while much less information is available on the presence, distribution, and ecological impacts of macroplastic (MaP), defined as plastic items larger than 2.5 cm (Zeri et al., 2018). It has been demonstrated that MaP can contribute to habitat degradation, facilitate the transport of alien species, entrap organisms, and be ingested, leading to bioaccumulation (Dalu et al., 2025; Garcìa-Gòmez et al., 2021). All these aspects can pose a serious threat to biodiversity, which is already under pressure from other anthropogenic drivers such as climate change and land degradation (MacLeod et al., 2021).

Recent studies have documented the presence of MaP in major freshwater systems such as lakes, rivers, and wetlands, and have modelled their transport and fate within the environment (Cera et al., 2022). The most common pathways involve both terrestrial and aquatic routes, each with well-documented and often severe impacts (Blettler and Wantzen, 2019; Xu et al., 2023; Altunışık et al., 2025). However, to the best of our knowledge, no studies have so far reported the occurrence of MaP in temporary ponds (TPs). According to Richardson et al. (2022), TPs are defined as small (<5 ha), shallow (<5 m) water bodies with less than 30% emergent vegetation. They are among the most abundant lentic systems worldwide and are characterized by an ephemeral hydroperiod. Their water availability typically depends on groundwater, rainfall, or snowmelt, which fill the basins for limited periods of time, generally in autumn and winter for lowland ponds, and in summer for high-altitude TPs (Taurozzi and Scalici, 2025). In mountain areas, high-altitude TPs may also act as key stepping stones for the dispersal of animal and plant species, while serving as crucial breeding and nursery habitats (Wissinger et al., 2016). Yet, despite their ecological importance, TPs remain understudied. At European level, legislation protects these environments, but with some important gaps: although the annexes to the Habitats Directive specifically include Mediterranean Temporary Ponds (MTPs) as priority habitats, other categories, such as mountain TPs, are largely overlooked. In Switzerland, which is not subject to EU environmental directives, TPs are instead protected under national biodiversity strategies and cantonal regulations (Federal Act on the Protection of Nature and Cultural Heritage (NCHA), 1996; Federal Act on the Protection of Waters (Waters Protection Act, WPA), 1991) although a specific legal framework comparable to the Habitats Directive is still lacking.

MaP pollution has already been recognized as a concern in high-mountain ecosystems (Pastorino et al., 2022). Nevertheless, evidences of the occurrence of these pollutants in high-altitude waterbodies remains scarce. Only a few studies have reported the presence of MaP in mountain lentic and lotic environments: Liro et al. (2023) and Rajwa-Kuligiewicz (2025) reported MaP accumulation in mountain rivers located near populated areas; MaP has also been documented in Italian glaciers (Parolini et al., 2021), mountain lakes (Madibekov et al., 2024; Pastorino et al., 2022; Free et al., 2014), and streams (Andrade-Muñoz et al., 2025). However, no macro- and mesoplastics were found in high-mountain remote lake on Carnic Alps (Pastorino et al., 2022). Despite this growing body of work, significant gaps remain concerning MaP occurrence in ponds, particularly in high-mountain ecosystems. In this note, we provide the first records of anthropogenic macrolitter (especially macroplastics) in alpine TPs located at the second highest mountain pass of the Swiss Alps. Our hypothesis was that pollution originates from direct, on-site sources. To the best of our knowledge, these observations represent the first evidence of MaP occurrence in high-elevation ponds worldwide.

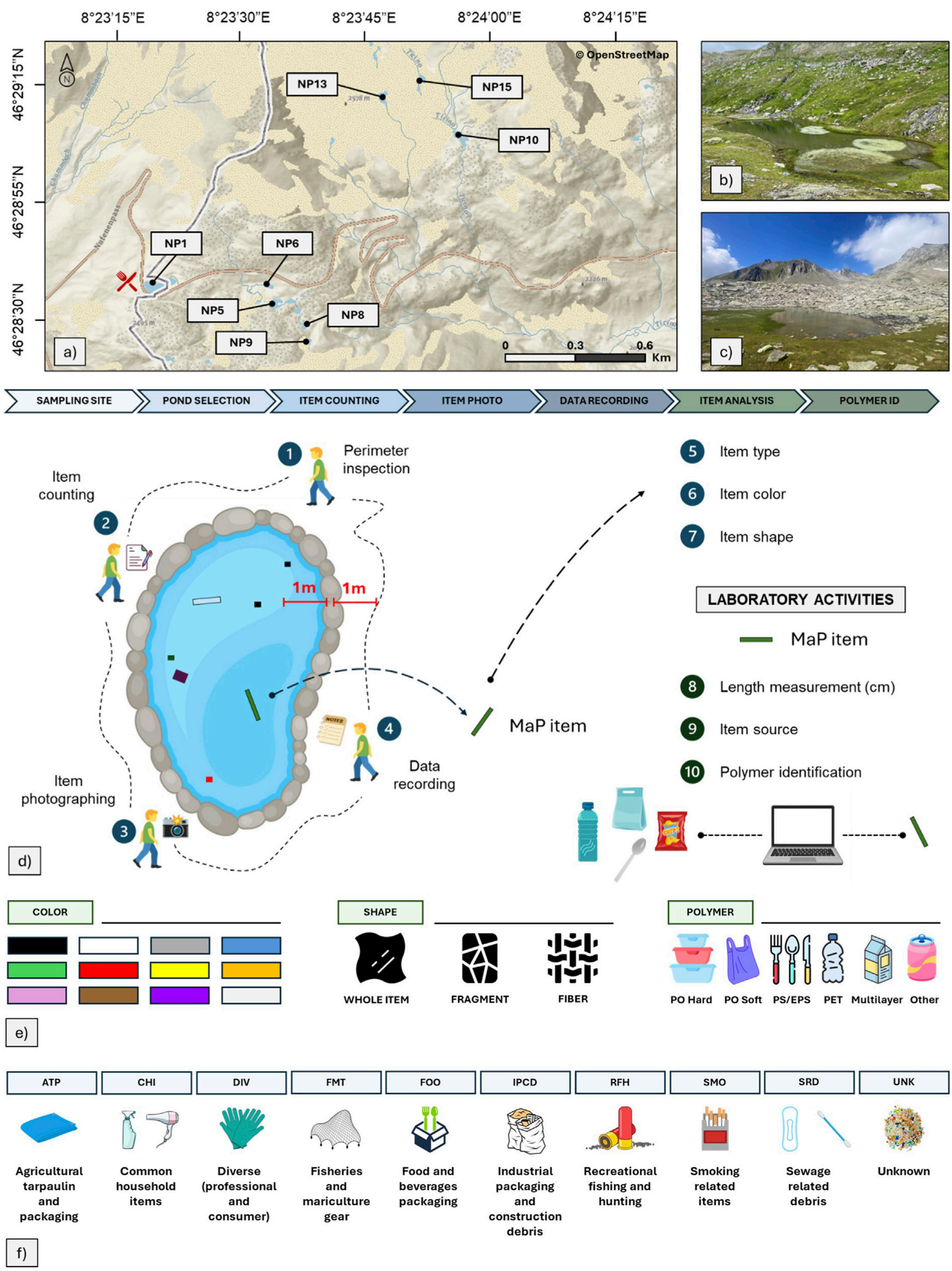


FIGURE 1
(a) Geographical location of the sampling sites in the Nufenen Pass (Switzerland); Sites NP1, NP5, NP6, NP8 and NP9 are altitudinally below the restaurant (red cutlery symbol), while sites NP10, NP13 and NP15 are altitudinally above the restaurant; **(b)** Field photo of NP6; **(c)** Field photo of NP13; **(d)** Schematic representation of field activities, including the perimeter inspection of the pond, the item counting, photographing and the data recording. On the right side, schematic representation of macroplastic items data type recorded analysis and laboratory polymer identification (PO, polyolefin; PS = polystyrene; PET = polyethylene terephthalate, according to Gallitelli et al., 2024); **(e)** Graphical representation of the colors considered, the item shape and item polymer; **(f)** Graphical representation of the 10 categories of MaP sources modified from Battisti et al. (2024) and Bruge et al. (2018). ATP,

(Continued)

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FIGURE 1 (Continued)
agricultural tarpaulin and packaging; CHI, common household items; DIV, diverse (professional and consumer); FMT, fisheries and mariculture gear; FOO, food and beverages packaging; IPCD, industrial packaging and construction debris; RFH, recreational fishing and hunting; SMO, smoking related items; SRD, sewage related debris; and UNK, unknown. MaP, Macroplastic.

2 Materials and methods

The study area is the Nufenen Pass (46°28′39″N, 8°23′12″E; 2478 m a.s.l.), the second highest altitude pass in Switzerland (Figure 1a). The sampling was conducted on 30 July 2025. Eight TPs were selected using satellite images from the Google Earth Engine (GEE). The selected ponds are located within a 1,630 m radius from the highest point of the pass accessible by car, corresponding to the refreshment area (restaurant), which represents a potential source of pollution and is frequently visited by tourists and hikers. All sampled ponds were isolated from each other and showed no visible surface hydrological connections (e.g., inlets, outlets, or connections via small streams) at the time of sampling. Specifically, the eight sites considered were: NP1 (46°28′38″N, 8°23′14″E; area = 3613.77 m^2, elevation = 2482 m a.s.l.); NP5 (46°28′36″N, 8°23′42″E; area = 2724.29 m^2, elevation = 2429 m a.s.l.); NP6 (46°28′38″N, 8°23′41″E; area = 531.74 m^2, elevation = 2436 m a.s.l.; Figure 1b); NP8 (46°28′35″N 8°23′47″E; area = 403.39 m^2, elevation = 2418 m a.s.l.); NP9 (46°28′32″N 8°23′49″E; area = 402.26 m^2, elevation 2412 m a.s.l.); NP10 (46°29′02″N 8°24′23″E; area = 1868.38 m^2, elevation = 2510 m a.s.l.); NP13 (46°29′08″N 8°24′06″E; area = 744.35 m^2, elevation = 2546 m a.s.l.; Figure 1c); NP15 (46°29′11″N 8°24′15″E; area = 1158.52 m^2, elevation = 2538 m a.s.l.). Sites NP1, NP5, NP6, NP8, and NP9 are located altitudinally below the restaurant, the main source of MaP in the area; sites NP10, NP13, and NP15 are located altitudinally above the restaurant.

During sampling, the ponds were inspected for macrolitter occurrence by walking along their entire perimeter. Both items present in the water and those found along the pond margin, within 1 m from the shoreline, were considered (Figure 1d). This buffer area was included to account for short-term water level fluctuations that are typical of TPs, where the littoral zone can shift depending on recent precipitation or desiccation events. Macrolitter items within the ponds were directly collected by hand by operators entering the water using waterproof boots. Given the shallow nature of all sampled ponds, no nets or boats were required. The adopted approach follows recommendations from previous studies assessing litter in small lentic systems, where the sampling area encompasses both the inundated and periodically exposed margins (Corcoran et al., 2015). Subsequently, the number of macrolitter items recorded in each pond was counted, photographed, and their physical characteristics documented. For each item, the following data were collected: type (expressed as the object itself or, in the case of fragments, the original object of provenance), color (following the categorization by Razzell Hollis et al., 2024), and shape (following the categorization of Lahens et al., 2018 into "whole item," "fragment," or "fiber"). In the laboratory, pond area (m^2), pond perimeter (m) and distance of the pond from the restaurant (m) were calculated using GEE Distance measurement tool (Supplementary Table S1). Macrolitter size (expressed in cm) was estimated using the ImageJ software (Abràmoff et al., 2004). Polymer identification (for MaP) followed the approach of Gallitelli et al. (2024), while the classification of sources/origins was based on Battisti et al. (2024) and Bruge et al. (2018). According to Gallitelli et al. (2024), polymers were categorized into polyolefin hard and soft (PO hard and PO soft), polyethylene terephthalate (PET), polystyrene and expanded polystyrene (PS/EPS), multilayer, and others (Figure 1e). Following Battisti et al. (2024) and Bruge et al. (2018), 10 plastic sources were distinguished (Figure 1f): ATP = agricultural tarpaulin and packaging; CHI = common household items; DIV = diverse (professional and consumer); FMT = fisheries and mariculture gear; FOO = food and beverages packaging; IPCD = industrial packaging and construction debris; RFH = recreational fishing and hunting; SMO = smoking-related items; SRD = sewage-related debris; UNK = unknown (Supplementary Table S2).

Macrolitter density (items per m^2) in each pond was calculated by dividing the total number of items by the pond area.

$$\text{Macrolitter density } (\text{items}/\text{m}^2) = \text{Total number of items} / \text{Pond area } (\text{m}^2)$$

Multiple linear regressions were performed to explore the relationships between macrolitter density and pond characteristics, including area, perimeter, distance from the nearest restaurant and distance from the nearest road. All statistical analyses were performed using R software (R Core Team, 2024; version 4.4.2), and significance was assessed at $p < 0.05$.

3 Results and discussion

Overall, 56 macrolitter items were recorded (Supplementary Table S3; 46 plastics, 10 non-plastics), with a mean of 7.0 ± 14.8 items per pond, 0.002 ± 0.004 items/m^2 and 0.02 ± 0.05 items/m. Most items were found in NP1 (n = 42, density = 0.116 items/m^2), followed by NP5 (n = 13, density = 0.0048 m^2) and NP6 (n = 1, density = 0.0019 m^2). NP1 is the pond closest, as the crow flies, to the managed restaurant and therefore to the main direct source of pollution identified. Conversely, no macrolitter items were found in NP8, NP9, NP10, NP13, or NP15, suggesting a possible influence of distance from pollution sources. These results represent the first reported data about macrolitter pollution on temporary alpine ponds.

Item shapes were evenly distributed. In total, 27 objects were classified as "whole items," meaning intact or without evident fragmentation, while 29 were recorded as "fragments" (Figure 2a). This suggests that part of the pollution event may be relatively recent: although plastics take a long time to degrade, their fragmentation into smaller pieces can occur rapidly, particularly in

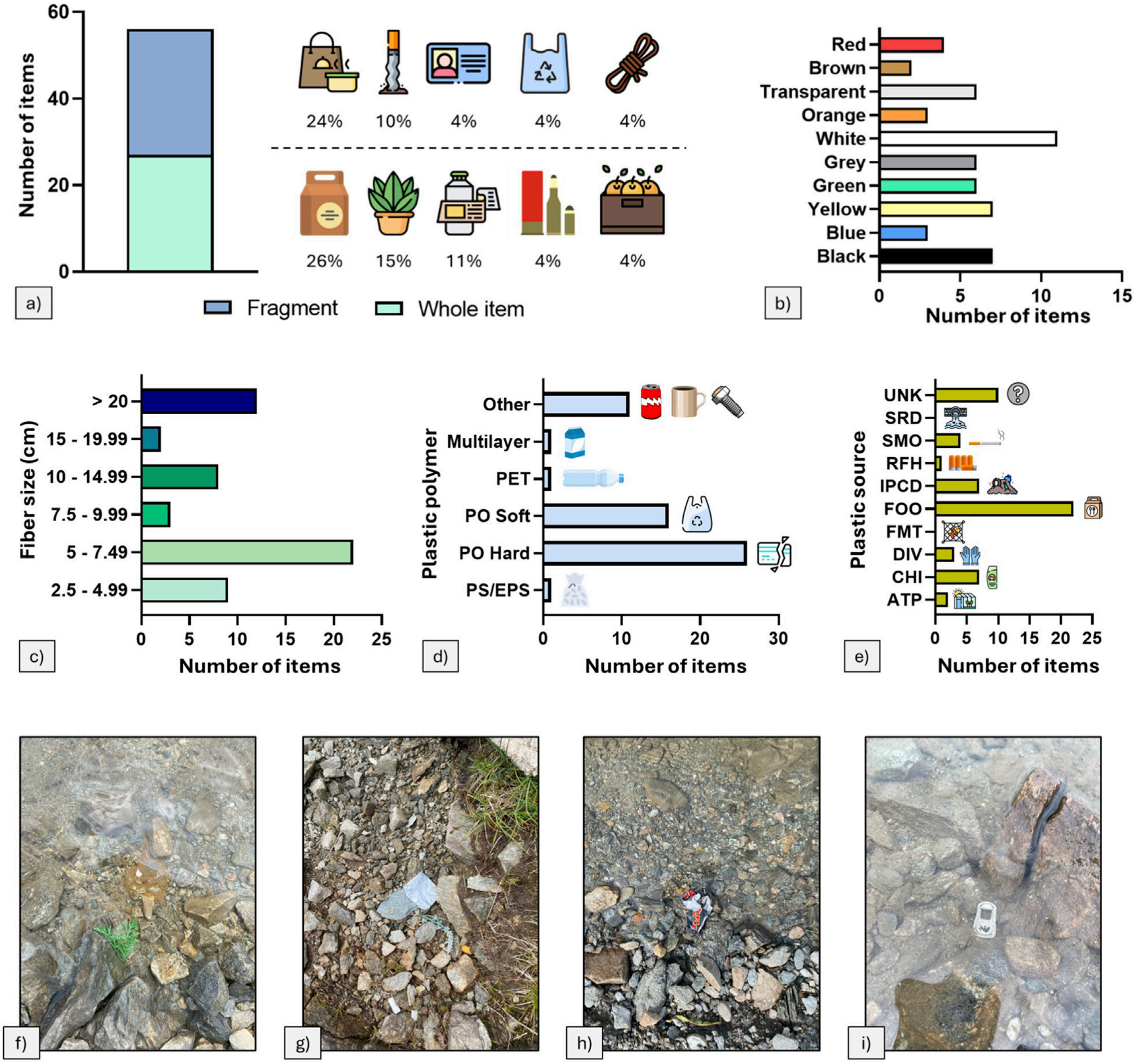

FIGURE 2
(a) Shape, number of items recorded as "whole item" and "Fragment" and relative percentage for the most abundant items identified; **(b)** Number of items per color; **(c)** Size class for the items found; **(d)** Number of items for each polymer considered (Gallitelli et al., 2024); **(e)** Plastic source and related number of items (Bruge et al., 2018; Battisti et al., 2024); **(f–i)** Field photo of the macrolitter found.

high-mountain environments where intense and frequent atmospheric phenomena accelerate this process (Carriera et al., 2024; Preda et al., 2024). At the same time, the presence of fragments may indicate two possible scenarios: a) they originated gradually over time, meaning pollution dates back at least several months before sampling, or b) they were released as fragments due to mechanical breakage by tourists or visitors (e.g., tearing food packaging). In any case, the high presence of plastic fragments can be harmful to the delicate fauna that inhabits these places. TPs, especially in summer, represent essential watering sites for mountain biota. Alpine temporary ponds are key breeding and foraging habitats for amphibians and host diverse macroinvertebrate assemblages, as shown by studies carried out in Swiss alpine areas (e.g., Siffert et al., 2022; Oertli et al., 2008). Therefore, many species of macroinvertebrates and small vertebrates (e.g., frogs, newts) use these environments as breeding sites and may be subjected to MP occurrence (Tatlı et al., 2025). The presence of plastic fragments can increase, as already demonstrated in the literature, the risk of suffocation, entrapment, or chemical damage due to the additives they contain (Gregory, 2009; Tatlı et al., 2025).

Item identification was performed primarily for the "whole item" category. Most MaP consisted of food-related packaging, bottle labels, artificial plants, and shotgun cartridges, with smaller numbers of twist ties, clothing labels, cables, fruit boxes, and plastic rings. Non-plastic items included bolts, cans, can tabs, aluminium packaging, and paper food packaging. The dominance of "plastic packaging" was also evident among identifiable fragments, along with cigarette butts, plastic cards, ropes, bottle rings, and plastic bags. Our findings are consistent with the existing literature on MaP pollution. As reported by Winton et al. (2020), most marine studies have identified plastic bags, bottles, and food packaging as the most common items of plastic pollution worldwide. Similarly, studies on beaches have highlighted cigarette butts, food wrappers, drink bottles, and cans as the dominant categories (Loizidou et al., 2018). The few freshwater studies available in the UK and Europe also reported these same items, which, together with our results, confirm that they represent the most common types of MaP even at high altitudes (Slaughter et al., 2011). In central western Alps, Parolini et al. (2021) mostly found food packaging and items from mountaineering equipment/clothing. It is also highly likely that the waste we recorded originated from direct pollution by local visitors. While cigarette butts, paper items, and some types of food packaging may be transported by wind and reach the ponds from distant sites, most of the other objects found are heavier and therefore less likely to be carried through atmospheric transport. Instead, they are directly linked to catering and recreational activities, which are fully consistent with the typical uses of the area by tourists, trekkers, hikers, and motorcyclists. Non-plastic fragments included pieces of ceramic cups and unidentified metal objects. These items have already been found in previous studies in coastal environments (Walther et al., 2024) and metals in Alpine environments (Pastorino et al., 2022), while there are no records of ceramics in Alpine ponds.

White was the most common colour (n = 11), followed by black (n = 7), yellow (n = 7), and grey (n = 7), with other colours less frequent (Figure 2b). Orange, transparent, and blue-yellow items were found only in NP1, whereas NP5 and NP6 contained only black, red, green, white, brown, and grey items. The size of the macrolitter recorded was highly variable, with a total length of 695.5 cm and an average of 12.4 ± 15.4 cm per item (Figure 2c). The largest items were found in NP5 and NP6, including a generic plastic object (80 cm), a cable (75 cm), and a fruit box (40 cm). By contrast, the smallest items mainly consisted of cigarette butts and unidentified plastic fragments, ranging between 2.5 and 3 cm. Most items (n = 33), however, measured between 5 and 10 cm. Only a few studies have reported the length of MaP items (Parolini et al., 2021), with an average size of 9.2 ± 1.5 cm (range 0.6–100.1 cm). These findings suggest that smaller items are the most frequently encountered in these ecosystems, potentially posing a greater risk to their fragile balance.

Polymer identification showed relatively homogeneous results across the different sites (Figure 2d). PO hard was the most represented polymer (n = 26), followed by PO soft (n = 16), whereas PS/EPS (n = 1), PET (n = 1), and multilayer (n = 1) were only marginally present. The “other” category, grouping less frequent polymers, included a substantial number of items (n = 11), mostly metallic objects. The highest occurrence of PO hard and PO soft in the ecosystems was not unexpected considering that PE, PP and PS account for 29.7, 19.3% and 6.4% of the European plastic demand in last years due to the extensive everyday use (Plastics Europe, 2024). Considering these broad polymer categories, it was not possible to directly infer the source of the items. However, when the secondary object, even in fragmentary condition, was sufficiently representative of the primary object, the source category was assigned following Battisti et al. (2024) and Bruge et al. (2018). FOO was the main source of pollution in the investigated sites (n = 22); UNK was the second most represented category (n = 10), while the remanent part of sources was identified in CHI (n = 7), IPCD (n = 7), SMO (n = 4), DIV (n = 3), ATP (n = 2) and RFH (n = 1). FMT and SRD sources were not detected in this study (Figure 2e). These results support our hypothesis that the primary source of pollution is direct and originates from visitors to the study area (Figure 2f-i). These findings are consistent with Parolini et al. (2021), who reported that the majority of macroplastics originated from food packaging and from the degradation of mountaineering gear and clothing, introduced along glacier trails through either intentional disposal or unintentional loss. The high proportion of food packaging is consistent with the habits of hikers and trekkers, who typically carry ready-to-eat, pre-packaged food. Although it is not possible to determine whether waste was discarded intentionally or unintentionally, it is clear that human presence is the main driver of pollution in these habitats. From a management perspective, greater awareness among tourists regarding waste disposal is recommended, together with a reduction in the use of food packaged in plastic, in order to minimize risks to these fragile environments. Some of the collected items bore recognizable brands (e.g., Emirates, Ricola, Mars, Bergen, Resicash), suggesting that litter may originate from both local tourism and long-distance visitors. The recurrence of the brand Mars, also reported by Arturo and Corcoran (2022), may indicate the widespread distribution and persistence of certain product types in mountain environments.

The analysis of macrolitter density (34% found in the littoral zone, 66% found in water) highlighted significant relationships with some physical characteristics of the ponds analyzed and with the distance from potential anthropogenic sources (Figure 3). In particular, the density of items per square meter increased significantly with pond area (R^2 = 0.738, p = 0.0063, Figure 3a), indicating that larger ponds tend to accumulate more waste. The relationship between macrolitter density and distance from the nearest road was negative but not statistically significant (R^2 = 0.31, p = 0.15). Conversely, a negative effect of distance from the restaurant was observed, with macrolitter density decreasing as distance increased (R^2 = 0.576, p = 0.029, Figure 3b). These values highlight the presence of anthropogenic pressure even in remote alpine environments of Switzerland: for instance, in Valais tourism contributes approximately 15% of the cantonal added value and recorded 4.43 million overnight stays in 2024 (https://www.valais4you.ch); similarly, in Ticino around 21 million visitors were estimated overall (overnight and day visitors) in earlier assessments (https://www.usi.ch/en/feeds/5850?). The high presence of tourists and day-trippers supports the interpretation that the origin of the waste is primarily anthropogenic and concentrated near human activity (Vargas et al., 2020). Finally, pond perimeter length was not a significant predictor of MaP density (R^2 = 0.25, p = 0.207, Figure 3c), indicating that the shape or contour of the ponds did not substantially influence macrolitter accumulation. Similarly, distance from the road was not a significant predictor of MaP density (R^2 = 0.31, p = 0.152, Figure 3d).

4 Implications for conservation

Despite their apparent remoteness and ecological integrity, alpine temporary ponds are not immune to macrolitter pollution, and their strong seasonal dynamics make them particularly

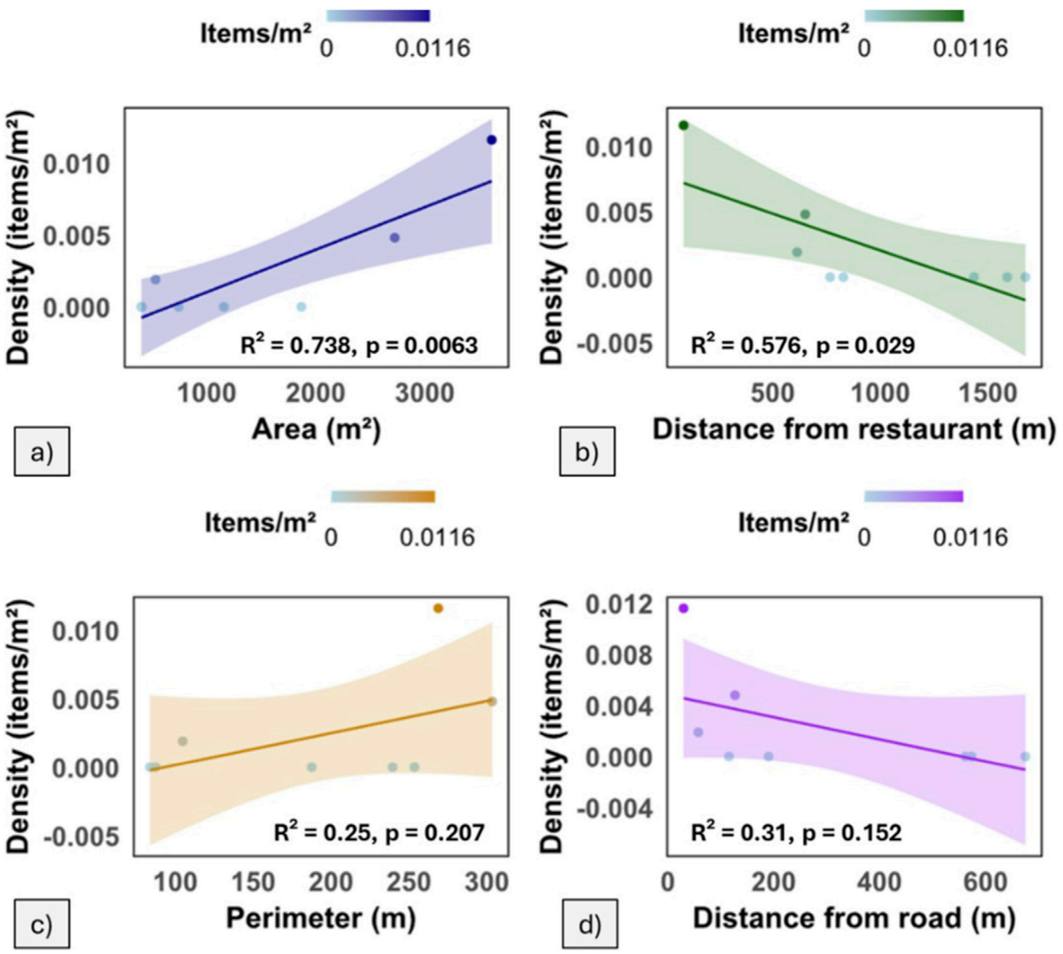

FIGURE 3
Relationship between macroplastic density (items per m^2) and physical characteristics of the ponds: **(a)** increase of density with pond area; **(b)** decrease of density with increasing distance from the restaurant; **(c)** item density relationship with pond perimeter; **(d)** item density relationship with pond distance from the road. The shaded area represents the 95% confidence interval of linear regression.

vulnerable to its impacts. The short hydroperiods that characterize these systems concentrate both biological activity and accumulated litter into narrow temporal windows, potentially amplifying physical disturbance, habitat alteration, and contamination during critical phases of pond development (Zacharias et al., 2007). Conservation strategies should therefore prioritize the prevention of litter inputs even in high-elevation contexts, recognizing that sporadic human presence, tourism, and long-range transport can introduce persistent debris into otherwise pristine environments. Given the sensitivity of alpine temporary ponds to disturbance, even low levels of macrolitter may disproportionately affect ecosystem functioning, sediment dynamics, and organism survival (Cera et al., 2022). Long-term conservation should focus on safeguarding hydrological integrity, minimizing physical disturbance, and integrating litter monitoring and removal into existing alpine conservation frameworks. More broadly, the recognition of temporary ponds as highly vulnerable yet often overlooked ecosystems should be translated into concrete protection measures, including stricter enforcement of anti-littering regulations, the application of fines for illegal dumping, increased surveillance by park rangers and local authorities, and the implementation of regular control and monitoring programs. Raising public awareness—particularly among visitors to alpine areas—can further reduce litter inputs and support the preservation of these small, ephemeral habitats as key components of mountain biodiversity and landscape resilience.

5 Conclusion

Temporary ponds are extremely fragile environments, and virtually nothing is known about the, presumably negative, interactions that released macrolitter may have with the organisms inhabiting high-altitude TPs. The slow release of chemical additives could further induce biochemical and physiological stress in fragile and endangered species. Combined with ongoing climate change, this slow pollution could exacerbate the negative impacts on TPs, potentially leading to the rapid disappearance of these habitats and the biodiversity they sustain. Additional experimental studies are therefore essential to confirm these observations and to develop conservation strategies aimed at reducing and eliminating pollution in these sensitive ecosystems while pollution is still at an early stage. Future research could also explore how human accessibility and tourism dynamics influence litter occurrence in alpine habitats. For instance, the construction of new mountain passes or infrastructures that facilitate access to high-altitude areas could potentially increase anthropogenic pressure and waste accumulation. It would also be valuable to investigate whether the intensity of tourist flows correlates with the presence of macrolitter and to what extent regional or cultural differences across the Alpine arc influence waste disposal behaviors and environmental awareness. Such comparative analyses could provide important insights into the design of targeted education and management strategies.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

DT: Conceptualization, Data curation, Formal Analysis, Investigation, Project administration, Software, Writing – original draft, Writing – review and editing. LG: Conceptualization, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. AC: Investigation, Visualization, Writing – original draft, Writing – review and editing. CC: Investigation, Visualization, Writing – original draft, Writing – review and editing. MS: Funding acquisition, Resources, Validation, Visualization, Writing – original draft, Writing – review and editing.

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