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Having fun and raising awareness: Italian students monitor airborne microplastic in school environments

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ABSTRACT

Although microplastics (MP, < 5 mm) are pervasive in the atmosphere and soil, with most of their sources concentrated in urban areas, public perception on MP as an environmental issue is still confined mostly to seas and oceans. Outreach activities are thus necessary to instil individual consciousness about our role in spreading such contamination, fostering pro-environmental behaviours particularly in young people. The environmental education project «Taking microplastics into the class», carried out with Italian high school students, aimed at: (i) collecting data on MP passive deposition in school environments and (ii) raising awareness about MP contamination. First, a group of 20 students was engaged with different hands-on field-, laboratory-, and computer-based activities (i.e., clean-up, MP sampling and analysis, dataset assembly, bench-scale toxicity tests), using interactive learning methods. The outcomes of each activity were then presented through peer-to-peer learning and questionnaire surveys, assessing perception, knowledge and behaviour in 163 high school students. Our findings show how scientifically driven and well-structured educational projects are very effective in stimulating students' knowledge acquisition, environmental awareness but also self-efficacy and trans-disciplinary skills. Peer-to-peer learning was proven as a valid method to encourage sustainable and pro-environmental behaviour in young citizens. All the methodologies are detailed to help developing future targeted outreach activities about MP sources and their transport in urban environments.

1. Introduction

Plastic pollution is a global problem affecting all environmental matrices, with potential harmful effects on ecosystems and human health (Li et al., 2023; Corsi et al., 2023a, 2023b; Wang et al., 2024; Ali et al., 2024). As mismanaged plastic litter continues to accumulate in soils, waterways, and oceans (Li et al., 2022; Borrelle et al., 2020), microplastics (MP, size <5 mm) are generated through weathering and degradation processes (Sutkar et al., 2023) or directly released upon use (Meizoso-Regueira et al., 2024).

Densely populated areas are a significant source of MP, including particles generated by tyre wear abrasion (Mattsson et al., 2023; Sommer et al., 2018) and textile fibres released through washing and drying of garments (Tao et al., 2022). Urban-generated MP are emerging contaminants found not only in large cities and their surroundings, but also in remote areas, as they can be easily dispersed through the air to long distances (Allen et al., 2022; Evangeliou et al., 2020). Nevertheless, evidence of ubiquitous MP contamination in soil and atmosphere is quite recent (Jahandari, 2023; Xu et al., 2024) compared to the extensive scientific literature on the marine environment and biota, with first observations dating back to the 1970s Carpenter and Smith Jr. (1972). In the United Nations 2030 Agenda for sustainable development, (micro)plastic pollution has potential repercussion on many Sustainable Development Goals (SDGs), such as SDG 11 (Sustainable cities and communities), SDG 12 (Responsible consumption and production) and SDG 15 (Life on land) (Enet, 2022; Walker, 2021). However, plastic debris is mentioned as a target indicator only in the SDG 14 – Life Below Water, related to the conservation and sustainable use of oceans, seas, and marine resources (Walker, 2021; https://sdgs.un.org/goals/goal14).

Media coverage and the public perception of MP contamination as a critical environmental issue are mostly associated with seas and oceans (Soares et al., 2021; Henderson and Green, 2020; Catarino et al., 2021) and public surveys on MP occurrence and dispersion in urban

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environments are overlooked. Therefore, while there is an urgent need to increase MP monitoring effort in urban environments to estimate MP levels and identify major sources and pathways (Jahandari, 2023), there is an equally urgent need to educate the public about our own role in spreading MP contamination. Without immediate and effective mitigation actions on the production, use and disposal of plastic waste in the coming years, MP contamination will continue to increase at an alarming rate (Borrelle et al., 2020). This multifaceted problem requires a globally coordinated action of all stakeholders, including governments, producers, consumers, researchers, media, and civil society (Frantzi et al., 2021; Lau et al., 2020). A real progress in mitigating this environmental issue can only occur making plastic more sustainable, pursuing the transformation of the plastic life cycle toward circular economy with concrete implementations according to the "3Rs rule" (reduce, reuse, recycle) (Chun T'ing et al., 2020; Mahaliyana and Nugawela, 2024).

Citizens, as final consumers of plastic materials, play a key role in this process (Fogt Jacobsen et al., 2022), as their decisions and daily behaviours can shift plastic production and consumption practices (SAPEA, 2019); Hartley et al., 2018, Beeharry et al., 2017). Therefore, they must be involved, informed and motivated to encourage the adoption of sustainable consumption behaviours (SCB). These are defined as socially and ecologically responsible ways of purchasing, using, and disposing of goods and services (Wolff and Schönherr, 2011), as well as pro-environmental behaviours (PEB), that is to take actions to maintain, restore, or improve the health of environmental systems (Kurisu, 2016).

In the long term, it is particularly important to raise awareness among the younger generations to shape their future SCB and PEB. In recent years, several studies have assessed the consciousness of young consumers about environmental issues, and their ability to make virtuous, sustainable choices in the field of the environmental literacy. Sustainable behaviours (both SCB and PEB) should be acquired not only through formal school education, but also through non-formal education, for example considering the influence of family, personal and social norms as well as the interaction with external groups and associations, supporting awareness and lifelong learning (Liu et al., 2023; Syberg et al., 2018; Kurisu, 2016; Miguel et al., 2024).

Individual consciousness about the importance of preserving and protecting natural resources should be instilled at school (Whitmarsh, 2022). Introducing environmental knowledge into school curricula is thus essential to provide a scientifically sound basis for risk perception and understanding of human impact on the environment, including MP contamination. Moreover, this action allows to promote SDG-oriented responsible behaviours in general (Velempini, 2025; Liu et al., 2023; Uehara, 2020).

To date, several studies have documented the perception, knowledge and behaviour about plastic waste and MP among young people belonging to university communities (Righi et al., 2024; Boca et al., 2023; Qu et al., 2023; Dowarah et al., 2022; Galati et al., 2022; Raab and Bogner, 2021; Aikowe and Mazancová, 2021; Cammalleri et al., 2020; Janoušková et al., 2020; Situmorang et al., 2020), while fewer have focused on high school students and children (Oturai et al., 2022; Uehara, 2020; Wongklaw et al., 2020). Furthermore, none of these studies were conducted in Italy, and did not involve students in hands-on activities, to the best of our knowledge.

In this context, our environmental education project «Taking microplastics into the class» aimed at collecting data on (micro)plastic contamination in school settings to promote environmental literacy and sustainable behaviours among high school students at the local level. One of the main goals was to explore plastic pollution issues among adolescents, to understand which factors are key predictors for the development of virtuous future PEB (Uehara, 2020).

The project adopted innovative active learning methods (engaging students in hands-on activities, such as clean-up survey, air passive sampling, sample processing and analysis) as well as peer-based learning for local dissemination of the project results. Students were actively involved in every phase of the MP monitoring activities, both in the field and in the laboratory. In order to help them understand how plastic pollution directly affects us and to raise their awareness of the issue, the type and amount of MP detected was considered as an example of the airborne (micro)plastic pollution to which they are exposed daily at school. As the adverse effects of MP on human health are still poorly understood and are likely to be mostly related to the nanofraction (Li et al., 2023), which is not covered by this educational project, only the potential human exposure pathways (i.e. ingestion through contaminated food and inhalation, Li et al., 2023; Jenner et al., 2022) were mentioned. This emphasised the lack of information and avoided unnecessary high levels of concern among students.

Following Oturai et al. (2022), our hypotheses were that, at such local scale, engaging students in every step of our environmental education project would enhance their PEB, including risk perception, self-efficacy and empowerment. The pedagogic implications of the mixed learning strategies used within the project are also presented.

2. Materials and methods

2.1. The environmental education project on MP contamination

The environmental education project «Taking microplastics into the class» was proposed to a scientific high school in Applied science located in Italy, as a candidate activity for the "Path for Transversal Skills and Orientation" (PTSO) promoted by the Italian education system (see https://alternanza.miur.gov.it/normativa.html). The goal of the PTSO is to enhance high school students' soft skills and make them acquainted with specific research topics at the University level. This education project was run from October 2023 to February 2024 within the program "Piano Lauree Scientifiche", as a voluntary-based extracurricular activity of 10 sessions, totalling 26 h, including both brief lecture-style presentations to introduce the project plan and specific topics, and active learning (i.e., field/laboratory activities and computer-based training). The last part of the project further included peer-to-peer learning and dissemination activities. Twenty students (12 males and 8 females) from 4 classrooms at the penultimate year of high school (curriculum in Applied sciences) participated to the project. The detailed programme is provided in Table S1 of the Supporting Information (SI).

2.2. Interactive lectures

The first activity session (Table S1) consisted of a frontal lecture (of about 40 min) in which the environmental issue of MP was introduced, covering plastic materials and waste (PlasticsEurope, 2023) their persistence and degradation processes (Andrady, 2017), MP occurrence in environmental matrices and their potential impact on animals and humans (Li et al., 2023; Jenner et al., 2022; Santos et al., 2021; Macali and Bergami, 2020; Cózar et al., 2014). Emphasis was given to MP sources in urban environments and their spreading through the air (Mattsson et al., 2023; Corsi et al., 2023a, 2023b; Shao et al., 2022; O'Brien et al., 2020; Zhang et al., 2020; Hernandez et al., 2017) to make the students more aware of how close MP contamination can be in our every-day life. During this introductory meeting, the project's objectives, schedule and methodologies were also presented, providing the students with the required knowledge to understand the project targets and plan. The lecture was set as an informal meeting (e.g., held in a simple classroom instead of the auditorium, having young researchers presenting, asking opinions to the students) on purpose to grasp students' attention and interaction.

In the following sessions, brief lectures and discussions (of about 10–30 min) with visual presentations were always included to outline the activities on the agenda, recap key concepts, summarise results and clarify doubts. Topic covered included: plastic recycling process, methodologies used for MP analysis (size measurements and material characterization), and ecotoxicity testing (see Table S1). To keep students' attention and curiosity as well as foster learning, these sessions were given in different environments (e.g., their classroom, the University laboratory, the school computer room). For example, in the session covering the material characterization (Table S1, session 4), a guided tour at the University facilities was organised, explaining the use of useful techniques for MP analysis such as Scanning Electron Microscopy and Micro-Raman spectroscopy. The tour was followed by a discussion on the methodologies used in environmental sciences to determine material composition, weathering and surface properties, particularly related to plastic waste.

In some meetings, students' learning was tested through anonymous online self-assessment quizzes (using Mentimeter, easily accessed by students' mobiles). This interactive tool was also used to collect feedback to monitor the progress of the project.

2.3. Hands-on activities

Hands-on activities, coordinated by University researchers, included: clean-up at the school yard, airborne MP passive sampling, sample processing and analysis at the computer as well as set up of a laboratory toxicity test and microscopy observation. For MP sampling and processing activities, each students received a printed copy of the protocol (i.e., bulleted list of actions) to follow step by step, to familiarize with the rigorous scientific approach.

2.3.1. Sampling sites

At the school, three sampling sites to monitor MP levels were identified together with the students: two outdoor sites (Out1 and Out2) and one indoor site, within a classroom (Ind) (Fig. 1). The outdoor sites were selected as representative of two areas in the school yard, subjected to high (Out1) and low vehicular traffic (Out2). The Out1 site was located at the entrance of the school yard, in front of a large parking lot and close to a heavily trafficked road and bus stops (potential high MP load), while the Out2 site was placed in the back yard (potential background contamination). The location of the sampling sites is shown in Fig. 1.

2.3.2. Clean-up

To assess the most common litter materials in the school yard, a clean-up activity was first conducted. Students were divided in groups, manually collecting all the scattered litter in Out1 (covered area of approx. 410 m^2) and Out2 (covered area of approx. 730 m^2) that could be a source of MP contamination in the two outdoor sampling sites. All litter was brought to the laboratory, photographed, weighted and classified according to standard guidelines for beach litter monitoring (OSPAR Commission, 2010).

2.3.3. Air passive sampling

The collection of airborne MP in outdoor and indoor sites was carried out by passive sampling in line with recent literature (Stanton et al., 2019; Dris et al., 2016). Each sampler consisted of a stainless-steel funnel (diameter of 200 mm) placed above a glass bottle on a wood support (Fig. 1). After 14 days, the surface of the funnel was carefully rinsed with 3 L of ultra-pure water (0.2 μm-filtered) to collect all the particulate matter, including MP, deposited on the funnel (Stanton et al., 2019). The students, divided into three groups (one for each sampling site) and assisted by the researchers, were responsible for the set-up, monitoring, recovery and first processing of the samples.

First sample processing was carried out right after their recovery (at 14 d) by the students in the Chemistry laboratory at the high school. Water samples (Out1, Out2, Ind) were concentrated onto glass-fibre filters (Whatman GF/C, pore size of 1.2 μm, diameter of 47 mm, based on Dris et al. (2016) and Zhang et al. (2020)) using a glass filtration apparatus connected to a vacuum pump, rinsing with Ethanol to collect any potential particles adhered to the glass funnel. Samples deposited onto the filters were then placed in a labelled glass Petri dish until further analysis.

In order to introduce high school students to rigorous scientific research, strict MP contamination control measures were applied during MP sampling and laboratory processing, following Bergami et al. (2023) and Stanton et al. (2019). During the placement and recovery of the passive samplers, as well as sample processing, students always wore white laboratory coats and gloves, cleaned working surfaces with paper and filtered water and placed environmental blanks (one for each site) to determine potential airborne MP cross-contamination during all steps of sampling and processing. These blanks consisted of a Petri dish containing a glass fibre filter opened near the operators.

2.3.4. MP analysis and quality control measurements

The samples (Fig. 2, upper images) were transferred to the University facilities for first observation under digital microscope (Keyence VHX-7000) and processed to remove the mineral and natural organic matter (e.g., pollen, invertebrates, soil residues) deposited onto the filters

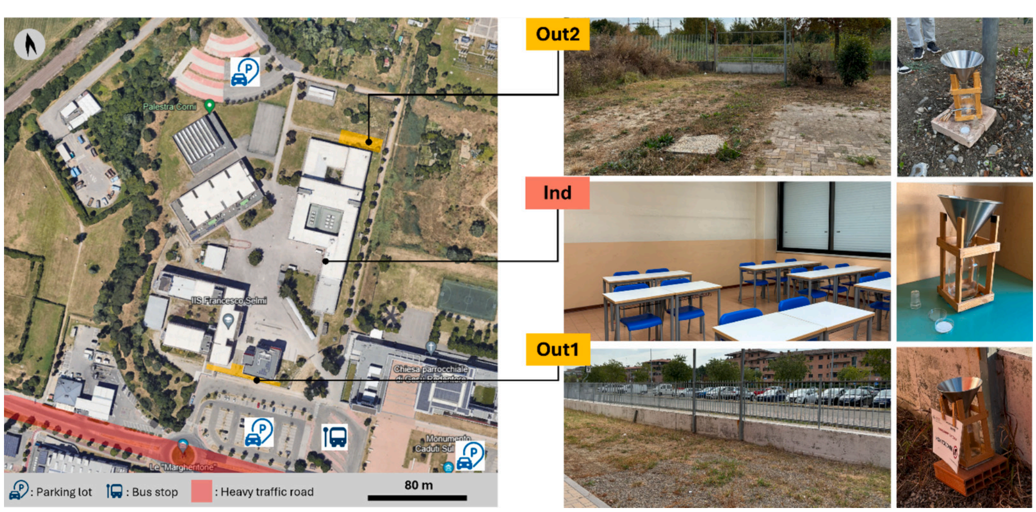

Fig. 1. Sampling sites (44°38′52″ N, 010°53′22″ E, a.s.l. 34 m) selected for (micro)plastic monitoring activities at the high school: two outdoor (Out1, Out2) and one indoor (Ind), within the classroom 4E. In the map (on the left), clean-up areas are marked in yellow, while full black circles indicate the positioning sites of air passive samplers (on the right). Parking lots, bus stop and heavy trafficked road are also indicated (icons from Flaticon.com). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

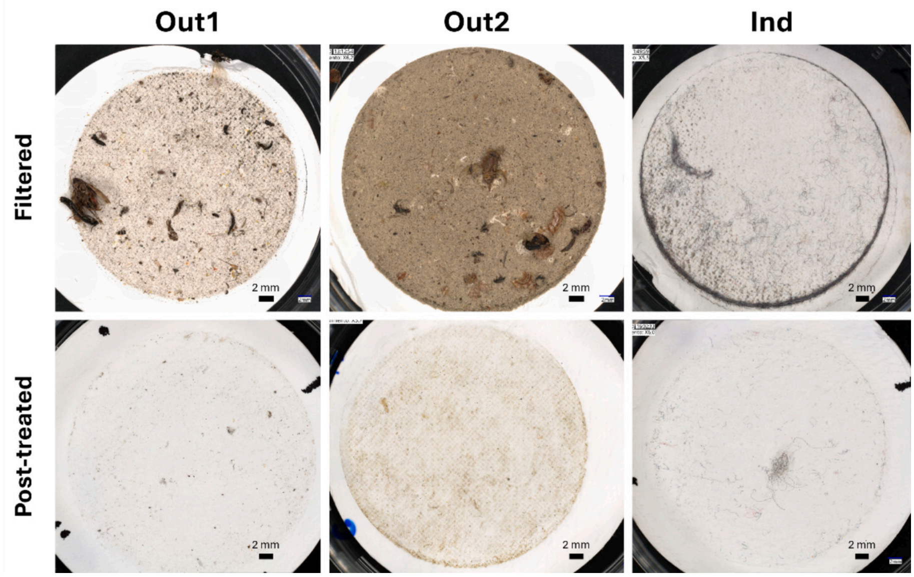

Fig. 2. Air passive samples collected in outdoor (Out, Out2) and indoor (Ind) sites for 14 d, concentrated onto glass fibre filters (upper) right after recovery and sample treatment for natural matter removal (lower). Scale bar: 2 mm.

(Fig. S1), which would hamper MP detection, leading to their underestimation. Such sample treatment included a floatation step using 100 % rapeseed oil (Radford et al., 2021), 24-h incubation with 25 % hydrogen peroxide at 50 °C with gentle agitation, and filtration onto new glass-fibre filters (Fig. S2, S3). After treatment, the samples (Fig. 2, lower images) were newly imaged using digital microscopy and a sub-sample (n = 65) of the MP candidates from the three sites was characterized using the Micro-Raman spectroscopy (LabRAM HR Evolution equipped with LABSPEC 6 Horiba Scientific) to determine their polymeric composition (Mancuso et al., 2023; Zhang et al., 2020). Raman spectra were processed using Spectragryph software (V. 1.2.16.1, 2023) (Menges, 2023). These steps were carried out by the University researchers involved in the project.

2.3.5. Counting and measurements of MP candidates

Representative microscopy images of the MP candidates deposited on the filters from the three sites were provided to the high school students, who, in pairs, performed MP counting and size measurements using the open-source software ImageJ (v.1.54u, (Rasband, 1997-2018) installed on the school computers. Due to time constraints, based on the number of images inspected by the students, it was estimated that about 1 % of the filters were analysed in the session. MP candidates were classified by shape (fragments, fibres, films), colour (Fig. 3) and maximum length recorded, with data organised into spreadsheets. We found that it was difficult for the students to discriminate between fragments and film categories. Only a few films were identified in one site. Therefore, in the results section MP candidates were attributed only to two categories (fragments or fibres). Moreover, MP candidates having a size <20 μm were removed from the dataset as of difficult identification, while those with a size >1 mm (e.g., some long textile fibres) were reported by the students as “size above 1 mm”.

Students also inspected environmental blanks used to assess field and

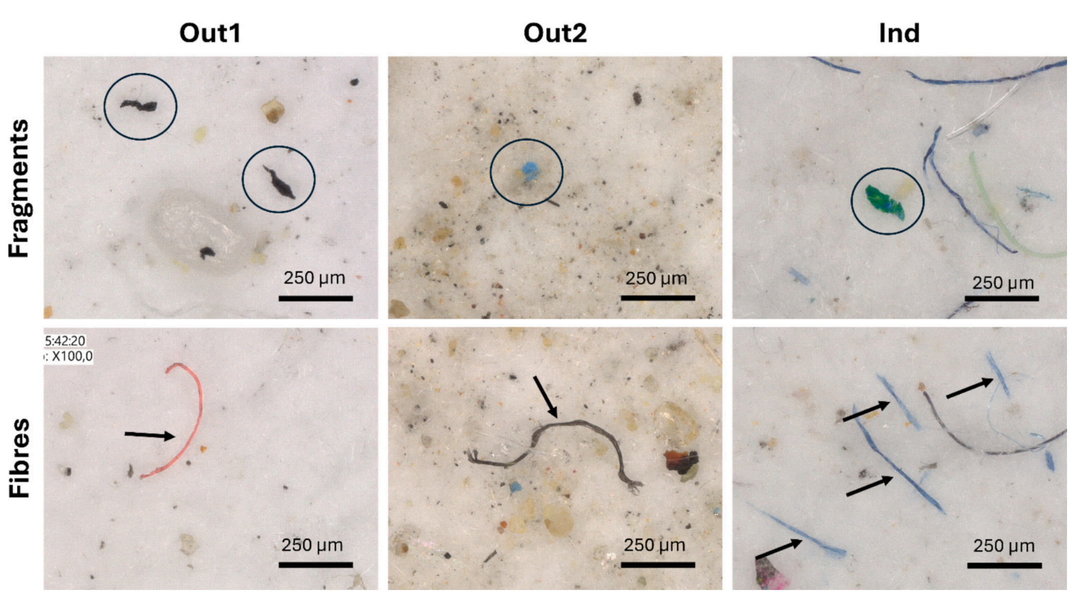

Fig. 3. Examples of MP candidates identified in outdoor (Out1, Out2) and indoor (Ind) samples and analysed by the high school students: fragments (black, light blue and green colour, displayed within the circles) and textile fibres (red, black and light blue colour, displayed by arrows). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

laboratory contamination by comparing the number, shape and size of the MP candidates with those found in the samples, based on Bergami et al. (2023).

2.3.6. MP effects on soil organisms

Along with the monitoring of MP in the atmosphere and in urban environments, another emerging subject branch of research focuses on MP impacts on soil biota and their interactions with other soil pollutants such as heavy metals (An et al., 2023; Khalid et al., 2021). To this aim, a laboratory activity was performed, introducing the students to ecotoxicity testing to evaluate the effects of soil contaminants (i.e., high density polyethylene micro-sized fragments and Cadmium, Cd) on a model organism, the springtail *Folsomia candida*. This microarthropod is a well-known soil model organism, sensitive to pollutants (Selonen et al., 2021; Maria et al., 2014) and easy to breed and study under controlled conditions (Fountain and Hopkin, 2005), ideal for a laboratory experience with students.

Before starting the laboratory activity, students were briefed on the ecological role of soil microarthropods, as an important part of soil biodiversity, and the tools used for their sampling. Students, in pairs, then familiarized with springtail specimens, by observing them under the stereomicroscope and gently transferring them using a thin brush.

The long-term toxicity test with *F. candida* was conducted following OECD guidelines (OECD, 2016) by exposing the organisms ($n = 10$, in triplicate) to single contaminant (MP at 1000 mg/kg or Cd at 200 mg/kg) and in combination (both MP and Cd). The Cd concentration was chosen based on (Nakamori et al., 2008), reporting an average mortality rate of 40 % in *F. candida* after 28-d of exposure at this concentration. A control group with no contaminants was considered and three replicates for each experimental group were included. Due to time constrains, the test was ended before the chronic time-point (28 d) indicated by OECD (2016). After 21 d, the students counted the live adult springtails collected by floatation (OECD, 2016) in each replicate and calculated the mortality rate for each group as lethal end-point. The approximate number of *F. candida* juveniles was also recorded by the students and presented as a qualitative observation.

2.4. Peer-to-peer learning and dissemination

Following the field/laboratory activities, to take stock and fully understand what have been done, the students were invited to split into two groups in order to prepare:

i) a presentation of the research activity conducted to show to other students at their own school during dedicated seminars (peer-to-peer learning) and,
ii) a newspaper article based on the project contents to be published, after revisions, on a local well-known newspaper for public dissemination.

Students freely chose either the presentation or the newspaper article based on their interest and skills. A total of 15 students were assigned to the first activity, divided in sub-groups of 5 people covering three sections of the presentation: Introduction (explaining the emerging environmental issue posed by plastic waste and MP), Methods (describing the project field and laboratory activities), Results of the project and final considerations. The remaining 5 students wrote the newspaper-style report about the project, including an interview with the researchers involved.

2.4.1. Peer-based knowledge transfer, questionnaire design and administration

Peer-to-peer knowledge transfer was carried out through dedicated seminars, in which groups of 3–4 students among those involved in hands-on activities took turns presenting the issue of MP contamination, their work and the results achieved during the environmental education project to their school peers. This ensured their involvement in the dissemination activity and a fair distribution of the effort and responsibility among them. School teachers and University researchers supervised the activity as moderators to stimulate discussion among the peers.

To evaluate the effectiveness of the peer-to-peer learning, two questionnaires were developed by the researchers together with the students, to be administered before (first questionnaire, Q1) and after (second questionnaire, Q2) their seminars to the school peers. Questionnaire surveys Q1 and Q2 full texts are provided in the SI.

Briefly, Q1 consisted in 9 closed-ended questions, organised in the following sections:

(i) respondents' profile (questions n. 1–3), aimed at grouping the participants based on variables such as their gender and affiliation (section, year, class);
(ii) perception (questions n. 4–9), used to determine the level of concern of the respondents, on a scale of 1-minimal concern to 5-very high concern, as well as their risk perception through a binary question (e.g., "Do you think that MP contamination is an issue present at your school?", possible answer: Yes/No);
(iii) knowledge about MP contamination using both binary (n. 5) and multiple-choice single answer (n. 6–8) questions aimed to assess whether the student is already familiar with the topic and verify students' knowledge about MP sizes, shapes, and occurrence, respectively. These latter questions were repeated in Q2 to evaluate any improvement in the students' knowledge ascribable to peer-to-peer learning.

Q2 was organised in 16 questions, covering respondents' profile (n. 1–3), perception and knowledge. With respect to Q1, the perception section (questions n. 4–6 and 14–16) included additional questions to evaluate change in the students' level of concern after the seminar and their opinion on the most serious consequences of plastic contamination and economic decisions related to plastic/waste management as well as the most effective mitigation measure. Question n. 16 finally assessed their opinion about the need for future local initiatives of environmental education, on a scale from 1-no need to 5-in favour of similar initiatives. Regarding the knowledge level (questions n. 7–13), this was further expanded compared to Q1 with three additional questions (n. 11–13) on MP type mostly found in indoor settings, MP effects on soil fauna and possible ways for human intake.

Questionnaires were delivered to each peer group participating to the seminar as an online Google Form. Q1 was filled by the peers about a week before the seminar to assess their background knowledge and perception about MP contamination, while Q2 was administered right after the seminar to determine change in students' knowledge and perception associated with the peer-to-peer learning. After completing Q2, the peers attending the seminars received immediate feedback from the presenting students.

2.5. Questionnaire analysis

Q1 and Q2 answers collected from the different classrooms were organised as anonymous aggregate data in spreadsheets according to the profile of respondents: gender (female, male, not available) and high school education level (first year vs three last years) as variables. Indeed, in the Italian secondary education system, high school is divided in two sections: the first two years are mandatory and they mostly cover core subjects to provide a knowledge baseline to all students; the last three years usually include more diversified and specific subjects to prepare the students to specialized work or higher education level. This explains the two education levels considered as groups in data analysis.

While questions from the Perception section were expressed as relative frequency of observed answers, questions from the Knowledge section were considered as quantitative items, assigning a binary score

(1 for correct answers, 0 for wrong ones). For each question, a total score per student and the frequency of responses were determined.

Statistical analysis of the Knowledge quantitative items was performed according to Righi et al. (2024) considering the whole student sample. Data normality was assessed using the Shapiro–Wilk test. Difference in the total score of the students associated with their gender (female vs male) and education level (first year vs three last years) was assessed through the Mann–Whitney test. The correlation between the students' knowledge and their level of concern (question n. 4) or background knowledge on plastic contamination (question n. 5 in Q1 and n. 7 in Q2) was assessed using the Kendall rank correlation. Data visualization and analysis were performed using Microsoft Excel (version 2502) and R (version 4.2.2, 2022-10-31, 64-bit) and RStudio (2024.04.1 + 748 release for windows) (R Core Team, 2022; RStudio Team, 2024).

3. Results and discussion

3.1. Litter monitoring in the school yard

With the clean-up activity, 1.6 kg of litter (metal, plastic, paper, cigarette butts and other material) was collected in the outdoor sites, of which 0.6 kg were plastic waste and cigarette butts. In Out1, at the entrance of the school yard, the litter was mainly composed of metallic confetti (more than 1000 pieces estimated), pieces of plastic bag and paper shreds (Fig. S4 A), while in Out2 a prevalence of single-use plastic items (cups, bottles and snack packaging), followed by cigarette butts (almost 450 estimated), paper shreds and aluminium cans was found (Fig. S4 B). Not recyclable waste (classified as other litter) mostly included fabric confetti and corks were picked up from Out1, and stationery materials and electric waste from Out2. Based on the clean-up survey, estimated litter density accounted for 0.44 g/m^2 in Out1 and 1.54/m^2 in Out2 of which plastics and cigarette butts densities were 0.25 g/m^2 in Out1 and 0.65/m^2 in Out2.

Results of the clean-up were discussed with the students, who attributed the difference in litter amount and composition between the two sites to their location and main usage: although Out1 is a transit area, it is used for celebration events by the students (thus explaining the high number of confetti found). In contrast, Out2 is more "hidden" in the backyard, but high school students use to spend their lunch/break time there, eating and smoking. Indeed, 432 cigarette butts were found in Out2, while only 16 were collected in Out1 site.

Clean-up is potentially one of the first citizen science-based activity developed to raise awareness about plastic litter and MP. Such education approach in urban environments is key in attaining SDG11 and SDG12, as young citizens can learn from experiences within their local communities and reflect on waste management and the "three Rs" principle (Recycling, Reuse, and Reduce) (Chun T'ing et al., 2020; Velempini, 2025). Several studies underline how the active participation of citizens in field monitoring projects leads to increased knowledge, ecological awareness, empowerment and PEB about plastic waste (Pahl and Wyles, 2017; Hidalgo-Ruz and Thiel, 2013). For instance, Locritani et al. (2019) showed how high school students (16–17 y) participating to an educational extracurricular project about marine litter, were much more interested in this environmental issue following beach clean-ups, with effects on their perception and knowledge.

In our study, we confirmed the validity of this methodological approach by empowering the students involved. The active discussion of the clean-up results further led to the suggestion to add more recycling bins in the school yard to encourage PEB among their peers. In addition, periodic clean-up initiatives at the school could be scheduled, for example during civic education lessons (a mandatory course in Italian high schools) to raise awareness among young people at different ages about environmental issue.

3.2. Airborne MP contamination in the school environment

MP monitoring at school through passive sampling for a period of 14 days resulted in a diversity of MP candidates in terms of shape, colour and size (considering size cut-off from 20 to 1000 μm) among the sites considered. In the environmental blanks, 24 MP candidates were found (Table 1), of which 13 fragments (54 %) and 11 fibres (46 %). Most MP candidates were black (8), brown (4), transparent (3) or blue (3), with fibres average length of 298 ± 173 μm (1 fibre above 1 mm length) and much smaller fragments of 89 ± 84 μm. On average, 4 ± 1 n MP candidates (either fibres or fragments) per filter were found in the blanks, in line with recent monitoring studies (Bergami et al., 2023; Jenner et al., 2022).

Since in this study only sub-samples were inspected by the students, sample normalization was not carried out and results are reported as not normalised MP candidates. To refer to the potential MP cross-contamination of the samples, a comparison between sub-samples and blanks was made and discussed with the students, highlighting how scientific research should follow rigorous protocols and criteria (Prata et al., 2020). This aspect was considered important for high school students as scientifically-oriented learning activity (PTSO) (Locritani et al., 2019).

In the samples, a total of 379 MP candidates was identified by the students: 137 fibres and 242 fragments. All particles were smaller than 5 mm, thus classified as MP (Table 1). Prevalent colours were black (24 %), blue/light blue (22 %), yellow (18 %). Across samples, most textile microfibres were of blue/light blue ($n = 67$, 49 %), transparent ($n = 21$, 15 %), and black ($n = 17$, 12 %) colours and of higher average length (388 ± 247 μm), while most of the fragments were black ($n = 74$, 31 %), yellow ($n = 64$, 26 %) and of smaller dimensions (71 ± 54 μm). Moreover, in the indoor site 12 fibres longer than 1 mm were recorded, differently from the outdoor sites (3 fibres >1 mm in Out1 and 2 in Out2). The students also recorded a single fragment longer than 1 mm, in Out1.

Overall, a clear difference in MP candidates between outdoor and indoor school environments was found. Textile microfibers were predominant in the Ind site (69 % of the total), whereas a higher number of fragments was observed in Out1 (79 %) and Out2 (82 %) (Table 1, Fig. 4A,B). Despite their size was comparable, MP candidates were differentiated by colour across the three sites, with blue and light blue fibres mainly found in Ind ($n = 59$, 67 % of the total fibres), transparent fibres in Out1($n = 12$, 40 % of the total fibres) and black ($n = 8$, 42 %) in Out2 (Fig. 4 B). Other microfibres colours included white, purple and brown. Interestingly, the colours of the fragments were more homogeneous across the samples, with a prevalence of black (38 % in Out1, 20 % in Out2 and 33 % in Ind) and yellow/orange (30 % in Out1, 28 % in Out2 and 18 % in Ind) colours (Fig. 4 A). These key outcomes of the monitoring activity were summarized by the researchers and then reported to the students.

Our preliminary results about MP in total atmospheric deposition at the school are in line with reports for outdoor (Chang et al., 2023) and indoor environments (Dris et al., 2016), both in term of MP shape and colour. While fragments dominated MP composition in Out1 and Out2, textile fibres were abundant in the settled dust within the classroom (Ind), highlighting different main MP sources (Mattsson et al., 2023; Tao et al., 2022; Sommer et al., 2018): fibres in Ind were mostly released from the students' textile garments and fragments in Out1 and Out 2 were potentially released from degradation of plastic materials. As expected from the sampling design, a higher number of MP was found in Out1 (located to a heavily trafficked road) compared to Out2 in the school back yard, with a higher proportion of black fragments in Out1, which could be related to particles released from tyre abrasion and road dust (Sommer et al., 2018). Indeed, MP deposition and abundance in outdoor environments have been found to positively correlate with weathering conditions, urban architecture but most important with human activity (Allen et al., 2019; Dris et al., 2016).

Table 1
Amount (n, %) and length of MP candidates (size range: 20–1000 μm), as mean ± SD (range min–max), in the blanks and samples for each site. *indicating the presence of MP candidates with size above 1 mm.

Site	Blank				Sample			
	Fibres		Fragments		Fibres		Fragments	
	n	Size mean ± SD (min–max)	n	Size mean ± SD (min–max)	n	Size mean ± SD (min–max)	n	Size mean ± SD (min–max)
Out1	4 (44 %)	169 ± 46 (118–208)	5 (56 %)	71 ± 53 (20–160)	30 (21 %)	399 ± 205 (120–955*)	113 (79 %)	71 ± 51 (22–324*)
Out2	3 (50 %)	210 ± 26 (191–228)	3 (50 %)	68 ± 34 (28–88)	19 (18 %)	256 ± 262 (43–913*)	89 (82 %)	69 ± 66 (21–523)
Ind	4 (44 %)	470 ± 144 (272–595)	5 (56 %)	118 ± 127 (42–345)	88 (69 %)	413 ± 251 (27–993*)	40 (31 %)	78 ± 30 (21–153)

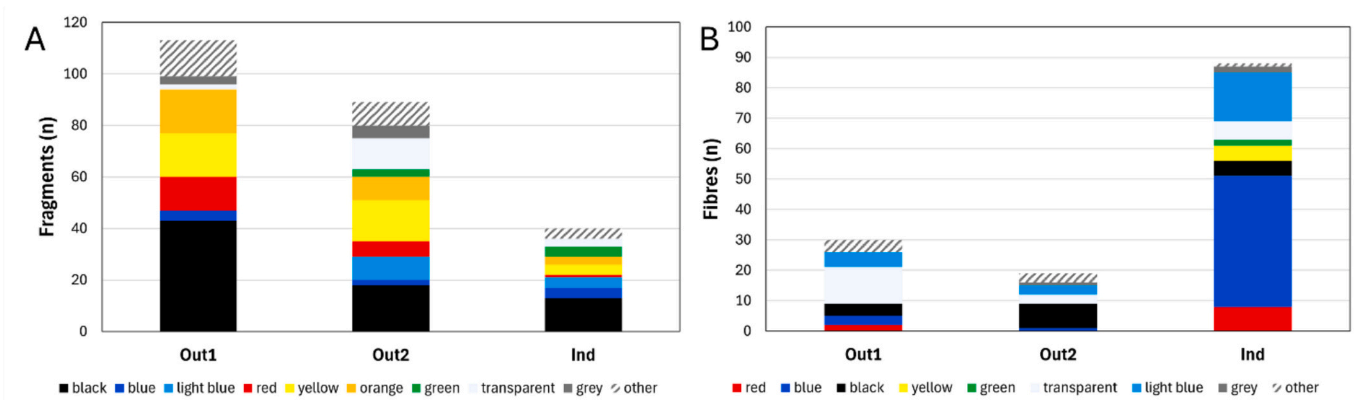

Fig. 4. Colours of the candidate MP fragments (A) and fibres (B) in outdoor (Out1, Out2) and indoor (Ind) samples, as identified by the high school students.

Regarding MP colour, Zhao et al. (2022) recently underlined how this may affect plastic solar absorbance and UV transmittance, thus determining their photoaging. MP coloured with dark pigments, such as carbon black, could persistent longer in the environment as black colour can effectively prevent UV light alteration of the polymer. Differently, the abundance of yellow and orange fragments found in the outdoor sites could be associated with the weathering process of light-coloured plastics due to prolonged solar exposure (Key et al., 2024; Martí et al., 2020).

The preliminary characterization by Micro-Raman confirmed the presence of synthetic plastic polymers: polypropylene (6.2 %), polyethylene terephthalate (10.8 %), polyacrylonitrile polymer (3.1 %) and composite materials (24.6 %) at all sites (Fig. S5, Table S2), in line with other monitoring surveys in urban environments (Chang et al., 2023; Wright et al., 2020) showing the ubiquity of MP in both indoor and outdoor school environments. Moreover, 24 % of the microfibres analysed were of natural or cellulose-based composition, in agreement with previous studies (Wright et al., 2020; Stanton et al., 2019; Dris et al., 2016).

Since counting and measuring all the MP candidates on the filters was not possible due to time constraints, the polymeric characterization was performed on sub-samples only, as this is very time-consuming (Luo et al., 2022). The final remark presented to the students was that further analyses are needed to outline a comprehensive picture of the MP contamination at the school. Nevertheless, the goal of this activity was considered met as the students were showed astonishment about the amount of MP candidates concentrated onto the filters (Fig. 2), their diversity (Fig. 3) and small sizes (Table 1), underlining how their risk perception about MP contamination have changed. For instance, they were unaware of the amount of MP they may be exposed to even indoors, where one of the main sources is dispersion from textile materials they themselves are wearing. Similar to clean-ups, the active MP monitoring performed in this study highlighted how scientifically-driven activities can successfully be used to inform young citizens and convey ecological knowledge (van de Wetering et al., 2022), also implementing their educational path toward sustainability in line with SDG4 “Quality education” (Velempini, 2025).

3.3. Impact of soil pollution on springtails

The 21-d ecotoxicity test with *F. candida* showed an increase in the springtail mortality both after single exposure to the contaminants (20 ± 10 % for MP and 33.3 ± 15.3 % for Cd) and when combined (53.3 ± 32.1 % for MP-Cd), compared to the control group (6.7 ± 11.5 %) (Fig. 5). These results suggest an addictive effect of HDPE micro-sized fragments and the heavy metal, in line with (An et al. (2023). As a further signal of stress in the groups exposed to MP and/or Cd, no juvenile was found in the test vessels after 21-d, in agreement with (Campbell et al., 2000) for Cd, compared to the control group.

Although the high school students had no background knowledge on zoology, ecotoxicology and environmental chemistry, this laboratory experience, combined with brief introductive meetings and discussion was successful in showing them how soil pollution (including emerging contaminants such as MP) can affect organisms’ survival (as shown in Fig. 5) and reproduction. This activity is thus recommended not only to raise awareness about potential MP impacts on soil community, but also as a part of a university orientation path for Natural or Biological Sciences. Students, indeed, challenged themselves in the lab, by observing, counting and studying the vitality of live organisms under the microscope, with evident positive effects for their self-efficacy.

3.4. Effectiveness of dissemination and peer-to-peer learning

Following field and laboratory-based active learning, the dissemination carried out by the students (i.e., preparation of an oral presentation and writing a newspaper article about their experience) allowed

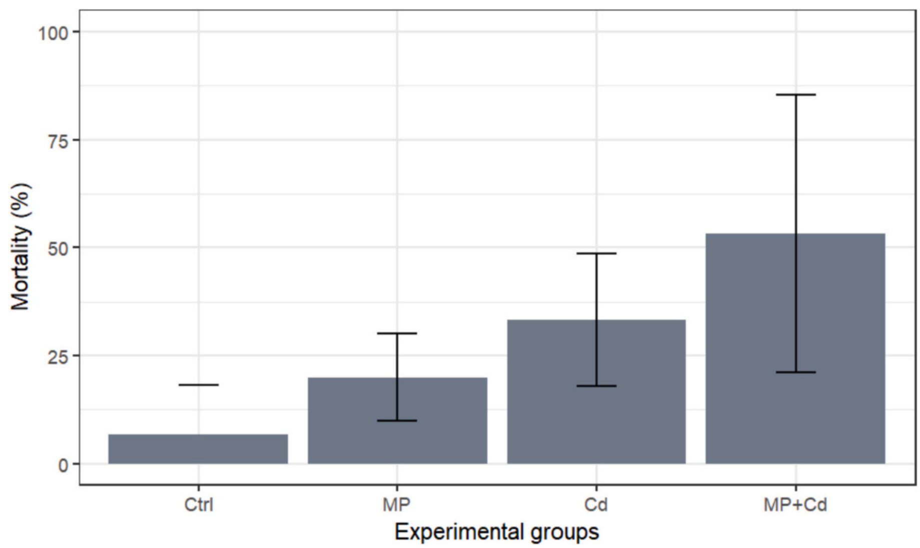

Fig. 5. 21-d mortality percentage (mean ± SD) of springtail *F. candida* after single exposure to HDPE fragments (MP, at 1000 mg/kg), Cadmium (Cd, at 200 mg/kg) and combined (MP-1000 and Cd-200) compared to the control (Ctrl) group.

them to test and improve their management and communication skills through scientific outreach. From a pedagogical point of view, these steps further served to the students to review and reflect on their experience as well as to test the level of acquired knowledge (Kolb, 1984; Healey and Jenkins, 2000). This part of the project was considered successful as all students still actively participated, working in small teams and completing the assigned tasks on time, despite other school course and exams to attend and prepare. Effectiveness of the peer-based knowledge transfer was assessed through data collected in Q1 and Q2 surveys. Q1 was filled in by 179 high school students, 118 males (66 %) and 61 females (34 %), while Q2 was completed by 163 students (thus with 16 absentee), 97 males (60 %), 58 females (36 %) and 8 who did not wish to specify their gender (5 %). Most of the students (134) attending the seminars belonged to the Applied sciences curriculum (111 from the first year, 23 from the third year), and 29 students were from the last three-years of the Biotechnology curriculum.

Before the seminar, most of the students taking the Q1 survey had heard of MP (158, 88 % of the total) and were on average/high concerned about MP impacts on the environment and human health (level 3–4: 149, 88 % of the total). Only 17 students expressed very high concern about the subject (level 5: 9 %) and few (level 1–2: 13, 7 % of the total) were not much/at all worried about it (Fig. 6 A). The question "Do you think that plastic and MP are an issue found in your school?" further assessed the students' perception of MP as a problem: 122 students (68 %) answered positively, indicating average concern over MP as a risk.

Following the seminar, an increase in the students' level of concern was observed (Fig. 6 B), although it was not significant ($p = 0.1132$), with a higher number of students (30, 18 %) selected 'very high concern' about MP contamination (level 5). Moreover, when asked if they were more concerned about MP contamination due to the seminar, most of the students agreed or strongly agreed (level 4–5: 108, 67 %), highlighting the effectiveness of the peer-based learning in conveying key environmental concepts.

In Q1, background knowledge about MP was assessed through three questions about MP size range, shape(s) and matrices in which they can be found. No difference in the students' total score for knowledge questions was found according to their genders (Fig. S6 A,B) and class affiliations (S6 C,D). Data analysis showed no correlation between the students' level of concern and their background knowledge about MP (tau = 0.1156, p-value = 0.08165). Interestingly, most of the students (157, 88 % of the total) knew or grasped that MP can be found in every environment (water, soil, atmosphere and the biota). Almost half of the students (78, 44 %) answered correctly that MP size is below 5 mm, while the other half (85, 47 %) selected a size below 0.001 mm and very few (16, 9 %) chose other options. The selection of MP shapes resulted more ambiguous, with about one third of the students (59, 33 %) selecting "irregular" shape, 39 students (22 %) choosing "not

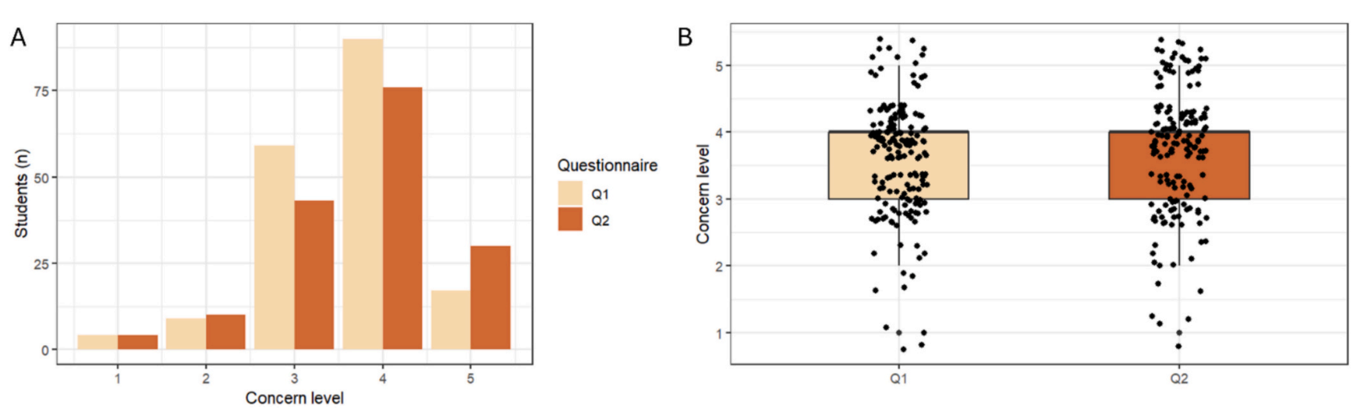

Fig. 6. Level of concern (scale from 1-minimal concern to 5-very high concern) in Q1 and Q2 surveys displayed for each level (A) and for the whole students' samples (B).

determined" and very few selecting other options ("fibrous": 8, 4 %, "spheric": 7, 4 %). The correct answer ("all of the above") was selected by 66 (37 %) of the students.

Considering these questions, results from Q2 showed no difference according to the students' genders (Fig. S7 A,B) and class affiliations (Fig. S7 C,D); however, considering the whole student sample, a significant increase in their knowledge total score ($p < 2.2e-16$) was found (Fig. 7).

Almost all students (161, representing 99 % of the total in Q2) answered correctly that all abiotic and biotic matrices can contain MP (Fig. S8). Additional knowledge questions posed in Q2 only allowed us to verify the students' comprehension of the project results, as presented by their peers. Results indicated that the students attending the seminars retained key information (Fig. S9), as the majority correctly answered the question "Which is the main MP type found in indoor environments?" (141, equal to 87 % selected textile microfibers) and "In the case study presented, which were the effects of MP on soil fauna?" (153, equal to 94 % selected mortality increase). Only the question "How are humans exposed to MP?" showed a lower percentage of correct answers (Fig. S9), with 102 students (63 %) correctly selecting: "Through ingestion and inhalation". Nevertheless, more than half of the participants answered correctly to this questionnaire item. The lower percentage of right answers was attributed to the presence of an alternative option: "Through ingestion, skin absorption and inhalation", which was indeed partly correct. This latter option was selected by 56 students (34 % of the total).

As highlighted in our previous study Righi et al. (2024), these surveys also allow us to collect interesting data about people perception of environmental issues. In Q2, to the question n. 6 "Do you think there will be negative consequences due to current economic choices about plastic?", interestingly only a small group of students (17, 10 %) selected "Yes, with repercussions mostly on young people". 52 % of the students ($n = 85$) answered positively referring to environmental and human health in general, while 27 % ($n = 44$) still believed the marine environment would be the most affected (Fig. S10).

In line with this, to the question n. 13, "In your opinion, which is the most serious consequence of plastic and MP", 66 % of students ($n = 108$) chose the potential effects on human health and 28 % ($n = 45$) opted for the pollution of seas and oceans. The options related to the air quality decrease and the high costs of MP removal were less considered (Fig. S10).

Finally, to the question n. 16, " In your opinion, which of the following activities/measures is the most useful to mitigate (micro) plastic contamination?", all the options were more or less equally considered by the students, with the most selected one as "Laws regulating and/or limiting the use of plastic materials", chosen by 34 % of the students ($n = 55$) (Fig. S10).

Questionnaire surveys associated with interventions and workshops have been highlighted as effective tools to assess changes in citizens' attitude toward engaging in nature-based projects (Locritani et al., 2019; Hartley et al., 2018). Yet, our notable results should be ascribed to the specific target (more than 160 high school students reached) and the learning methods considered in this study. Future studies should incorporate follow-up assessments to evaluate the long-term retention of the students' knowledge, SCB and PEB encouraged by the project. In contrast, previous surveys focusing on larger student samples including children (Wichmann et al., 2022) or with a high age gap (from children of 7–9 to 18 years old) reported no significant differences in knowledge and/or perception and behaviours following dedicated workshops or seminars (Oturai et al., 2022; Uehara, 2020). Oturai et al. (2022) suggested that this could be related to the large age group considered, advising caution with the design of future citizen science activities including children as participants.

Nevertheless, the strength of our study could be attributed to the long educational project carried out, with dedicated time and personnel, compared to others presented in the literature, but also to the active learning strategies adopted, including peer-to-peer learning. Adolescents are often portrayed as self-centered, unlikely to react to school-based environmental interventions. However, our study confirms that multiple active interventions based on different educational modules are indeed effective, more than single lectures (Campbell et al., 2000), underlining the importance of environmental education project in this age group. van de Wetering et al. (2022) suggest in fact that environmental education can effectively overcome or mitigate the psychological barriers that often prevent young people from engaging in PEB. In addition, near-peer teaching and learning experiences lead to improved self-efficacy, empowerment and awareness (Bester et al., 2017).

3.5. Pedagogic implications and future developments

Although some shortcomings can be identified, this study adopted a well-structured educational project to inform young citizens about the extent of (micro)plastic contamination in a familiar urban environment (i.e., their school), convey ecological knowledge and raise environmental awareness.

Based on Kolb's experiential learning theory (1984), effective learning (i.e., new knowledge, skills and attitudes) can be achieved through four steps: concrete experience, reflective observation, abstract conceptualization and active experimentation. In this project, students were fully involved in the activities from many perspectives, first as observers (when following the presentation of the activities, then as researchers (when they were carrying out sampling and analysis during hands-on activities) and finally as teachers (when they prepared the dissemination material and showed the work to their peers).

Knowledge acquisition was thus achieved through planning, action, thinking and confrontation (Kolb, 1984; Healey and Jenkins, 2000). For

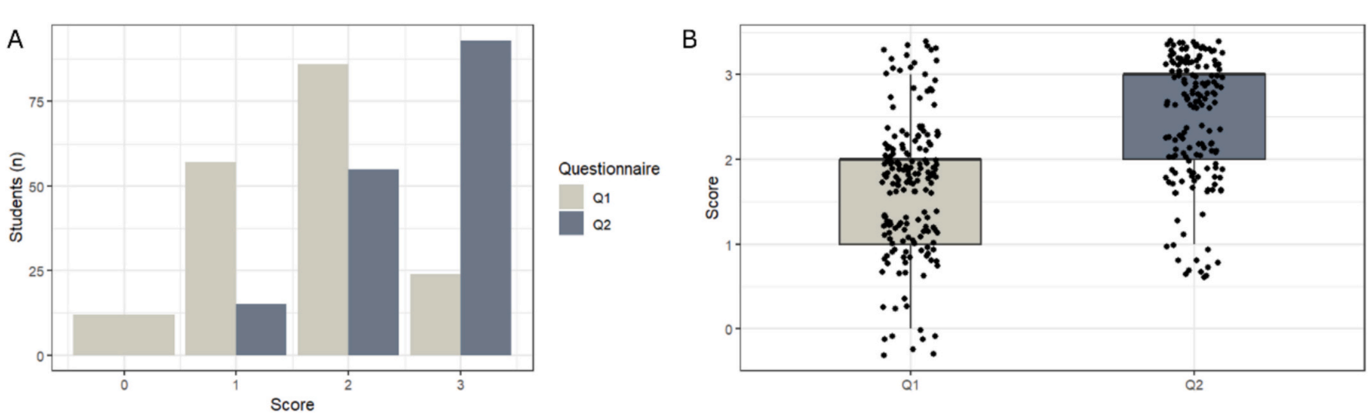

Fig. 7. Students' total score about MP knowledge in Q1 and Q2 surveys displayed for each score level (A) and for the whole students' samples (B).

instance, to ensure that the students could familiarize with the protocol used for MP isolation and identification, even though advanced sample preparation and polymer identification was not carried out by them, a guided tour at the University facilities was conducted, using direct observation (Krakowka, 2012) instead of a passive frontal lecture to help them understand the whole process and analytical techniques. Several studies have underlined the importance of fieldtrips (e.g., excursions, study tours) as valuable active learning method to acquire knowledge and improve understanding of theoretical processes (Krakowka, 2012; Kwasek and Piwek, 2020; Liu, 2023). Furthermore, through discussion and preparation of the dissemination material in the classroom, students were able to reflect back on their experience and test the level of knowledge acquired (Kolb, 1984; Healey and Jenkins, 2000; Krakowka, 2012).

From a pedagogical point of view, the use of many different learning methods was thus successful to reach effective learning, in line with the literature (Kolb, 1984; Campbell et al., 2000; Healey and Jenkins, 2000). A previous study on airborne particulate matter also demonstrated that participatory observation structured following different learning steps was successful in improving high school students' knowledge, skills and attitudes toward environmental issues (Gkiolmas et al., 2020).

In future environmental education projects dedicated to MP research, a higher involvement of the students in advanced analytical steps could be achieved with dedicated training modules and through simplified demonstrations, virtual tours, or by designing collaborative analytical sessions with researchers, for example using pre-prepared samples (e.g., MP deposited on glass slides for identification) or providing access to data visualization tools allowing students to interpret complex datasets.

Overall, this project can serve as a baseline to build extensive citizen science-based programs on MP monitoring over long periods (e.g., considering different seasons) and at large scale (with different schools participating). This can contribute to building further awareness and stimulate long-term engagement, which are key aspects of environmental education programs in attaining United Nations 2030 Agenda SDG targets (Velempini, 2025).

The proposed activities might be inserted into worldwide educational initiatives, such as the GLOBE (Global Learning and Observations to Benefit the Environment) program (https://www.globe.gov/about/learn/program-overview) to promote SCB and PEB. For instance, GLOBE Italia is coordinating the MICROPLA SC/art project about MP pollution in the hydrosphere involving high school students from different locations in Italy (https://www.globeitalia.it/micropla-sc-art/il-progetto.html).

Our study provides methodologies to build targeted projects on airborne MP and/or focused on urban-based sources of MP pollution. As the MP research field is continuously developing and harmonized protocols for MP categorization are emerging (Cowger et al., 2020; Belz et al., 2024), in future studies standardised guidelines could be provided to students as support during visual identification of MP candidates, which was found to be a particular challenging step of data acquisition. This aspect, combined with a list of best practices for quality assurance/quality control measures, will allow to improve data consistency and accuracy in student-led analysis. In addition, the potential incorporation of active air sampling methods will provide a more robust dataset on the abundance of airborne MP (Zheng et al., 2024).

4. Conclusions

The environmental education project «Taking microplastics into the class» allowed us to collect some preliminary data on airborne MP levels in indoor and outdoor sites in an Italian high school. In parallel, the project is a successful example of university orientation and SDG-driven environmental education with notable pedagogic implications, promoting public awareness in young citizens about the manifold MP sources and their transport in urban environments.

Overall, although the project presented here appears well-structured, long-lasting and very time-demanding (both for students and researchers), we aimed to provide all methodologies used and related results as a prompt for future small, targeted activities, which can be carried out on this specific topic. Indeed, the activities described in this study are well suited to be considered as independent modules and customized depending on case-by-case feasibility (time, personnel, equipment and facilities available). As shown, every module combines conventional and innovative educational methods ensuring an active involvement of the students, increasing their knowledge and stimulating their transdisciplinary skills and environmental awareness. We also demonstrated how peer-to-peer learning is a valid educational method that can be applied in the field of environmental education.

To the last question of Q2 "From 1 to 5, would you like to see more outreach and awareness initiatives on (micro)plastic contamination in the place where you live?", most of the students agreed (level 4: 79, 48 %) or strongly agreed (level 5: 34, 21 %), while very few expressed low interest (level 2: 10, 6 %) and no one chose level 1-no need. This underline how the students themselves are in favour of similar initiatives. This work calls for more scientific-based studies on a range of environmental issues, testing and quantitatively assessing the use of innovative learning methodologies for environmental literacy.

Ethics approval

No ethical approval was necessary for this study. Aggregated data were derived from anonymous contributions of volunteers participating in the survey.

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Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

org/10.1016/j.crsust.2025.100309.

Data availability

The datasets are available from the corresponding author upon request.

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