Environmental Science Advances

PAPER

View Article Online
View Journal

Cite this: DOI: 10.1039/d5va00376h

Human health and exposure to microplastics and nanoplastics: a cross-sectional survey on public risk perception in Italian adults

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Received 22nd October 2025
Accepted 16th April 2026

DOI: 10.1039/d5va00376h

rsc.li/esadvances

Microplastics (MPs) and nanoplastics (NPs) are emerging as significant environmental hazards in the contemporary era for both plants and animals. Additionally, they have been found to accumulate in the human body, underlying the need to understand their health impact and to assess public awareness and risk perception. In an Italian sample, a cross-sectional survey was conducted using a river sampling enrolment and an online questionnaire filled by 242 participants at the national level. Respondents showed substantial concern about potential health effects, particularly towards carcinogenic risks, despite the lack of robust scientific evidence. Overall, 65% have heard of MPs and NPs, but still significant mistakes emerged in their definitions and in determining toxicological outcomes. 78% of participants perceived MPs and NPs as threatening yet poorly understood hazards. Behavioural intentions, such as reducing consumption of fish or using toothpaste if contaminated, correlated significantly with increased actual knowledge. Media sources, associated with socio-demographic and risk perception variables, seemed to influence participants' actual knowledge (*e.g.*, TV, radio, or newspapers as the frequent source of information *vs.* wrong beliefs about carcinogenicity). Despite some important limitations, the findings suggest the urgent need for targeted communication strategies to bridge the evidence-to-practice gap, correct misinformation, and promote proactive behaviours and good practices at the public level by reinforcing environmental health literacy among citizens.

Environmental significance

Plastic is now the most widespread pollutant worldwide. It can be degraded into smaller fragments, micro- and nanoplastics (MPs and NPs), by chemical and physical agents. Once absorbed by plants and animals, toxic effects such as obstruction, chronic inflammation, cell death, chlorophyll reduction, plant growth inhibition, and endocrine disruption alter plant survival and animal behaviour, leading to significant ecosystem alterations. MPs and NPs have been found in human tissues. Public perception of risk is a key component of environmental risk management, but the flow of scientific information to citizens is not smooth, contributing to misunderstandings of essential information. Our findings confirmed the urgent need for targeted risk communication to the public to correct misinformation and promote proactive behaviours.

Introduction

Plastic residues are Earth's most common pollutants. Synthetic plastics were first created with an ecological purpose, to substitute African elephant ivory and to prevent their hunt, by the chemist Baekeland in 1906.[1] Different types of plastic polymers are used for different purposes, which increases the complexity of the topic.[2] Chemical, physical, and biological factors can induce plastic residue degradation into micro- and nano-plastics (MPs and NPs, respectively).[3–5] During degradation, additives are also released with MPs and NPs, such as bisphenol A, which can induce toxicity alone or in combination, requiring separate risk assessment.[6–8] Nowadays, studies focused on assessing the toxicity of MPs and NPs are increasingly strengthening the importance of this topic. The biological hazard is still not fully clarified. In plants, the primary outcomes are physiological; in animals, several studies have reported biometrical and developmental alterations, DNA damage, and increased tumoral masses.[9–13] Considering all these pieces of scientific evidence, it is important to study how the public perceives the hazard of plastic pollution to develop the most effective communication campaigns, with the aim of fostering protective environmental and health behaviours at the personal level and more effective public awareness and respect for regulatory principles. The evidence-to-practice gap is an important topic associated with risk perception.[14] Knowledge of a phenomenon influences personal judgment of potential hazards, altering subjective risk perception.[15] Effects on human

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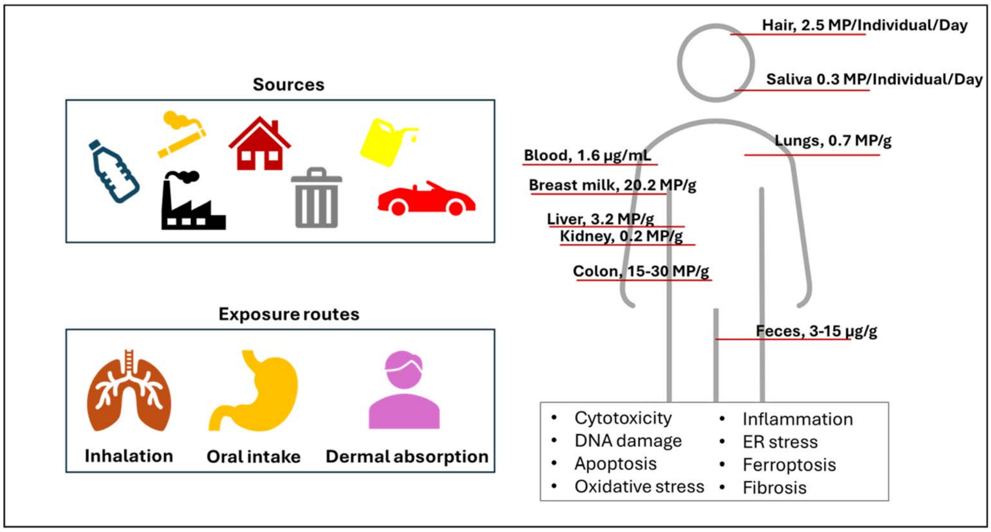

Fig. 1 MPs/NPs and human health. Plastic residues can be generated mainly from industrial production, domestic activities and vehicle emissions. Once in the environment, humans are exposed *via* inhalation, oral intake and dermal contact. MPs and NPs have been found throughout the human body and in the tissues with no correlation with specific habits.

health are harder to assess. Recently, MP and NP fragments have been found in the lungs, placenta, breastmilk, and other tissues, causing endocrine disruption.[16,17] Moreover, a prospective, multicenter observational study found a correlation between MPs and NPs and cardiovascular events in 304 patients with or without MPs and NPs in their excised carotid plaques.[18] The authors reported that patients found with plastic residues were more affected by myocardial infarction, stroke, or death from any cause. This result suggested that the environment influences human health, and plastic residues could contribute to this. Fig. 1 presents the knowledge and scientific evidence about how humans are exposed and the associated health risks.

The present study aims to assess the levels of awareness and actual knowledge, outline the perceived risk in the general population regarding MPs and NPs in environmental and food matrices, and provide insights for risk communication initiatives.

Methods

Study design and sample enrolment

The study consisted of an observational survey with a cross-sectional design. The sample was enrolled using a non-probabilistic method *via* primary social channels (WhatsApp, Facebook, and Instagram), following the so-called 'river sampling' method.[19] Participation in the study was voluntary and free of charge. The questionnaire was completed anonymously, self-administered, and took about 15 minutes on average. All participants were asked for consent: in the first section of the online form, two mandatory questions included hyperlinks to the study information and data processing documents. Only after ticking the "I approve" box for both items were they able to complete the questionnaire. The study was approved by the Internal Review Board of the University of L'Aquila (protocol no. 670/2023, dated 04/01/2023).

Questionnaire design

The questionnaire was developed based on the hypothetical model in Fig. 2, and it comprised the following parts (SI1):

(1) Sociodemographic data (age, gender, educational qualification, and employment status) and mode of information (*e.g.* TV, websites, social network, newspaper, *etc.*), comprising 7 questions (15 items in total);

(2) Actual knowledge possessed by the interviewees and their beliefs (*e.g.* plastics, MP and NP characteristics, pictograms used for plastic product management, environmental and food matrix contamination, absorption routes and consequences on human and animal systems/functions), comprising 23 questions (78 items in total);

(3) Perceived risk of exposure to microplastics and nanoplastics, comprising 5 questions (14 items in total);

(4) Behavioural intention (referred to consumption of seafood and use of toothpaste potentially contaminated by MPs/NPs) and one experienced behaviour (buying plastic bags), comprising 5 questions (11 items in total).

The questions were formulated based on previous international studies focused on environmental science and risk perception. We collected a set of similar tools from different papers to compare their content, methodological approaches, and data interpretation.[15,20–26] The scientific topics section (actual knowledge) was enriched by integrating with other scientific papers/institutional documents.[1,16–18,27–31] The questions collected were translated in Italian and made into the first 'wide' draft, and a face validity evaluation was conducted with an experts' panel (with expertise in environmental science, genomics, and epidemiology). After selecting items (*e.g.*, if similar across different papers) and adding new original items to address content not covered in previous experiences, the panel produced a second draft of the questionnaire with attention to transcultural adaptability. The subsequent round consisted of a short pilot phase to

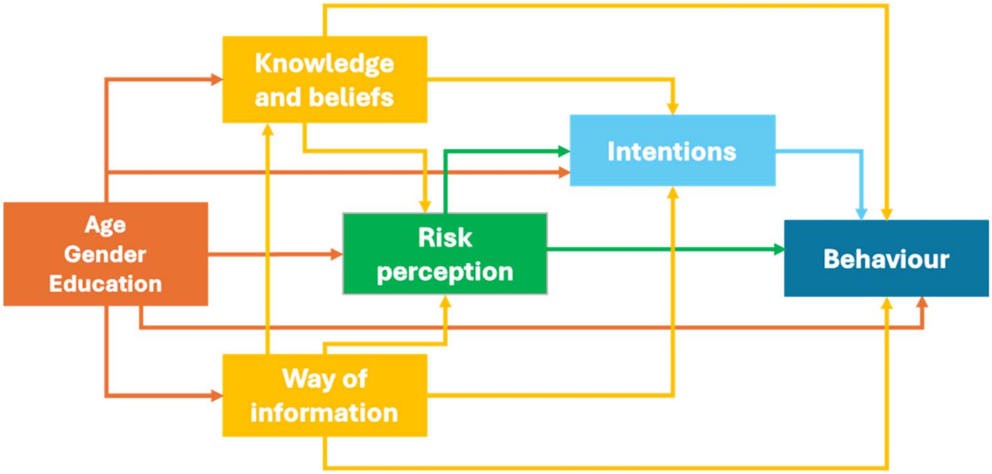

Fig. 2 Research framework based on previous scientific literature to explain the behavioural intention and experience in this study.

test the feasibility of completing the questionnaire (form length, text comprehensibility, level of interest, *etc.*).

Statistical analysis

Statistical analysis was conducted using STATA/BE 17.0 software. Likert scales were used for psychometric constructs (knowledge, risk perception, *etc.*) and converted to ordinal numerical variables.

Actual knowledge items were converted and grouped into subscale scores ranging from −1 (worst level) to +1 (best level) (SI2). Categories of correctness for knowledge subscales are defined as: 'Excellent' (score > +0.50), 'Good' (+0.25 < score ≤ +0.50), 'Moderate' (0.00 < score ≤ +0.25), 'Poor' (−0.25 < score ≤0.00), and 'Very Poor' (score ≤ −0.25). Similarly, risk perception items were converted to subscale scores ranging from 1 (lowest) to 5 (highest), and the central value of the interval scale (3.00) served as the cut-off for low/high perceived risk. The dimensional structure was evaluated using Exploratory Factor Analysis (EFA) to identify the number and nature of factors underlying the set of items: The 'Dread' component and 'Knowledge perceived' component of risk perception were confirmed consistent with the dimensionality defined by Slovic *et al.*[15] and Jenkins *et al.*,[20] and the internal consistency of the two constructs was assessed using Cronbach's alpha (SI2). Parametric and nonparametric statistical tests were used to assess the associations between categorical variables (chi-squared test with Fisher's correction) and to determine the differences between groups for ordinal numeric variables (Wilcoxon's, Kruskal–Wallis's, and Dunn's tests). In the comparison between subgroups, the effect size eta-squared (η_H^2) was calculated for numeric ordinal variables and the effect size Cramer's V was calculated for categorical variables.

Results

Sample characteristics

The sample comprised 242 respondents, 68.2% of whom were women (Table 1) with an average age of 36.4 ± 14.1 years. 60.2% held a 'high' educational qualification (Bachelor's or postgraduate degree). 55.4% were 'employed' in different job sectors: university and research (14.7%), white collar jobs (14.7%), education (12.1%), trade and distribution (9.6%), health care and social assistance (8.3%), and armed forces and defence (7.0%); only 5.1% worked in industry and none in agriculture, forestry and gardening; 31.4% were students.

Actual knowledge

Overall, 64.6% of the interviewed said that they have heard of microplastics and nanoplastics; specifically, 16.3% and 34.5% affirmed that they do not remember or have never heard of microplastics and nanoplastics, respectively. 37.1% and 36.0% cannot name or exactly define microplastics and nanoplastics, respectively (with significantly lower proportions among those who heard of them, $p < 0.001$ in Fisher's exact test in both cases). As shown in Fig. 3, 'Excellent' levels (mean score > +0.50) were found on five of the eleven scales regarding actual knowledge: environmental matrices contaminated with MPs

Table 1 Socio-demographic characteristics of the sample

	No. (total: 242)	(%)
Gender		
Female	165	68.2
Male	77	31.8
Education level[a]		
High	145	60.2
Medium	90	37.3
Low	6	2.5
Occupation[a]		
Employed	134	55.4
Housework	4	1.7
Student	76	31.4
Unemployed	19	7.9
Retired – others	8	3.3
Age (years) mean ± st. dev.	36.4 ± 14.1	

[a] 1 missing.

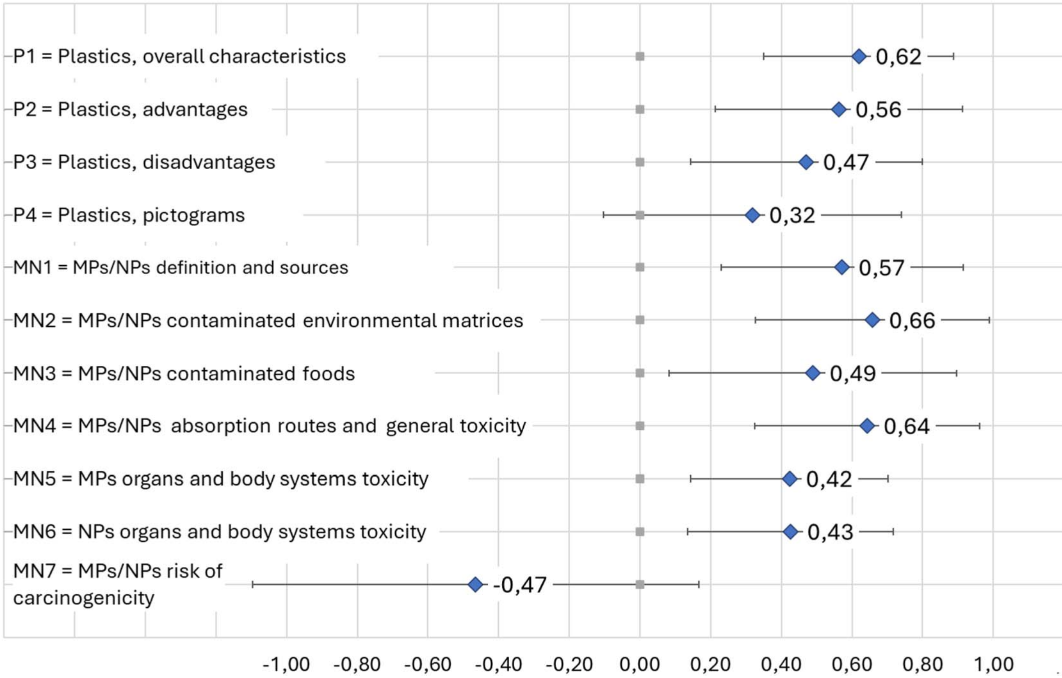

Fig. 3 Level of actual knowledge about plastics, microplastics and nanoplastics: mean value and standard deviation of the subscale scores from −1 (lowest correctness) to +1 (highest correctness).

and NPs (MN2, 0.66 ± 0.33); exposure and general toxicity of MPs and NPs (MN4, 0.64 ± 0.32); overall characteristics of plastics (P1, 0.62 ± 0.27); definition and sources of MPs and NPs (MN1, 0.57 ± 0.34); advantages of plastics (P2, 0.56 ± 0.35). 'Good' levels of actual knowledge (mean scores ranging from +0.25 to +0.50) were found on five others of the eleven scales: foods contaminated with MPs and NPs (MN3, 0.49 ± 0.41); disadvantages of plastics (P3, 0.47 ± 0.33); organ and system toxicity of MPs (MN5, 0.42 ± 0.28) and NPs (MN6, 0.43 ± 0.29); correct interpretation of pictograms used on plastic products (P4, 0.32 ± 0.42). Among the most notable gaps on single items (SI3), the incorrect number of existing types of plastics (36.8% said that they did not know and 44.4% indicated too many); the decomposing time for a plastic bottle (13.8% said that they did not know the answer and 63.8% indicated less than 400 years); the lack of knowledge about the release of microplastics and nanoplastics from road marking paints (53.2%), from toothpastes (53.0%), from cosmetic exfoliating products (48.3%), from ship hull paints (41.7%), from rubbing tires on the road (38.2%); underestimation of the likelihood of finding microplastics in the country air (by 54.4% of the sample), in uncultivated soil (35.4%), and, among foods, in fruits (56.1%), grains (52.1%), tap water (50.4%), vegetables and greens (40.6%), and milk and dairy products (38.2%). 60.3% were unaware that MPs and NPs can also be introduced into the human body through the skin and mucous membranes and that they both were found to be associated with toxic effects on humans and other living species (*e.g.*, molluscs, fish, crustaceans, insects, amphibians, reptiles, birds, wild mammals, and domestic animals) such as hypercholesterolemia (not indicated by 73.7% and 71.7% of the sample, respectively), cardiovascular system effects (not indicated by 62.6% and 61.2%, respectively). A 'very poor' level of actual knowledge (score <−0.25) emerged about the carcinogenicity risk of exposure to MPs and NPs (MN7, −0.47 ± 0.63). Specifically, 70.0% and 68.0% regarded MPs and NPs, respectively, as 'certain'/'probable'/'possible' carcinogens and did not gave the correct answer, *i.e.*, 'the internationally competent scientific bodies still have discordant opinions'; furthermore, 54.2% agreed with the statement that 'all plastics may be potential carcinogens'.

The channels 'often' used by interviewed to get information on health and the environmental issues are the following: social networks such as WhatsApp and Facebook (70.9%), websites (70.7%), TV (42.3%); 25.0% and 24.2% 'often' used specialized magazines/journals and books, respectively; the most rarely considered channels were radio and conferences, which respondents 'never' used in 42.0% and 42.5% of cases, respectively. TV, radio, and newspapers were most frequently used by people aged 50 years and older compared to younger people: 80.0% *vs.* 33.5% ($p < 0.001$), 29.0% *vs.* 15.5% ($p < 0.05$), and 41.0% *vs.* 23.9% ($p < 0.001$). Social networks, inversely, were the 'most frequently' used channel by a higher proportion of people younger than 50 years (75.8% *vs.* 46.0%, $p < 0.01$).

In univariate analysis, no significant differences were found in actual knowledge levels considering the education level, except in the case of scale scores on pictograms (P4), which are significantly higher among people with 'high' (mean = 0.40 ± 0.39) than with 'medium-to-low' education (mean = 0.19 ± 0.44, $p < 0.001$, Wilcoxon's test). Differences were found between genders, particularly more correct actual knowledge among women: the most notable differences emerged regarding mode of exposure and general toxicity of MPs and NPs (MN4, mean score = 0.67 ± 0.31 for women *vs.* 0.58 ± 0.32 for men, $p < 0.05$ in Wilcoxon's test) and toxicity to specific organs and systems from MPs (MN5, 0.46 ± 0.26 *vs.* 0.34 ± 0.29, $p < 0.01$) and from NPs (MN6, 0.46 ± 0.29 *vs.* 0.36 ± 0.29, $p < 0.05$). No statistically significant differences were found in the proportion of people who heard about both MPs and NPs concerning information channel, except among those who reported using websites (70.4% of those heard about both categories *vs.* 53.7% of those who 'rarely' or 'never' use that channel, $p < 0.05$ on chi squared test) 'often' and those who 'often' use specialized magazines/journals (79.6% *vs.* 62.2%, $p < 0.05$). Among users of different information channels, a higher level of correctness in specific topics was found:

- Among those who most frequently use specialized magazines/journals, concerning definition and sources of NPs and NPs (MN1, $p < 0.05$ in Wilcoxon's test), contaminated environmental matrices (MN2, $p < 0.01$), contaminated foods (MN3, $p < 0.05$), and mode of exposure and general toxicity of MPs and NPs (MN4, $p < 0.01$);
- Among those who most frequently use newspapers, concerning contaminated environmental matrices (MN2, $p < 0.05$), contaminated food (MN3, $p < 0.01$), and exposure mode and general toxicity of MPs and NPs (MN4, $p < 0.05$);
- Among those who attend conferences and seminars, concerning contaminated environmental matrices (MN2, $p < 0.05$) and exposure mode and general toxicity of MPs and NPs (MN4, $p < 0.05$);
- Among those most frequently using social networks, concerning organ- and system-specific toxicity from MPs (MN5, $p < 0.05$).

With respect to the cancer risk induced by MPs and NPs (MN7), the higher proportions of error are in those who most frequently use TV programs ($p < 0.01$), radio programs ($p < 0.01$) and newspapers ($p < 0.01$) as information channels, in a worsening sense (*i.e.* the more frequent the use, the lower the correctness of the information possessed).

Regarding specific regulations on the levels of MPs/NPs in environmental and food matrices, only 38.9% and 30.1% of the sample reported that they exist at the national or European level. Among the possible public strategies or technological solutions regarding plastic that the governments should adopt, four are indicated by almost all the interviewed: 'educate the people' (97.4%), 'encourage initiatives and technological solutions for the remediation of natural environments such as beaches and oceans' (95.6%), 'use alternative materials instead of plastic whenever possible' (95.3%), and 'promote separate collection and recycling of plastic' (95.2%); other solutions were considered desirable by a large part of the sample: 'improve water purification technology' (89.8%), 'use biodegradable plastic' (86.4%), 'ban the sale of plastic bags' (78.9%), 'make plastic products lighter to reduce their overall quantity' (77.5%), and 'offer free reusable bags' (73.7%).

Behavioural intentions and experience

72.9% of the sample say they 'rarely' or 'never' buy non-biodegradable plastic bags (*e.g.*, at the supermarket checkout), while the remainder do so 'sometimes', 'frequently' or 'all the time' (Fig. 4). The main reasons for buying concern the availability (70.6% do it because they forget reusable bags and 47.2% because they easily find them) or desirable features (52.8% because they are reusable, 42.9% because they are light, 35.7% because they are comfortable, and 21.5% because they are cheap). After buying and using plastic bags, 90.2% of respondents reuse them, 83.0% use them as garbage bags, and only 7.5% discard them immediately. 77.6% of respondents express their intention to change their fish

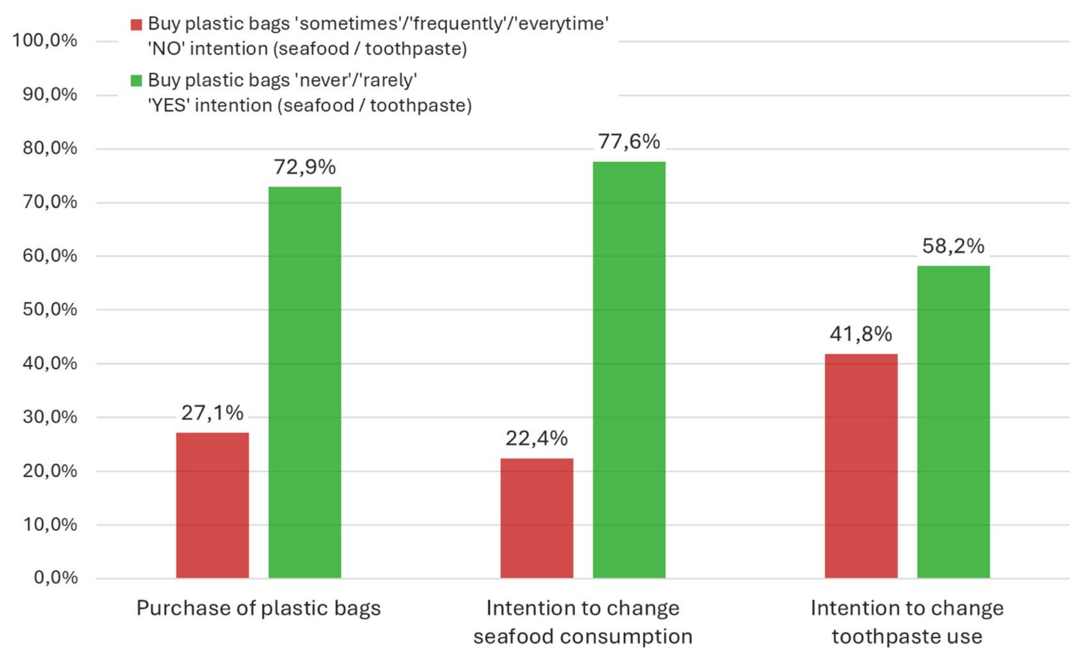

Fig. 4 Behaviours and intentions to change. The figure shows the frequency of behaviours experienced (buying a plastic bag) and the presence of intentions to change behaviours (use of toothpaste and consumption of fish/seafood).

or seafood consumption (no longer consuming them or reducing their consumption) if they learned that they contain MPs. The remainder (22.4%) would consume them as usual. A lower proportion (58.2%) would modify their toothpaste use if they learned that it contained MPs (*i.e.*, reducing use, no longer using it, or looking for alternatives, such as certified contaminant-free products or natural alternatives). The remainder (41.8%) would use it as usual (Fig. 4). No statistically significant differences were found between actual knowledge and the frequency of plastic bag purchases. Conversely, the actual knowledge score on the general toxicity of MPs and NPs (MN4) was significantly higher among those intending to change their consumption of fish and seafood than among non-intenders ($p < 0.05$, Wilcoxon's test). Similarly, scores for organ- and system-specific toxicity of MPs (MN5) and NPs (MN6) appear significantly higher for intentional *vs.* unintentional changes in toothpaste use ($p < 0.05$ in both cases). The actual knowledge about carcinogenicity risk from MP and NP exposure (MN7) resulted in significantly lower scores among both those intending to change fish and seafood consumption ($p < 0.05$) and those intending to change toothpaste use ($p < 0.05$), indicating the stronger but erroneous belief about the evidence, still inconclusive, that these contaminants cause cancer.

Risk perception

Respondents were asked to indicate which among six images depicting plastic material dispersed/in contact with environmental and food matrices concerned them more than the others (SI1): the highest proportion of preferences was for the image 'Animals entangled in plastic' (indicated by 37.5%) followed, in order of frequency, by: 'Ocean with plastic waste' (32.1%), 'Food with plastic' (10.8%), 'City with plastic waste' and 'Beach with plastic waste' (both indicated by 11.7%) and 'Park with plastic waste' (0.4%). 89.6% of the sample believed that MPs were already present in the human body, 8.3% were unsure, and only 1.3% did not. Table 2 shows the content and average scores of a Likert-scale measure of risk perception for MPs and NPs, inspired by psychometric models for assessing risk perception in the human health domain as proposed in previous studies.[15,20]

Only in one item belonging to the 'Knowledge perceived' factor, the mean score was above the central scale value (>3.00), that is 'Knowledge by Science' (3.07 ± 0.93); for all other items (controllability, familiarity, personal knowledge, and presence of knowledge), the mean scores were lower (<3.00). The items belonging to the 'Dread' factor all have mean scores above the central scale value: seriousness of harm, 3.64 ± 0.85; worry, 3.61 ± 0.95; likelihood of harm, 3.53 ± 0.85.

After evaluating the internal consistency (using Cronbach's alpha) and dimensional structure (using Exploratory Factor Analysis), eight of the ten items were grouped into two subscales corresponding to the dimensions 'Knowledge' (alpha = 0.70, acceptable) and 'Dread' (alpha = 0.82, good) from which the items related to the characteristic 'Newness' and 'Immediacy' were excluded since their inclusion lowered Cronbach's

Table 2 Characteristics of interest for the perceived risk related to MP and NP hazards. Mean scores and standard deviation for each item on an interval scale from 1 ('not at all') to 5 ('completely')[a]

Thinking about risks from MPs and NPs, choose the value that best corresponds to your opinion (interval scale from 1 = 'not at all' to 5 = 'completely')	Mean ± st. dev.
Is your health likely to be harmed by consuming food or water containing micro- or nanoplastics? (*D*-likelihood of harm)	3.53 ± 0.85
Do you think the damage to your health could be serious if you consumed food or water containing micro- or nanoplastics? (*D*-seriousness of harm)	3.64 ± 0.85
Are you concerned about the potential risks of consuming food or water containing micro- or nanoplastics? (*D*-worry)	3.61 ± 0.95
Do you think the health risks of microplastics/nanoplastics are natural and not artificial? (*D*-natural/mankind)	1.67 ± 1.12
Overall, do people have control over how exposed they are to this problem? (*K*-controllability)	1.81 ± 0.84
Do you think you know the health risks posed by micro- or nanoplastics? (*K*-familiarity)	2.20 ± 0.86
Do you think consumers are adequately aware of the health risks posed by micro- or nanoplastics? (*K*-knowledge: personal)	1.69 ± 0.82
Is it easy to know if the food you're about to eat or the water you're about to drink contains micro- or nanoplastic residues? (*K*-knowledge: presence)	1.76 ± 0.89
Do you think science is adequately aware of the health risks posed by microplastics/nanoplastics? (*K*-knowledge: science)	3.07 ± 0.93
In your opinion, is micro- or nanoplastic contamination a recent problem and, therefore, was not present in the past? (newness)	2.44 ± 1.13
In your opinion, would the potential harm to your health from micro- or nanoplastics be immediately apparent, meaning it wouldn't take long for them to become apparent? (immediacy of effect)	2.14 ± 1.06

[a] The prefix "*D*" indicates that the item belongs to the dimension "Dread" and '*K*' to the dimension "Knowledge perceived".

Table 3 Pattern matrix and single item factor loadings for the Likert scale on MP and NP risk perception obtained by EFA with the principal component factor method and varimax rotation

Items	Factor 1	Factor 2	Uniqueness
D-Likelihood of harm	**0.801**	0.057	0.356
D-Seriousness of harm	**0.900**	0.044	0.187
D-Worry	**0.815**	0.081	0.329
K-Controllability	−0.001	**0.727**	0.472
K-Familiarity	0.248	**0.690**	0.462
K-Knowledge of science	0.459	**0.438**	0.597
K-Personal knowledge	0.013	**0.757**	0.426
K-Presence of knowledge	0.068	**0.652**	0.571

alpha value below the limit of acceptability (alpha < 0.70).[32] Exploratory factor analysis (EFA) was performed using the principal component factor method and the application of orthogonal rotation with the varimax method of the initial factorial solution to allow for more precise interpretation.[33] The two dimensions that emerged correspond to the two principal components, both of which have an eigenvalue >1, and they collectively explain 57.5% of the variance, that is, of the information contained in the dataset. The interpretation of the factors was obtained by considering the so-called saturation matrix (Table 3), which reports the correlations between the original variables and the identified factors: factor 1 groups the variables according to the dimension of threat ('dread'), while factor 2 groups the variables related to the dimension of perceived knowledge of the danger ('knowledge'). The variable 'Knowledge by Science' was included in this second dimension even though the factor loading (equal to 0.438) is slightly lower than that associated with factor 2 (0.459) due to consistency with the literature that places this variable in the 'Knowledge' dimension[20] and considering that the difference between the two values is minimal (these items, therefore, do not appear as clearly classifiable concerning the two dimensions).

Based on the of factorial scores 1 ('dread', *D*) and 2 ('knowledge', *K*) reported by the respondents, the sample was classified into four groups as follows: Group 1, $D < 3.00$ and $K < 3.00$; Group 2, $D < 3.00$ and $K \geq 3.00$; Group 3, $D \geq 3.00$ and $K \geq 3.00$; Group 4, $D \geq 3.00$ and $K < 3.00$ (Fig. 5).

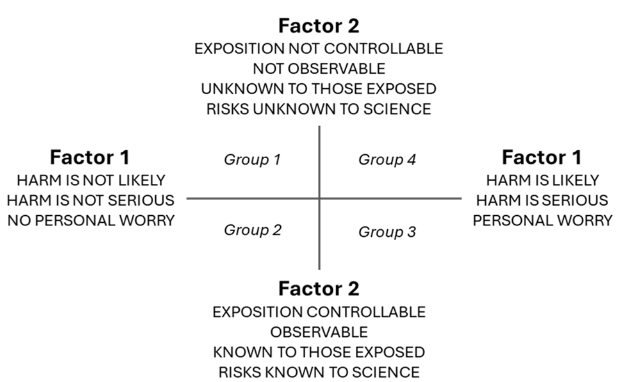

Fig. 5 Sample grouping according to Slovic P.[15] Classification of the sample based on factor 1 and factor 2 derived from factor analysis on the perceived risk scale about MP and NP hazards. Axes represent the interval scale from 1.00 (min) to 5.00 (max), intersecting at a 3.00 scale value.

78.4% of the respondents belong to Group 4, that is, they perceive the risk as a high threat component and are concerned that their knowledge of the hazard is poor. In other words, they think that microplastics and nanoplastics pose a threat and that knowledge about this hazard is scarce. The remainder of the sample belongs to Group 1 (12.8%; low perceived threat and knowledge of the hazard) and to Group 3 (8.8%; high perceived threat and knowledge of the hazard). Factorial scores calculated on a scale from 1 (lowest value) to 5 (highest value) for the 'Dread' component and the 'Knowledge perceived' component were placed in a Cartesian diagram, whose axes intersect at the point corresponding to the central scale value = 3.00 (Fig. 6 and 7), in analogy to literature studies on perceived risk analysis on human health and environmental hazards,[15] some referring to food.[34,35] The mean values referring to the total sample were 3.59 for the 'Dread' component and 2.11 for the 'Knowledge' component, indicating that the hazard investigated (MPs and NPs) is perceived as 'threatening and poorly known' overall, although the positioning on the interval scale is only slightly shifted to the middle value of the scale (3.00), thus far from the extremes. Stratifying the values by subgroups of the sample (Fig. 6), we find that the perception of threat is more pronounced for men (mean 'Dread' score = 3.62 *vs.* 3.58 in women, n.s. on Wilcoxon's test), for those with lower levels of education (3.66 for those with lower-to-middle *vs.* 3.56 for those with high degrees, n.s.) and for those older (3.71 in those with 50 years of age and older *vs.* 3.56 in those with less than 50 years of age, n.s.); inversely, the perceived lack of knowledge of hazard is more pronounced among women (2.06 *vs.* 2.22, n.s.), those with higher education (mean 'Knowledge' score = 2.03 *vs.* 2.24, $p < 0.01$) and younger people (2.05 *vs.* 2.36, $p < 0.01$).

Stratifying the factor scores by subgroups of the sample referring to behavioural intentions and experiences (Fig. 7), the perception of threat appears more pronounced among those who never or rarely buy plastic bags (mean 'dread' score = 3.61 *vs.* 3.51, n.s. on Wilcoxon's test), among those who manifest the intention to no longer consume possibly contaminated fish and seafood or reduce their consumption (3.68 *vs.* 3.29, $p < 0.01$) and among those who express the intention to stop using possibly contaminated toothpaste or reduce its consumption (2.18 *vs.* 2.02, $p < 0.01$); inversely, the perception of lack of knowledge of danger is slightly more pronounced among those who buy plastic bags more frequently (2.07 *vs.* 2.13, n.s.) and among those who do not intend to change their consumption of possibly contaminated fish and seafood (2.10 *vs.* 2.11, n.s.) and nor change their use of possibly contaminated toothpaste (2.02 *vs.* 2.18, n.s.).

Fig. 8 and Table S4-1 show the levels of information correctness possessed by the sample of respondents, stratified by the risk perception group. Group 4 reports higher scores more frequently than the others (six of the eleven scales). In comparison, Group 3 more frequently reports lower scores than the others (in seven of the eleven scales), although the only statistically significant difference in the overall comparison is

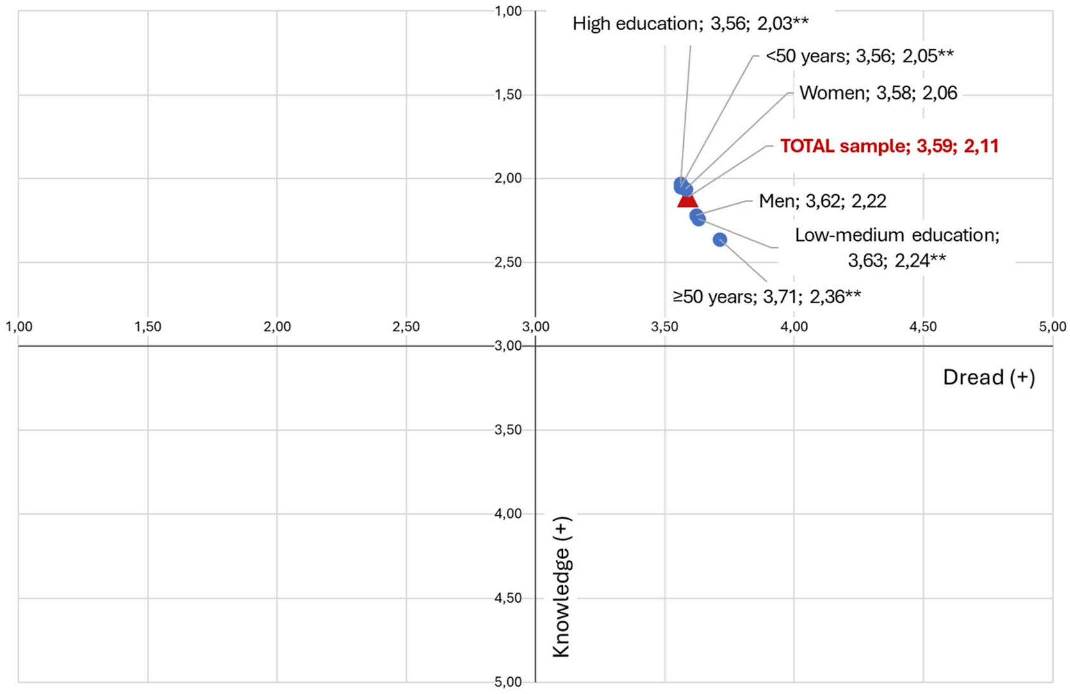

Fig. 6 Location of the overall sample and subsamples on factors 1 ('Dread') and 2 ('Knowledge') derived from factor analysis on perceived characteristics of MP and NP hazards. Average factor scores on a Cartesian diagram, the axis representing intervals' scale from 1 (min) to 5 (max). $^{**}p < 0.01$, Wilcoxon's rank-sum test.

found for the MN4 scale (absorption routes and general toxicity of MPs and NPs) for which Group 1 reported a mean value of 0.56 ± 0.29, Group 3 of 0.53 ± 0.39 and Group 4 of 0.68 ± 0.30 ($p < 0.05$ in the Kruskall–Wallis test). As reported in Table S4-1, some pairwise comparisons between the G1, G3, and G4 groups showed significant differences in Dunn's test with

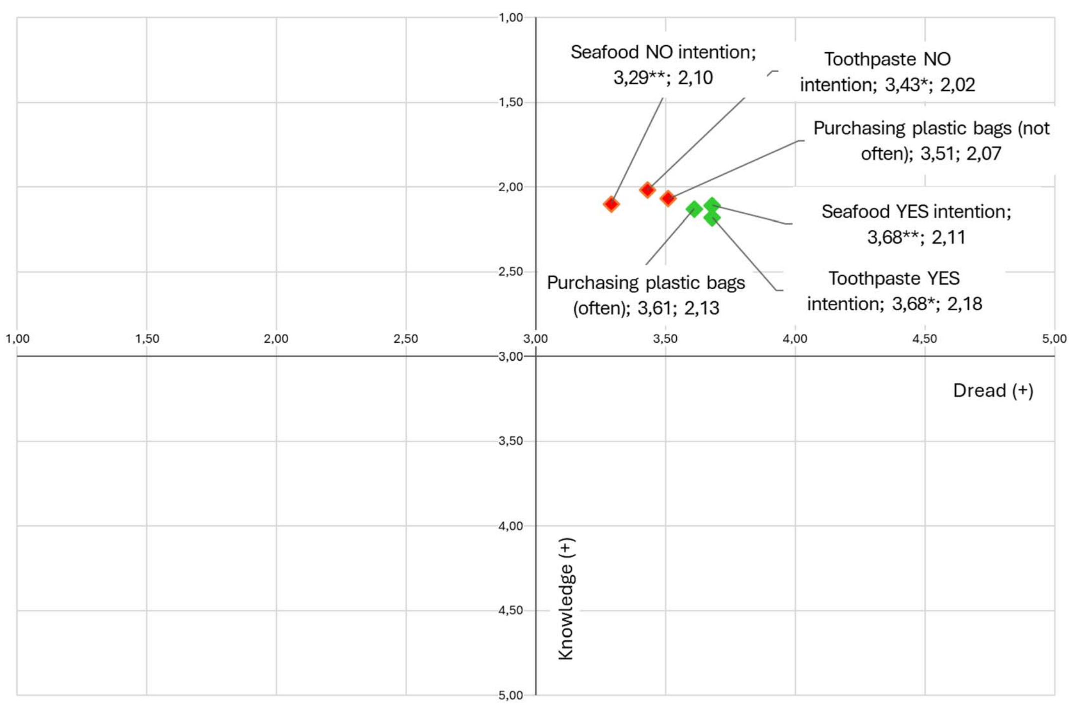

Fig. 7 Location of stratified subsamples on factors 1 ('Dread') and 2 ('Knowledge') derived from factor analysis on perceived characteristics of MP and NP hazards. Average factor scores on a Cartesian diagram of axes representing intervals' scale from 1 (min) to 5 (max). $^{*}p < 0.05$, $^{**}p < 0.01$ Wilcoxon's rank-sum test.

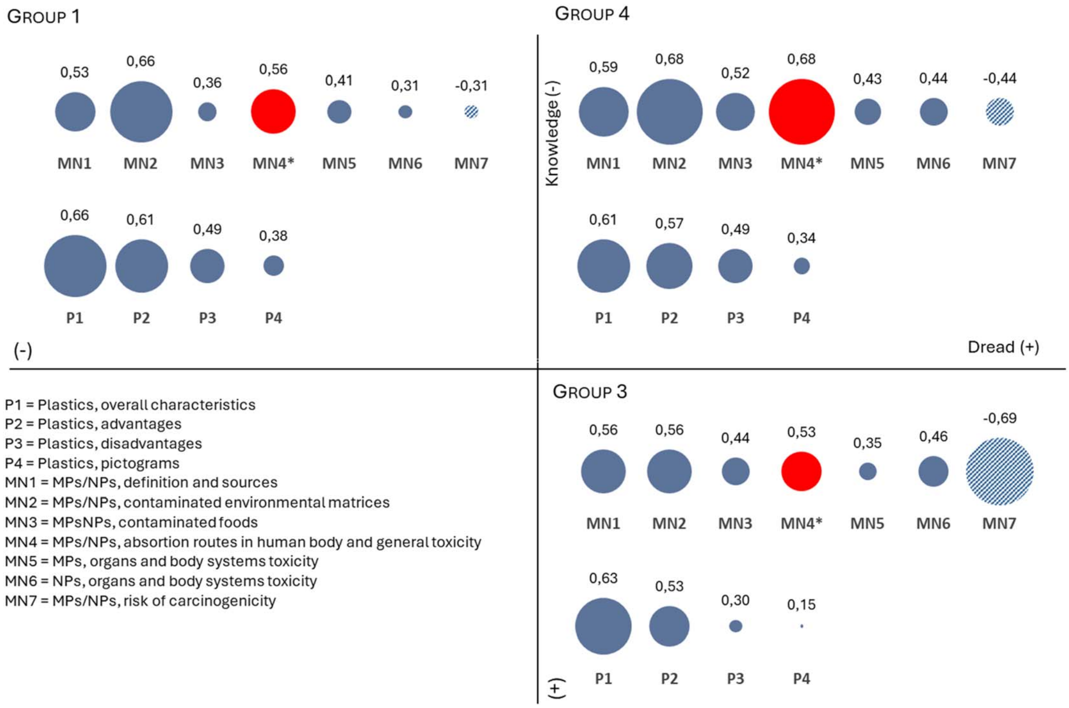

Fig. 8 Level of actual knowledge stratified by risk perception groups. Mean score values from −1 (min correctness) to +1 (max correctness) (*$p <$ 0.05 in the Kruskal–Wallis test).

Benjamini–Hochberg correction for P3, P4, MN3, MN4, MN6, and MN7. The effect size for the difference between the three groups was always 'small' ($0.01 \leq \eta_H^2 < 0.06$, SI4).

The proportion of the sample claiming to use 'often' specific channels of information on health and environmental issues was uneven across the three different risk perception groups

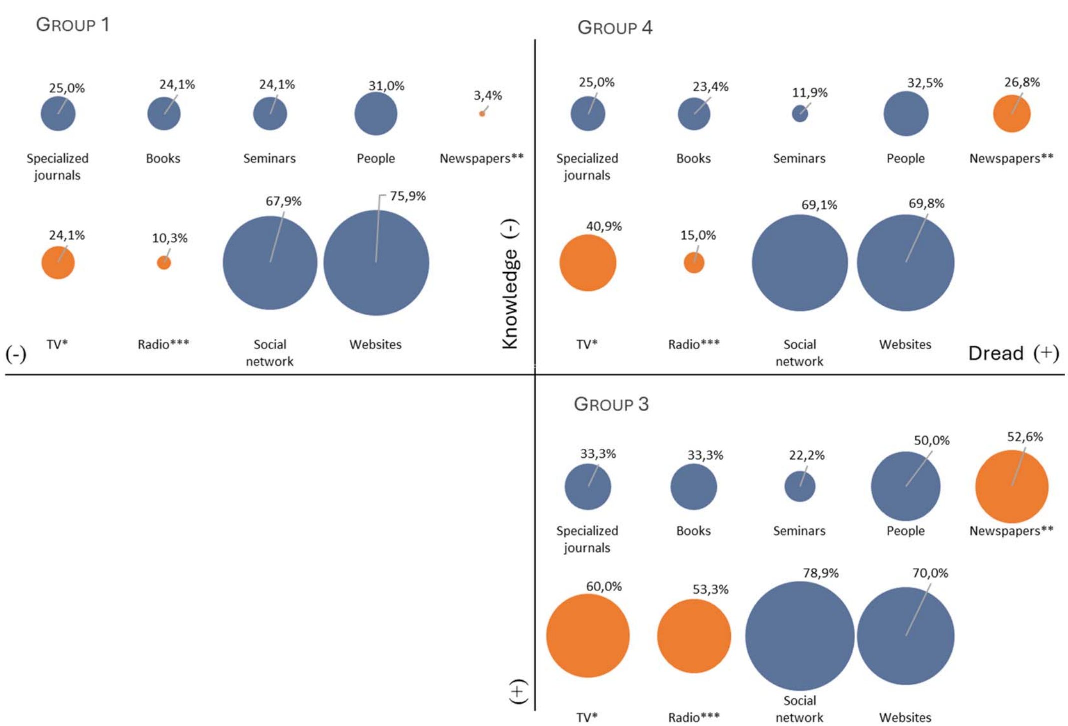

Fig. 9 Media and MP/NP risk perception. Use of different media to learn about health and environmental risks: % proportion of interviewed 'often' using each media, stratified by risk perception groups (*$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$ in Fisher's exact test).

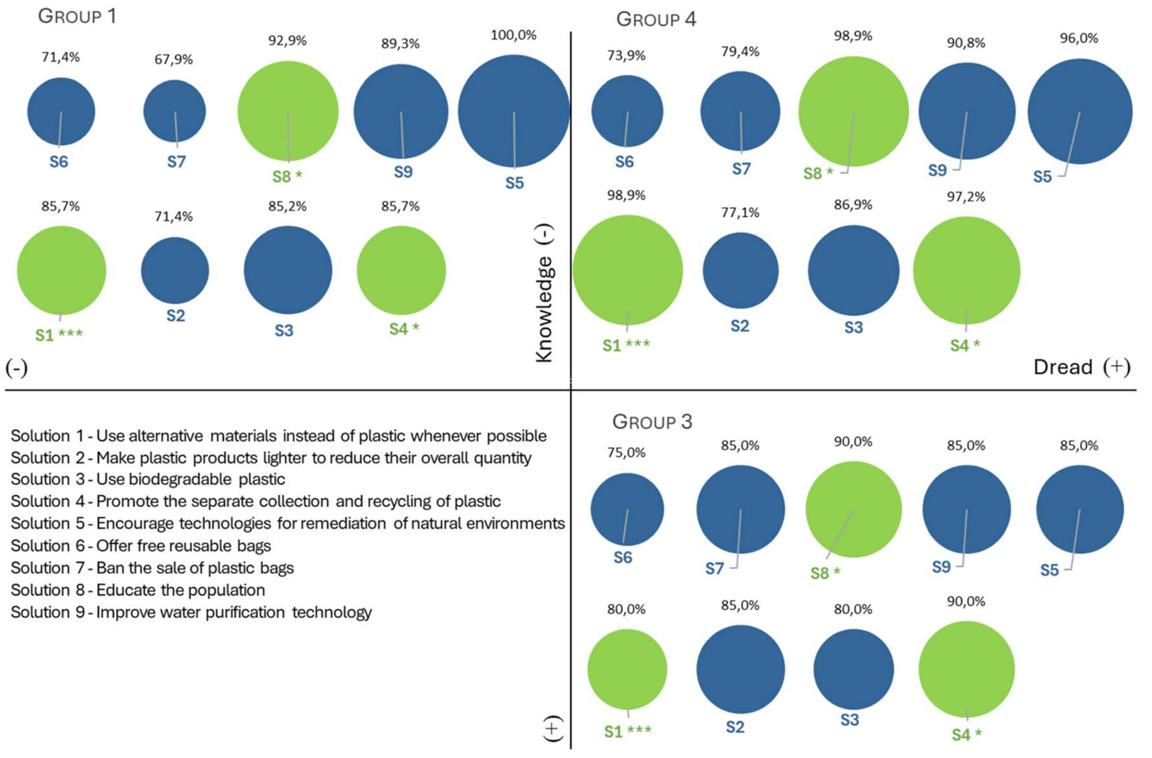

Fig. 10 Possible public strategy or technology solutions regarding plastics that the governments should adopt: % proportion of interviewed approving each solution ('YES' response option) stratified by risk perception groups (*p < 0.05 and ***p < 0.001 in Fisher's exact test).

(Fig. 9 and Table S4-2): within Group 3 (those with a high perception of threat but convinced that the hazard is known), the proportion of those claiming to use 'often' TV programs (60.0% *vs.* 24.1% in Group 1 and 40.9% in Group 4, $p < 0.05$ in Fisher's exact test) is significantly higher, as well as the proportion of radio program listeners (53.3% *vs.* 10.3% in Group 1 and 15.0% in Group 4, $p < 0.001$ in Fisher's exact test) and newspaper readers (52.6% *vs.* 3.4% in Group 3 and 26.8% in Group 4, $p < 0.01$ in Fisher's exact test) is higher. On the other hand, the use of social networks, Internet sites, specialised magazines/journals, books, conferences, and acquaintances' contacts appears to be more evenly distributed, with no statistically significant differences among the three groups. As reported in Table S4-2, the effect size for the difference between the three groups was always 'small' (0.10 ≤ Cramer's V < 0.30, SI4).

The proportion of the sample indicating different possible strategies or technological solutions that the governments should adopt is overall large but, in some cases, significantly different across the three different risk perception groups (Fig. 10 and Table S4-3): within Group 4 (those with a high perception of threat and convinced that the hazard isn't known), the proportion of those indicating 'the use of alternative materials' (98.9% *vs.* 85.7% in Group 1 and 80.0% in Group 3, $p < 0.001$ in Fisher's exact test with a 'medium' effect size Cramer's V = 0.315) is significantly higher, as well as the proportion indicating 'educate the people' (98.9% *vs.* 92.9% in Group 1 and 90.0% in Group 3, $p < 0.05$ in Fisher's exact test, small effect size Cramer's V = 0.187) and 'promote the separate collection and recycling of plastic' (97.2% *vs.* 85.7% in Group 1 and 90.0% in Group 3, $p < 0.05$ in Fisher's exact test, small effect size, Cramer's V = 0.189) is higher (SI4).

Discussion

This observational study aimed to evaluate the awareness, modes of information, and risk perception regarding health hazards from MP and NP exposure across environmental and food matrices, enrolling a sample of adult Italian general population. Overall, 16% of respondents had never heard of MPs and 34% had never heard of NPs; more than a third misunderstood the definitions. Similar findings emerged from a representative survey in Germany, which found that most of the sample (80%) knew the term 'microplastic'.[36] Conversely, in a study conducted in Shanghai, a higher proportion of participants showed poor knowledge of the issue: only 26% reported being informed about MPs.[21] Despite the study population being relatively young and highly educated, scarce actual knowledge was evident concerning some specific items such as the number and types of plastic; plastic bottle decomposition time; release of MPs and NPs from road sign paint, toothpaste, cosmetics, ship hull paint, tires on the road; contamination of 'unsuspected' matrices such as country air and uncultivated soil, fruits, grains, tap water, vegetables, and milk and dairy products. Moreover, insufficient information was reported regarding possible absorption through the skin and mucous membranes; specific potential toxic effects on animal organisms, such as hypercholesterolemia and cardiovascular diseases; overestimated carcinogenicity risk. These findings can be compared with similar results from research on students', environmentalists', and beauticians' beliefs about the presence of MPs in cosmetics: everyone knew about plastic pollution, but professionals were surprised to learn about the number of MPs and NPs in cosmetic products, which they described as unnatural and unnecessary. In that survey, Anderson *et al.* reported that all participants stated their intention to change behaviour by using products without MPs, suggesting that properly informing people is a valid solution to reduce plastic use.[37] Indeed, even in the present study, the intention to change behaviours, particularly fish/seafood consumption or toothpaste use, was significantly associated with some specific actual knowledge. However, the erroneous belief that MPs and NPs are definitively carcinogenic was also found to motivate changes in attitudes and behaviours, as well as in risk perception, even though their carcinogenicity has not yet been established.[38]

Oturai *et al.*[39] administered a questionnaire to 7- to 16-year-old children participating in the 'Mass Experiment', a Danish citizen science project on environmental topics related to plastics. The survey focused on three areas: plastic pollution, climate change, and biodiversity loss. Results showed that plastic pollution caused the greatest concern, while biodiversity loss caused the least. Despite this, the youngest children perceived loss of biodiversity as riskier, confirming the role of age in the risk perception of plastic pollution. Also, the educational background matters, as in the research on MP knowledge and awareness conducted among college students in Taiwan *via* online sampling. Almost all of them were aware of the issue, but science students answered more correctly than the other faculties, showing the importance of information in raising awareness and interest in a topic.[40] Among German students, most of the participants described MPs as dangerous, and none stated that plastics were not dangerous at all. Primary concerns were related to human health, and only secondarily to the environment. Interestingly, given the last statement, the impact on animals was greater than on humans.[41] A survey conducted on a representative sample of the adult Norwegian population found a similar picture since respondents mainly associated MP consequences on the environment rather than on personal life.[42] This evidence is in line with the present research, which used high-impact images of plastic pollution in the questionnaire: our results revealed greater concern about dispersion in the aquatic environment and the direct impact on animal species affected by waste ('ocean with plastic waste' and 'animals entangled in plastic'). This could indicate either a more 'environmentalist' rather than 'health-related' orientation/competence, or a more widespread belief that the impact on human health stems primarily from ocean pollution and animal-based food chains. Although our sample possesses a high level of expertise and cultural background, the problem of MPs is more frequently associated with environmental factors and strictly 'ecological' impacts (confirming the findings in the knowledge questions, namely, a lack of awareness that other sources can also directly impact plant-based food sources). Similarly, in the European survey by Filho *et al.*,[43] ocean pollution was perceived as 'extremely serious', while air and soil pollution were less concerning, a trend also confirmed by the number of scientific publications, which were very sparse compared to those on water ecosystems. In a survey conducted among farmers, a widespread concern was also identified regarding the use of plastic items in agriculture.[44] Interestingly, more than 80% of the sample was male, while it is usually proven that women tend to be more interested and collaborative in this type of study,[45] as in our survey. More than 70% of participants stated that the use of plastics in agricultural practices was increasing, describing it as dangerous to the environment and expressing concern. However, only 58% declared that they should recycle and correctly dispose of plastic waste. The study underscores the importance of distinguishing between concern, risk perception, and behaviour.[44] This observation is in line with our finding about the absence of association between the level of awareness about MP and NP hazards and the buying bag habits. Nevertheless, we found a statistical association between the risk-perception profile and opinions on solutions to be adopted at the public level (*i.e.* by governments): the group of participants perceiving MPs/NPs as threatening and poorly known offered a more favourable opinion about education initiatives targeting people, the use of alternative materials to plastics, and appropriate collection and recycling of plastics. In our survey, the MP/NP hazards are overall perceived as 'threatening and poorly understood', even though the scores are slightly off the central value of the Likert scale (3.00), thus far from the extremes. The stratifications highlight that the higher perceived lack of knowledge about the phenomenon (the 'knowledge' dimension of risk perception) is statistically associated with socio-demographic characteristics (higher among younger people and those with higher educational qualifications) but not with actual behaviours (purchasing plastic bags) or intentions to change behaviour (consumption of fish and seafood or use of contaminated toothpaste). Conversely, the perception of threat (the 'Dread' dimension of risk perception) is not statistically associated with socio-demographic variables, while it is significantly higher among those who would change their behaviour. Indeed, the research literature generally reports that younger people are more concerned about plastic pollution than older people and engage in more 'pro-environment' behaviour. Moreover, a higher academic level, with a focus on scientific backgrounds, correlates with greater consciousness. For example, to define the role of demographic characteristics related to 'plastic-issue' consciousness and behaviours, Miguel *et al.*[46] developed a questionnaire administered to Portuguese citizens. Only 47% of participants reported knowing the term 'microplastics' before taking the questionnaire. In addition, 18–25 year olds demonstrated a higher perception of the problem than those who were 61 years or older. Higher education was also associated with higher concern and consideration of recycling as pro-environmental behaviour.[46] Moreover, in a study involving sixteen European countries, based on an online survey, almost 64% of participants reported using plastic items daily, of which 61% were employed in packaging. Women and 18 to 25 year olds were more active in reducing their use of plastic objects. In addition, higher education levels were associated with higher knowledge of terms such as 'bioplastics', 'biodegradable' and 'bio-based'.[43] In addition, perceived threat appeared as one of the most important mediators of people's attitudes and intention towards preventing microplastic pollution.[47] Analysing the differences between risk perception groups based on information obtained, it appears that those with higher levels of perceived threat (dread) and belief that the danger is poorly understood (knowledge perceived) have more accurate actual information (although the only scale for which this difference is statistically significant concerns exposure routes and general toxicity of MPs/NPs). This is consistent with the hypothesis that the more the actual information, the greater the perceived risk. The importance of an effective information strategy has been further demonstrated, *e.g.*, by comparing answers to questions on marine litter from 7 to 17 year old students before and after attending a course on the topic. The authors observed that students increased their concern about the topic and gave more precise and correct answers following the educational project.[44] As found by other authors, at this age, the primary source of information is school, more than social media.[48] Moreover, the importance of actual knowledge as an antecedent affecting risk perception of ocean MP pollution has been demonstrated by Yoon and colleagues, who also found that perceived risk has a positive impact on environmental behaviour intention.[25] In our findings, the use of different channels for information on health and environmental topics differs significantly by age group and education level: older and less educated people mainly used TV programs, while social networks were primarily used by younger adults and moderately by older ones. Radio and newspapers were, on average, less frequently used sources for this type of content; however, they were used more by older people. For some specific content, a significantly higher level of knowledge was found among those who frequently read newspapers and specialised magazines, among those who attended conferences, and among those who get information from social networks, particularly on organ and system toxicity. Interestingly, a reverse finding emerged: a higher error rate regarding the presumed, but not yet definitive, evidence of the carcinogenicity of MPs and NPs among those relying on TV, radio, and newspapers as their information sources. This result could be explained by the lower accuracy and depth of information acquired from 'generalist' channels, which are quick to access and offer little opportunity for reflection. These findings confirm results from other research papers on the emphasis in media communication on the harmful effects of MPs not aligning with scientific evidence[49] and the need for accurate and balanced media report on MPs.[50] Among information channels, TV, radio, and newspapers are statistically more frequent in risk perception Group 3, *i.e.*, those with a high perception of threat but are convinced the danger is known; there are no differences compared to other channels, particularly social networks. Kramm and colleagues[36] highlighted the importance of media narratives, as respondents who have heard negative media narratives about microplastics are more likely to have a higher risk perception than those who have not, and this would influence the association between age, gender and risk perception.[36]

Strengths and limitations

MP and NP contamination of environmental and food matrices is of growing interest, and public awareness is crucial to reducing exposure to health risks and worsening pollution. The questionnaire we used was therefore developed based on numerous studies in the literature on the social dimensions and sources of information regarding the toxicity hazards and the environmental impact of the spread of MPs and NPs as explained in the Methods section. One of the main strengths of the present research is the scientific approach to assessing the subjective judgment of the threat of exposure to MPs and NPs (risk perception measure). Structured research on psychometric paradigms for risk characterisation includes a 'dread' component and a 'knowledge' component, although the labels may vary slightly across studies[15,20,34,35] The scientific interest is understanding which of these two components contributes more to risk perception. For example, the conviction that knowledge of 'new' hazards is lacking can lead them to be perceived as riskier (*e.g.*, genetic modifications), but they become more familiar over time. Being aware of the characteristics of risk perception that determine it will allow for more efficient risk management and improved risk communication. For example, suppose we know that a well-known hazard is perceived as so distressing and threatening that even communication could not reduce the risk perception. In that case, a manager might decide to delay the approval of a substance, product, or method to avoid losing consumer trust ('dread' component). Or, in another case, if a danger is perceived as risky but little known, a communicator might adopt a strategy to increase information by specifying the benefits or harm avoidance. Limitations must be noted regarding the non-randomised sampling method: 'river sampling' enrolment refers to researchers immersing themselves in the traffic flow of the web network, capturing some of the passing users. This approach could be affected by selection bias: people without internet access cannot participate, or the more people are interested in environmental and health protection topics, the more likely they are to participate in the survey. Nevertheless, this recent digital practice has been recognised as a valuable research tool in exploratory studies,[19] given that 91.9% of citizens had internet access at home in Italy[51] and that online surveys are more socially desirable than telephone or face-to-face interviews.[52] Because of enrolment bias, the sample was unevenly distributed across Italy, with an apparent disproportion between residents of the South and the Islands, who are in greater numbers (particularly in the Abruzzo region) than in other areas, probably due to social network connections activated at the local level. Another possible selection bias is the sample's characterisation as having a high socio-cultural level since it is predominantly female (females : men ratio = 2.14 : 1), young (36 years on average), highly educated, comprised more than 30% of students and with a high proportion being employed in the education and academic sectors. However, this feature could suggest an even lower level of awareness/sensitivity in a better-balanced population sample, with the right proportion of people from socioeconomically disadvantaged groups. Moreover, the small sample size could reduce statistical power, and the poor homogeneity prevented the application of multivariate statistical analysis. Finally, the present study is not longitudinal, and no causal inferences can be made, particularly regarding psychological mechanisms or motivations that were not directly measured.

Conclusions

Despite its limitations, our study suggests that environmental health literacy is a potential determinant of risk perception and behavioural change in the general population, specifically regarding plastic personal management and personal health protection. The primary implications of our findings for public health policies are: (1) the need for a systemic and scientifically based risk communication strategy, involving different media and intentional targeting of different recipients; (2) the content focused connection between the impact on the environment of plastic pollution and MP and NP distribution; (3) the enhancement of threat and fear-inducing messages on human health hazards strongly associated with intention of behaviour change; (4) consistent practical suggestions for adopting good practices on a real life dimension aimed at protecting own and public health.

Author contributions

Maria Scatigna: conceptualisation, data curation, formal analysis, methodology, resources, software, validation, writing – original draft (Methods, Results and Discussion), writing – review and editing. Massimo Alosi: conceptualisation, investigation, visualisation, writing – original draft (Introduction and Discussion), writing – review and editing. Anna Maria Giuseppina Poma: conceptualisation, project administration, supervision, writing – original draft (Conclusions), writing – review and editing.

Conflicts of interest

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

Data availability

Data are located in controlled-access data storage at the University of L'Aquila.

Supplementary information (SI) is available. See DOI: https://doi.org/10.1039/d5va00376h.

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