

Microplastic and microfibre pollution in confined aquifers: insights from Italy

Original

Microplastic and microfibre pollution in confined aquifers: insights from Italy / Balestra, V., Valle, M., Bellopede, R., Fiorucci, A.. - In: ENVIRONMENTAL RESEARCH. - ISSN 0013-9351. - 300:(2026). [10.1016/j.envres.2026.124416]

Availability:

This version is available at: 11583/3016418 since: 2026-10-07T20:04:34Z

Publisher:

Elsevier

Published

DOI:10.1016/j.envres.2026.124416

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)



Microplastic and microfibre pollution in confined aquifers: insights from Italy

Valentina Balestra^{a,b,*}, Matteo Valle^b, Rossana Bellopede^b, Adriano Fiorucci^b

^a Department of Agricultural, Forest and Food Sciences, University of Turin, Largo Paolo Braccini 2, Grugliasco, 10095 (TO), Italy

^b Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

ARTICLE INFO

Keywords:

Microplastics
Microfibres
Confined aquifers
Water pollution
Groundwaters
Anthropogenic microparticles

ABSTRACT

Groundwaters are essential resources for environment and societies, especially for its use in agriculture and as drinking water. Growing evidence suggests that microplastics (MPs) accumulate in soil and infiltrate in groundwaters, ranging from 0.1 to thousands items/L. However, groundwaters research regarding MPs are lacking, especially in confined aquifers, and microfibre (MF) studies are at the early stages. Aquifer waters are often used for human consumption, however, even confined aquifers are not immune to seepage, especially where geology is complex or human activity modified natural stratigraphy. These aquifers are particularly vulnerable to pollution, as their limited exchange and slow flow rates can favor long-term accumulation. This study investigated anthropogenic microparticles (AMPs), such as MPs and MFs, in 25 confined aquifers of the NW Italy. AMPs were found in all sampling points, (mean and SD of 90.0 ± 64.3 AMPs/L) however, only 2.1% were synthetic. MPs were found in 13 aquifers, ranging from 0 to 6.3 MP/L (mean and SD of 1.9 ± 2 MP/L). Vinyl compounds and copolymers were the main types of MPs found, followed by polyesters, and other synthetics. Fibres represented major part of the AMPs (95.2%) followed by fragments (4.6%), however, MP were especially fragments (72.0%). Big particles (5-1 mm) accounted for only 17.3%, highlighting the increase of micro-pollutants with the decrease in the size considered. Possible sources of pollution could be linked to nearby human activities, especially agricultural ones, and water intakes, providing useful references for further research. Given the susceptibility of groundwater resources to contamination, anthropogenic stressors, and climate variability, alongside their essential ecological functions and significance as a primary source of potable water, it is imperative to implement strategies focused on subsurface environment protection and sustainable management of water resources. Consequently, MP and MF investigations are required to elucidate groundwater system dynamics, evaluate environmental health conditions, and identify potential sources.

1. Introduction

Microplastics (MPs) contaminate terrestrial and aquatic ecosystems on a global scale. The concept of MP was first proposed by Thompson et al. (2004), who described it as plastic debris with a maximum size of 5 mm, originating from the breakage of plastic objects or from small intentionally manufactured plastic materials. This initial definition has subsequently been refined by various scientific institutions and environmental organizations, with variations depending on the intended scope. More recently, it has been extending to include semi-synthetic and chemically modified natural polymers too (European Commission, 2024), and specific definition has also been introduced for fibres (International Organisation for Standardisation, 2023). Consequently, MP

definition remains under active debate.

The intrinsic characteristics of plastics contribute to their persistence and widespread distribution in natural ecosystems. The small size of MPs and their morphological characteristics further increase their harmfulness and mobility, allowing them to be dispersed across long distances through atmospheric, terrestrial, and aquatic pathways (Allen et al., 2019; Liu et al., 2019b). MPs can be assimilated by organisms via direct ingestion or indirectly, such as through trophic transfer, exhibiting toxic, oxidative, and inflammatory effects, showing a growing ecological and public health challenge (Assas et al., 2020; Devereux et al., 2021; Jahan et al., 2019; Romeo et al., 2015; Wright et al., 2013), while investigations on the effects of biodegradable plastics only recently has begun (Malafeev et al., 2023). Increasing evidence confirmed the

* Corresponding author. Department of Agricultural, Forest and Food Sciences, University of Turin, Largo Paolo Braccini 2, Grugliasco, 10095 (TO), Italy.
E-mail address: valentina.balestra@unito.it (V. Balestra).

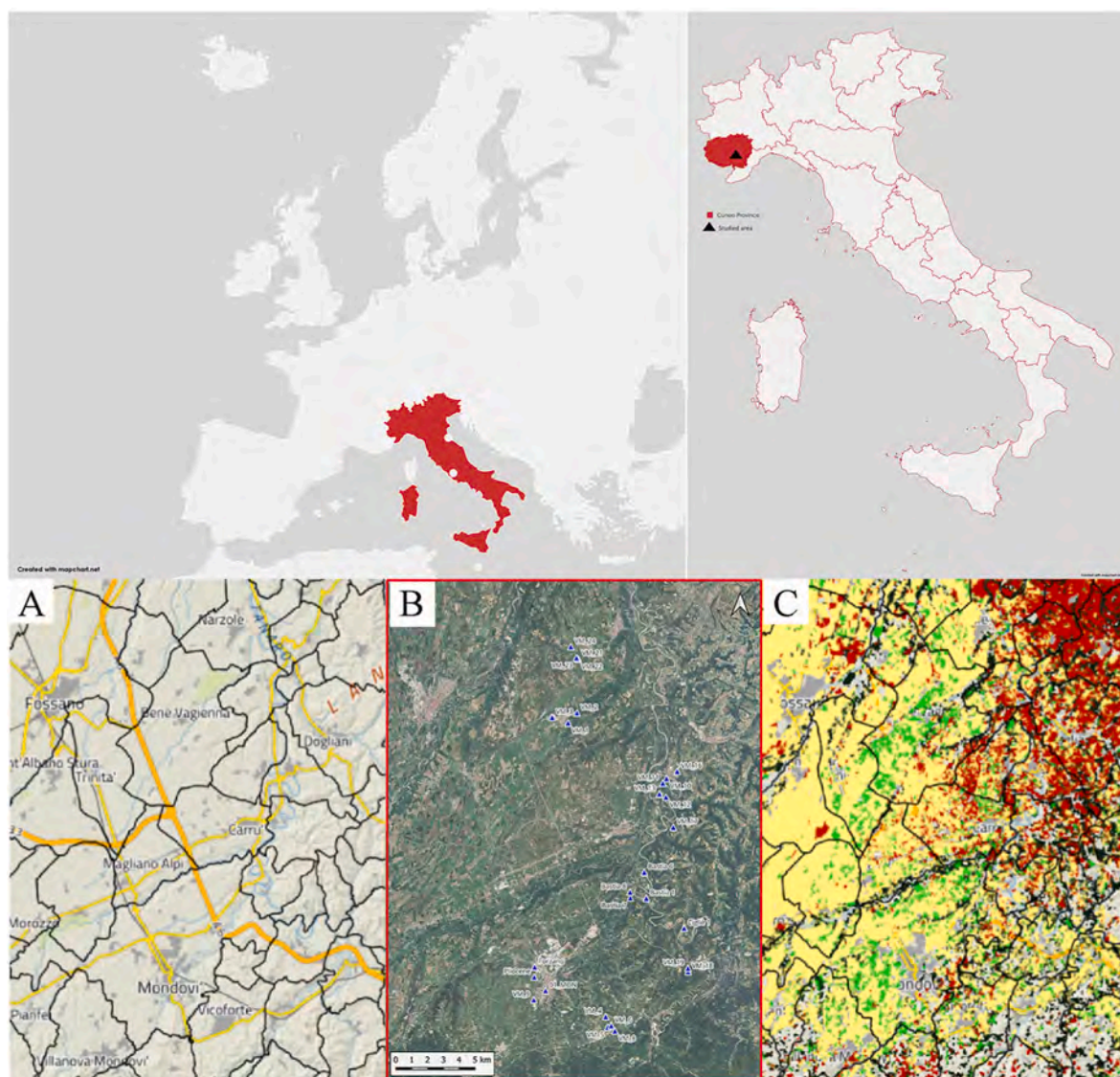


Fig. 1. Sampling points for water analyses in deep aquifers in Piedmont, Italy. At the top left: Italy; at the top right: study area in Cuneo province, Piedmont (maps from mapchart.net/italy, modified); below: characteristic of the studied area. Specifically, A: map of the municipalities (map from <https://www.geoportale.piemonte.it/visregpigo/>, accessed 24-02-2026 h 21:00, modified); B: sampling points and aquifers (map from <https://earth.google.com/>, Imagery ©2025 NASA, map data ©2025 Google, modified); C: map of the land use (map from <https://www.geoportale.piemonte.it/visregpigo/>, accessed 24-02-2026 h 21:00, modified). Legend: yellow: arable crops, red: permanent crops, green: permanent grassland, black: woodland and wood arboriculture, grey: other surface).

occurrence of MPs within human body, raising serious concerns regarding their potential adverse health effects too (Barceló et al., 2023; Cox et al., 2019; Kannan and Vimalkumar, 2021). Moreover, MPs can act as carriers or sinks for a wide range of pollutants, including pesticides, bisphenol A (BPA), persistent organic pollutants (POPs), heavy metals, and pharmaceutical compounds such as antibiotics (Cheng et al., 2023; Li et al., 2018; Liu et al., 2019c; Martín-Gómez et al., 2024; Rochman et al., 2013; Selvam et al., 2021; Wanner, 2021; Zhou et al., 2019). This contaminant-binding capacity substantially heightens the ecological and health risks associated with their environmental persistence.

Microfibres (MFs) are natural, regenerated (or man-made cellulosic, or artificial), and synthetic fibres of threadlike structure with diameter less than 50 µm, length ranging from 1 µm to 5 mm, and length to diameter ratio greater than 100 (Liu et al., 2019a), however, the definition is even more debated, depending especially on the field of application (textile industry, engineering, environmental pollution, etc.) (Okoyere et al., 2025). Over the past decade, MFs have emerged as a new class of pollutants of global concern, representing the most prevalent

form of MPs detected in the environment (Miller et al., 2017). Natural and regenerated MFs have been counted in MPs monitoring studies in the past, even if they weren't plastic, due to their colour, industrial processing, and additives (Obbard et al., 2014; Woodall et al., 2014), increasing MP concentrations (Wesch et al., 2016). However, even today it is not clear whether they can and should be included in the definition of MPs or not.

MFs originated from different anthropogenic sources, including textile production and use throughout their entire life cycle, cigarette filters, personal care products, and other manufactured fibrous products (Athey and Erdle, 2022; Liu et al., 2019a). As MPs, MFs can come from original natural or synthetic fibres intentionally manufactured and directly used within the textile and apparel industry without subsequent structural modification, or be the result of degradation of larger fibrous materials, occurring during processes such as textile manufacturing, product use, laundering, or disposal (Liu et al., 2019a). MFs have been found in different natural environments (Balestra et al., 2024a; Finnegan et al., 2022; Hasenmueller et al., 2023; Stanton et al., 2019; Suaria et al., 2020a, 2020b), as well as in animal (Le Guen et al., 2020; Remy et al.,

Table 1

Sampling point information. BA: bicarbonate-alkaline, BAC: bicarbonate-alkaline-calcium, BACM: bicarbonate-alkaline-calcium-magnesian, BAM: bicarbonate-alkaline-magnesian, BC: bicarbonate-calcium, BCA: bicarbonate-chloride-alkaline, BCM: bicarbonate-calcium-magnesian, BMC: bicarbonate-magnesian-calcium, SC: sulphate-calcium, SCM: sulphate-calcium-magnesian, SM: sulphate-magnesian.

Sample ID	Municipality	Date of sampling	Aquifer deep (m)	Year of construction of the water intake	Information	Altitude (m a.s.l.)	Main Facies	Sub-facies or Secondary Facies
VM1	Benevagienna	13/08/2024	80-90	90's	Irrigated agricultural well. Water taken from a PVC tank. Some pipe sections are in PE.	351	BC	SM
VM2	Benevagienna	13/08/2024	200	-	Water taken from a tank. Stainless steel pipe and autoclave.	320	BA	
VM3	Benevagienna	13/08/2024	170	70's	Water taken from a tank. Some pipe sections are in PE.	352	SC	BAM
VM4	Vicoforte di Mondovì	27/08/2024	>100	-	Not artesian well.	578	BAC	SM
VM5	Vicoforte di Mondovì	27/08/2024	198	-	70 m deep pump. Galvanized iron pipe. Some pipe sections are in PE.	542	BCM	
VM6	Vicoforte di Mondovì	27/08/2024	120	-	The well is salient and could even be artesian albeit with very modest flow rates. Some pipe sections are in PE.	524	BCM	
VM8	Vicoforte di Mondovì	27/08/2024	106	-	Artesian well, sample taken with pump on. Clean water.	523	BCM	
VM9	Mondovì	27/08/2024	180	-	Deep well used for garden irrigation. Very clean water. Some pipe sections are in PE.	440	BCM	
VM10	Farigliano	27/08/2024	200	50's	Artesian well. Fountain in the garden of a house.	247	BA	
VM11	Farigliano	27/08/2024	200	50's	The well is no longer artesian but is still fed by a highly pressurized aquifer. Sample taken from the sink of a private individual's kitchen	264	BA	
VM12	Farigliano	27/08/2024	200	40-50's	The well is no longer artesian but is still fed by a highly pressurized aquifer. Sample taken from the sink of a private garden	267	BA	
VM13	Farigliano	27/08/2024	200	40-50's	Artesian well. Sample taken directly from the pipe.	258	BA	
VM16	Farigliano	19/09/2024	150	50's	Aqueduct well	307	BA	
VM17	Clavesana	19/09/2024	120	-	Aqueduct well	387	BACM	
VM18	Niella Tanaro	19/09/2024	130	-	Aqueduct well	476	BAM	SC
VM19	Niella Tanaro	19/09/2024	130	-	Aqueduct well	453	BCM	
VM21	Benevagienna	31/10/2024	150	-	Aqueduct well	338	BA	SCM
VM22	Benevagienna	31/10/2024	150	-	Aqueduct well	338	BA	SCM
VM23	Benevagienna	31/10/2024	150	-	Aqueduct well	337	BAC	SM
VM24	Narzole	31/10/2024	150	-	Aqueduct well	334	BA	SCM
Bastia 1	Bastia Mondovì	04/08/2025	180-200	After the Second World War	Artesian well. Sample taken from a fountain in a private yard in the center of the village. Metal pipe.	297	BA	
Cigliè 1	Cigliè	04/08/2025	250	After the Second World War	Artesian well. Metal pipe	313	BCA	
Bastia 6	Bastia Mondovì	04/08/2025	180-200	After the Second World War	Artesian well. Sample taken from a fountain in a private garden. Metal pipe.	283	BA	
Bastia 7	Bastia Mondovì	04/08/2025	180	After the Second World War	Artesian well. Sample taken from a fountain near a road. Metal pipe.	293	BCA	
Bastia 8	Bastia Mondovì	04/08/2025	214	After the Second World War	Artesian well. Sample taken from a fountain near a house. Metal pipe.	297	BCA	

2015; Sforzi et al., 2024; Zhao et al., 2016) and human organs (Pauly et al., 1998; Taptiklis et al., 2025), documenting adverse effects on animal health (Jemec et al., 2016; Watts et al., 2015). Recent investigations highlighted potential concerns specifically regarding both natural and regenerated MFs (Athey and Erdle, 2022; Dris et al., 2016; Finnegan et al., 2022; Hasenmueller et al., 2023; Stanton et al., 2019; Taptiklis et al., 2025), being even an accessible source of carbon for microorganisms (Zambrano et al., 2019).

MPs, MFs, and other natural or regenerated materials of anthropogenic origin ranging from 5 mm to 1 µm which occur in other shapes are collectively encompassed under the single definition of anthropogenic microparticles (AMPs). in environmental studies (e.g. Balestra et al., 2024c; Hasenmueller et al., 2023). A prevalence of natural and

regenerated AMPs into the environment compared to synthetic ones was shown in previous studies (e.g. Balestra and Bellopede, 2025; Balestra et al., 2024a; Stanton et al., 2019). The same was highlighted in different research on animals (e.g. Remy et al., 2015; Zhao et al., 2016), suggesting a potential toxicological risk to ecosystems and species similar to MPs, owing to the dyes, additives, and other chemicals incorporated during production (Athey and Erdle, 2022; Kim et al., 2021a; Lusher et al., 2013).

Groundwaters are vital resources for environment and societies, especially as potable water and support in agricultural areas (Famiglietti, 2014; Saccò et al., 2024). Growing evidence suggests that MPs infiltrate and accumulate in groundwaters, ranging from 0.1 to thousands items/L (Carpanez et al., 2025; Hoang et al., 2025; Jin et al.,

2025; Re, 2019; Sumam et al., 2025). However, groundwaters are poorly studied, especially confined aquifers (Severini et al., 2022).

MPs may enter through recharge zones, preferential flow paths, or via leakage from overlying contaminated strata (Hoang et al., 2025; Sumam et al., 2025). Once introduced, MPs can be transported through interconnected pore spaces or fractures, depending on their size and characteristics (Hoang et al., 2025; Sumam et al., 2025). Into the aquifers, MPs may undergo colonization and aging (Chen et al., 2023), becoming carriers of pollutants such as heavy metals and organic microcontaminants (Kumar et al., 2025; Ren et al., 2021; Saha et al., 2025), and degrading into smaller items or nanoplastics. Owing to their low flow velocity and the prolonged residence time of groundwater, MPs may persist within aquifers for extended periods. The hydro chemical properties of groundwater are key factors governing the distribution, abundance, and mobility of MPs (Hoang et al., 2025; Sumam et al., 2025).

Deep waters and confined aquifers are often used for human consumption, therefore, MP pollution can raise concerns for water quality (He et al., 2025), as conventional filtration systems may not remove them.

Confined aquifers are groundwater reservoirs bounded above and below by low-permeability layers, which isolate them from direct surface influence (Margat and Van der Gun, 2013). Water within these systems is under hydrostatic pressure, often exceeding atmospheric levels. When a well penetrates such an aquifer, the internal pressure may cause water to rise naturally, and, in some cases, to flow freely at the surface, forming artesian wells (Maliva, 2016). These artesian conditions result from recharge occurring at higher elevations, where the permeable layer is exposed. Even though confined waters are often very old and protected, they are not immune to seepage (Zhao et al., 2026), especially where geology is complex or human activity modified natural stratigraphy. Confined and artesian aquifers are particularly vulnerable to persistent contaminants, as their limited exchange and slow flow rates can favor long-term accumulation (Chen et al., 2023).

Checking the reviews, at the moment, a very small number of papers analyzed MPs in groundwaters, however, cave waters were not usually added in these works, even if they are groundwaters. Specifically, confined aquifers remain even less investigated worldwide in the context of MPs (e.g. Chen et al., 2023; Severini et al., 2022). Therefore, monitoring confined aquifers became essential.

Given the susceptibility of groundwater resources to contamination, anthropogenic stressors, and climate variability, alongside their essential ecological functions and significance as a primary source of potable water, it is imperative to implement strategies focused on subsurface environment protection and sustainable management of water resources (Balestra et al., 2023; Re, 2019). Consequently, systematic investigations are required to elucidate groundwater system dynamics, evaluate environmental health conditions, and identify potential pollutants and their sources.

The aims of this study are therefore i) to investigate, for the first time, AMP pollution, including MPs and MFs, in Italian confined and artesian aquifers, ii) if present, to discuss abundances and characteristic of AMPs in these waters, iii) to verify possible correlations between AMP abundances and aquifers' depth, water chemical-physical parameters, main ions and metals, iv) to analyze possible source of pollution.

2. Materials & method

2.1. Study area

All samples were collected in the Cuneo province, Piedmont Region, NW Italy (Fig. 1).

In this area, below the Quaternary alluvial cover and in the hilly areas, various aquifer systems have been identified in the sedimentary successions of Plio-Pleistocene and Oligo-Miocene origin. Deep aquifers of these successions show a distinct geochemistry and, generally, lower

permeability respect to surface quaternary aquifers. Permeability is variable and generally between 10^{-4} and 10^{-7} m/s, depending on the lithological composition and the cracking degree of the rocks.

These aquifers are mainly present in two macro-areas with different hydrogeological and structural characteristics: Langhe and Monregalese (Monregalese and Cebano hills included), and Roero, where aquifers are often intercepted in the plain via deep wells, for drinking water, irrigation and industrial uses (Civita et al., 2011).

Different geochemical facies and associated water quality were identified in this area (Valle, 2025). Identified facies and sub-facies related to our sampling points were reported in Table 1.

2.2. Field sampling

Twenty-five water samples were collected in 25 different deep aquifers in the Cuneo province, Italy. The main information relating to the sampling and sampling points were shown in Table 1.

Water bulk samples (Hidalgo-Ruz et al., 2012) were collected with nitrile gloves and glass jars pre-cleaned with bi-filtered EMSURE ethanol absolute (Supelco, Sigma-Aldrich) and MilliQ water. Water was sampled directly from the mouth of the water intakes, therefore, blank control during sampling was not carried out. Pressurized water continuously discharged from the pipe. The containers were opened immediately adjacent to the pipe outlet, allowing direct and instantaneous collection of the flowing water, and were closed as soon as filling was completed. The container opening had a diameter comparable to that of the water jet, and filling occurred within a few seconds; therefore, the probability of external contamination can be considered negligible. Once sampled, glass jars were immediately closed with the cap. Samples were refrigerated at 6 °C until analysis in the laboratory.

2.3. Laboratory analysis

2.3.1. Contamination control in the laboratory

Throughout all procedures researchers wore nitrile gloves and cotton white lab coats. All sampling materials were pre-cleaned with bi-filtered ethanol and MilliQ water to avoid contamination, as well as all surfaces and tools used during laboratory analysis. Plastic tools were replaced with glass or metal alternatives, where possible. To prevent contamination during all laboratory activities, open containers, lab glassware, and equipment were covered with aluminum foil. All analyses were conducted within a fume hood.

The 30% H_2O_2 (Merck), absolute ethanol (VWR Chemicals and EMSURE Supelco Merck), and MilliQ water were filtered twice through a 1.2 μ m glass fiber filter (Enrico Bruno srl) to assess potential AMPs contamination from the chemicals and water used.

Blank control on air was performed using one open pre-cleaned petri dish during the laboratory analysis. Once the analysis was completed, the petri was washed with bi-filtered MilliQ water and filtered using the same procedure as the other samples.

The blank correction method applied for airborne contamination in this study assesses the results of unknown samples by subtracting the blank contribution (Shruti and Kutralam-Muniasamy, 2023 and references therein). This method is common and easy to use in MP analyses, however, it only allows for the correction of data about abundances, without the ability to distinguish between particles related to contamination and those originally present in the sample.

2.3.2. Methodology

The investigated particles (AMPs) were defined as those ranging in size from 5 mm to 1 μ m and composed partially or entirely of synthetic, semi-synthetic and chemically modified natural polymers. Within the definition of MP, only fully synthetic materials were considered. However, owing to the available instrumentation, this research specifically examined the size fraction between 5 and 0.1 mm. Research is currently focused more on synthetic materials (MPs). However, these authors

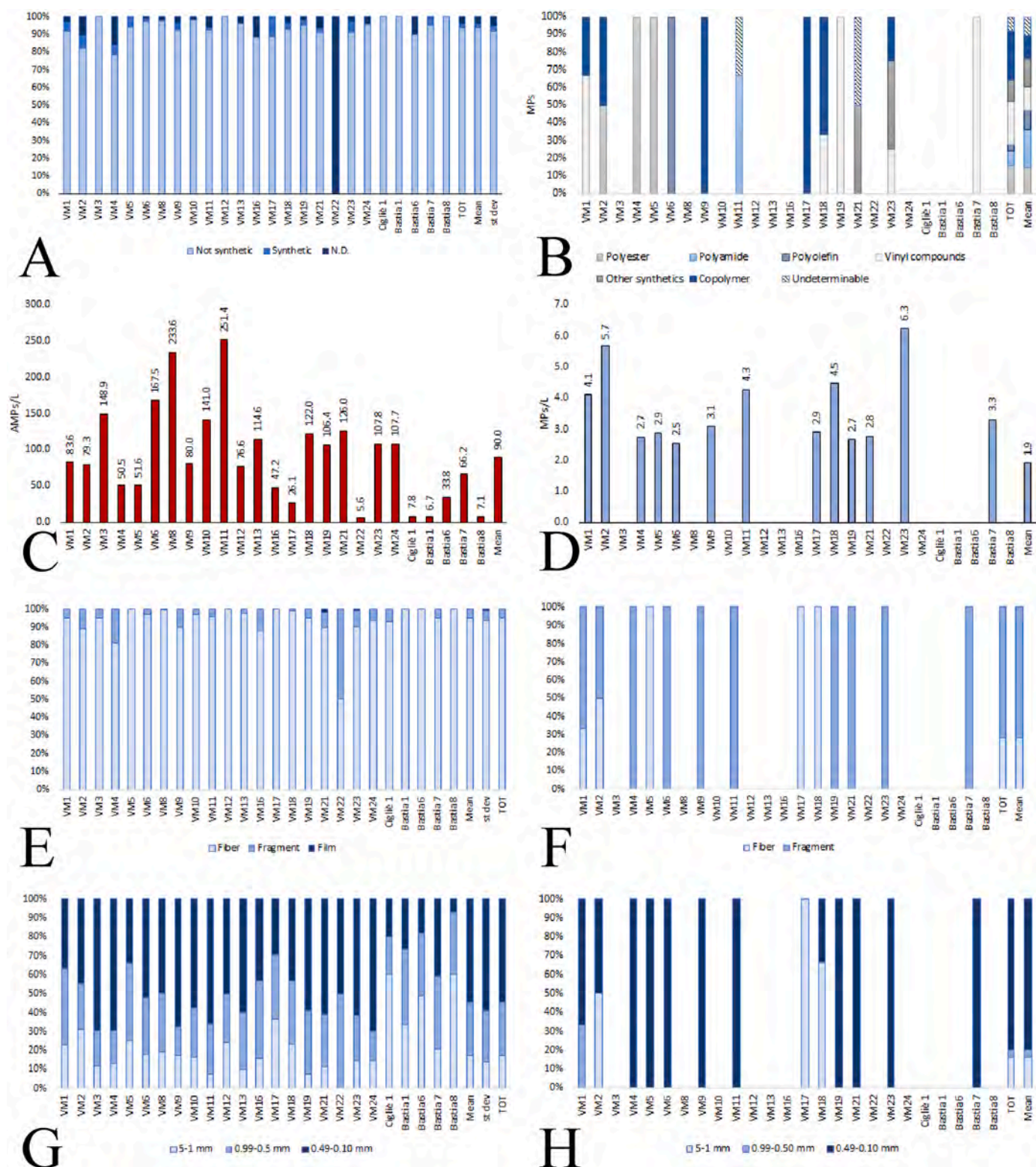


Fig. 2. Anthropogenic microparticle (AMP) abundances and characteristics in Italian confined aquifers. A: AMP composition; B: MP typologies; C: AMP abundance; D: MP abundance; E: AMP shape; F: MP shape; G: AMP size; H: MP size.

believe in the importance of showing that most of the microparticles found are often natural and regenerated materials, therefore, results are expressed in AMPs (total amount) and MPs (synthetic only).

Water samples were processed following the method previously outlined in Balestra et al. (2024b) in cave and karst system waters, adapted.

Samples were subjected to organic matter removal (OMR) using an amount of 30% hydrogen peroxide solution equal to half the sample. Samples were shaken (50 revs/min) for 2 h at 45 °C in a Shaker Water Bath (SBS30, Bibby Stuart Scientific). Once cooled, waters were then filtered through a 1.2 µm pore size silver filter (GVS Life Sciences, Membrane Disk 47 mm) to enhance IR spectroscopy analysis, using a

Table 2

Microparticle of anthropogenic origin found in Italian confined aquifers, with focus on microplastics (synthetic).

Filter Water	ml	Natural and regenerated	Synthetic	N.D.	TOT	Natural and Regenerated/L	Synthetic/L	N.D./L	TOT/L
VM1	730	56	3	2	61	76.7	4.1	2.7	83.6
VM2	706	23	2	3	28	65.2	5.7	8.5	79.3
VM3	618	46	0	0	46	148.9	0.0	0.0	148.9
VM4	732	29	2	6	37	39.6	2.7	8.2	50.5
VM5	698	17	1	0	18	48.7	2.9	0.0	51.6
VM6	395	64	1	1	66	162.4	2.5	2.5	167.5
VM8	672	153	0	4	157	227.7	0.0	6.0	233.6
VM9	325	24	1	1	26	73.8	3.1	3.1	80.0
VM10	391	54	0	1	55	138.5	0.0	2.6	141.0
VM11	704	163	3	11	177	231.5	4.3	15.6	251.4
VM12	692	53	0	0	53	76.6	0.0	0.0	76.6
VM13	672	74	0	3	77	110.1	0.0	4.5	114.6
VM16	720	15	0	2	17	41.7	0.0	5.6	47.2
VM17	690	8	1	0	9	23.2	2.9	0.0	26.1
VM18	672	76	3	3	82	113.1	4.5	4.5	122.0
VM19	752	38	1	1	40	101.1	2.7	2.7	106.4
VM21	722	83	2	6	91	115.0	2.8	8.3	126.0
VM22	710	0	0	2	2	0.0	0.0	5.6	5.6
VM23	641	63	4	2	69	98.4	6.3	3.1	107.8
VM24	678	70	0	3	73	103.2	0.0	4.4	107.7
Cigliè 1	256	2	0	0	2	7.8	0.0	0.0	7.8
Bastia 1	300	2	0	0	2	6.7	0.0	0.0	6.7
Bastia 6	296	9	0	1	10	30.4	0.0	3.4	33.8
Bastia 7	302	19	1	0	20	62.9	3.3	0.0	66.2
Bastia 8	282	2	0	0	2	7.1	0.0	0.0	7.1
TOT		1143	25	52	1220	2110.3	47.6	91.2	2249.1
Mean		45.7	1.0	2.1	48.8	84.4	1.9	3.6	90.0
st dev		42.1	1.2	2.5	44.3	62.1	2.0	3.7	64.3
%		93.7	2.0	4.3	100.0	93.8	2.1	4.1	100.0

glass vacuum pump. Filters were placed in glass petri dishes, covered with aluminium foil, and dried in an oven at 40 °C until completely dry.

2.4. Microparticle identification and characterization

Particles retained on the filters were examined under both visible and ultraviolet light using a Leitz ORTHOLUX II POL-MK microscope equipped with a DeltaPix Invenio 12EIII 12 Mpx camera, at magnifications of 2.5 × , 4 × , 10 × , or higher. Ultraviolet illumination was provided by an Alonefire SV10 flashlight (365 nm, 5 W), positioned on a handmade pedestal at a 45° angle. Visual comparisons were conducted using reference images of natural, artificial, and synthetic fibres documented in previous studies (e.g. Houck, 2009; Khan et al., 2017; Zhang, 2014).

Visual identification was performed in agreement with the strict selection criteria reported in prior studies (Crawford and Quinn, 2016; Hidalgo-Ruz et al., 2012; KIMO Sweden, 2007). Microparticles that could not be definitively identified as AMPs were excluded from the analysis. All filters were analyzed by the same laboratory operator to ensure consistency and minimise human error during AMP quantification and classification. The AMPs were categorised by shape, size, fluorescence and colour, following the standardised size and colour sorting system (SCS) proposed by Crawford and Quinn (2016) for MPs.

Spectroscopic analyses were performed on the total of suspected AMPs found on the filters, from each sampling area, using a µFTIR Shimadzu AIM-9000 microscope equipped with a Shimadzu IRTracer-100 spectrophotometer with ATR. Spectra were compared with the Shimadzu standard library and verified visually by the operator. Only spectra with a match degree ≥70% were accepted.

2.5. Statistical analysis

The statistical analyses presented were exploratory in nature and are intended to provide an initial interpretation of the observed patterns rather than definitive conclusions.

The softwares RStudio 2022.07.2.576 and PAST, Version 5 (Hammer

Table 3

Microplastic characteristics and typology found in Italian confined aquifers.

Sample	Type	Size [mm]	Colour	Fluorescence	Typology
VM1	fragment	0.19	transparent	blue	acrylic
VM1	fragment	0.24	blue	blue	PVC
VM1	fibre	0.66	red	red	EVA
VM2	fragment	0.15	transparent	blue	PES
VM2	fibre	1.68	black	no	copolymer
VM4	fragment	0.11	transparent	blue	PET
VM4	fragment	0.16	blue	no	PET
VM5	fibre	0.32	blue	no	PET
VM6	fragment	0.27	yellow	no	polyethylene chlorosulfonated (CSM)
VM9	fragment	0.1	green	no	copolymer
VM11	fragment	0.19	transparent	green	PA
VM11	fragment	0.16	blue and red	no	n.d.
VM11	fragment	0.17	white and blue	no	PA
VM17	fibre	2.27	red	red	EVA
VM18	fibre	0.2	transparent	blue	ABS
VM18	fibre	1.08	orange	orange	styrene ethylene butylene (copolymer)
VM18	fibre	1.26	blue	no	PS
VM19	fragment	0.14	white	blue	PVC
VM21	fragment	0.1	blue	blue	n.d.
VM21	fragment	0.16	black	no	PAC
VM23	fragment	0.1	blue	blue	polyvinylidene fluoride (PVDF)
VM23	fragment	0.13	green	blue	PAC
VM23	fragment	0.29	yellow	green	ABS
VM23	fragment	0.34	black	no	PU
Bastia	fragment	0.1	red	red	PAM

et al., 2001) were used to perform statistical analyses. Spearman correlation was used to explore possible correlations between AMP

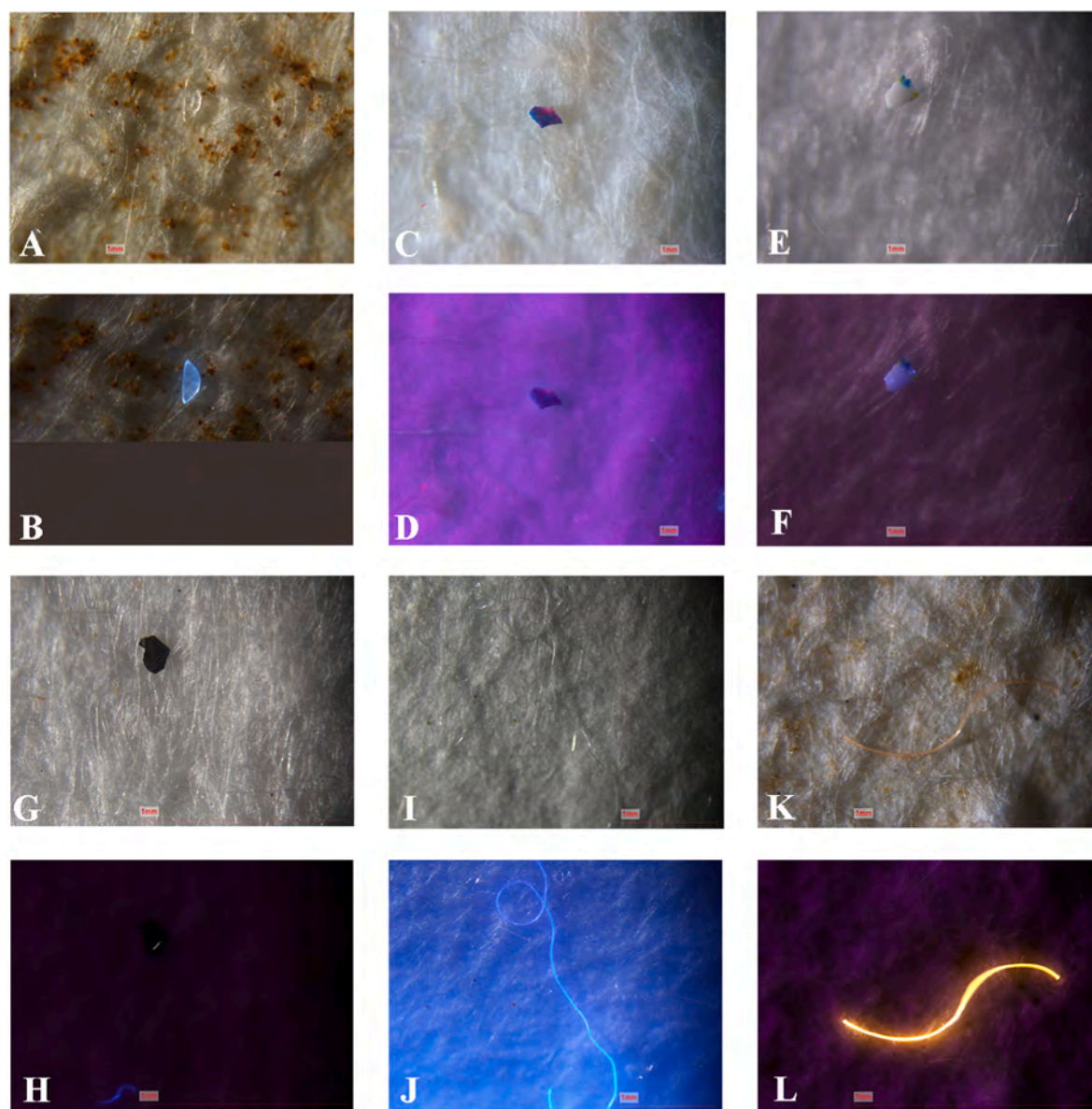


Fig. 3. Microplastics under microscope, with and without UV light. A,B: transparent fragment with blue fluorescence; C,D: blue fragment with no fluorescent and surface degradation; E,F: white fragment with blue fluorescence and surface biofouling; G,H: black fragment with no fluorescence; I,J: transparent fibre with blue fluorescence; orange fibre with red fluorescence.

abundances, aquifers' depth, water chemical-physical parameters and metals described in [Valle \(2025\)](#). A multiple comparison correction using the Benjamini–Hochberg false discovery rate (FDR) method was applied to control for potential false positives.

Redundancy analysis (RDA) was employed to discern water chemical-physical parameters and environmental factors that significantly affect the AMPs abundances.

3. Results

3.1. Abundance and composition

AMPs were found in all sampling points, while MPs were found in 13 out of 25 aquifers ([Fig. 2](#), [Table 2](#)), with totally different values. AMPs ranged from 0 to 231.5 AMPs/L ([Fig. 2C–Table 2](#)). Microscopic analysis showed that 93.8% of total AMPs were natural and regenerated materials, only 2.1% synthetics, and 4.1% not clearly distinguish ([Fig. 2A–Table 2](#)).

All possible MPs in each filter were analyzed by μ FTIR with ATR. No MPs were found in the blank control. MPs ranged from 0 to 6.3 MPs/L ([Fig. 2D](#)). Copolymers (28.0%) and vinyl compounds (24.0%) were the main types of MPs found in the waters of confined aquifers, followed by polyesters (16.0%), polyamides (8.0%), and polyolefins (4.0%). Other synthetics accounted for 12.0% ([Fig. 2B–Table 3](#)). The 8.0% was not clearly determinable. All kinds of MPs detected were shown in [Table 3](#).

3.2. Shape and size

Only fibres, fragments and films were found in the water samples. Fibres represented major part of the AMPs present in the analyzed waters (95.2%) followed by fragments (4.6%), and films (0.2%) ([Fig. 2E](#)). No beads, spheres and foams were found. Big AMPs (5–1 mm) accounted for only 17.3%, while 28.1% from 0.99 to 0.5 mm, and 54.6% from 0.49 to 0.1 mm, highlighting the increase of micropollutants with the decrease in the size considered ([Fig. 2G](#)).

Only MP fragments (72.0%) and fibres (28.0%) were found ([Fig. 2F](#)).

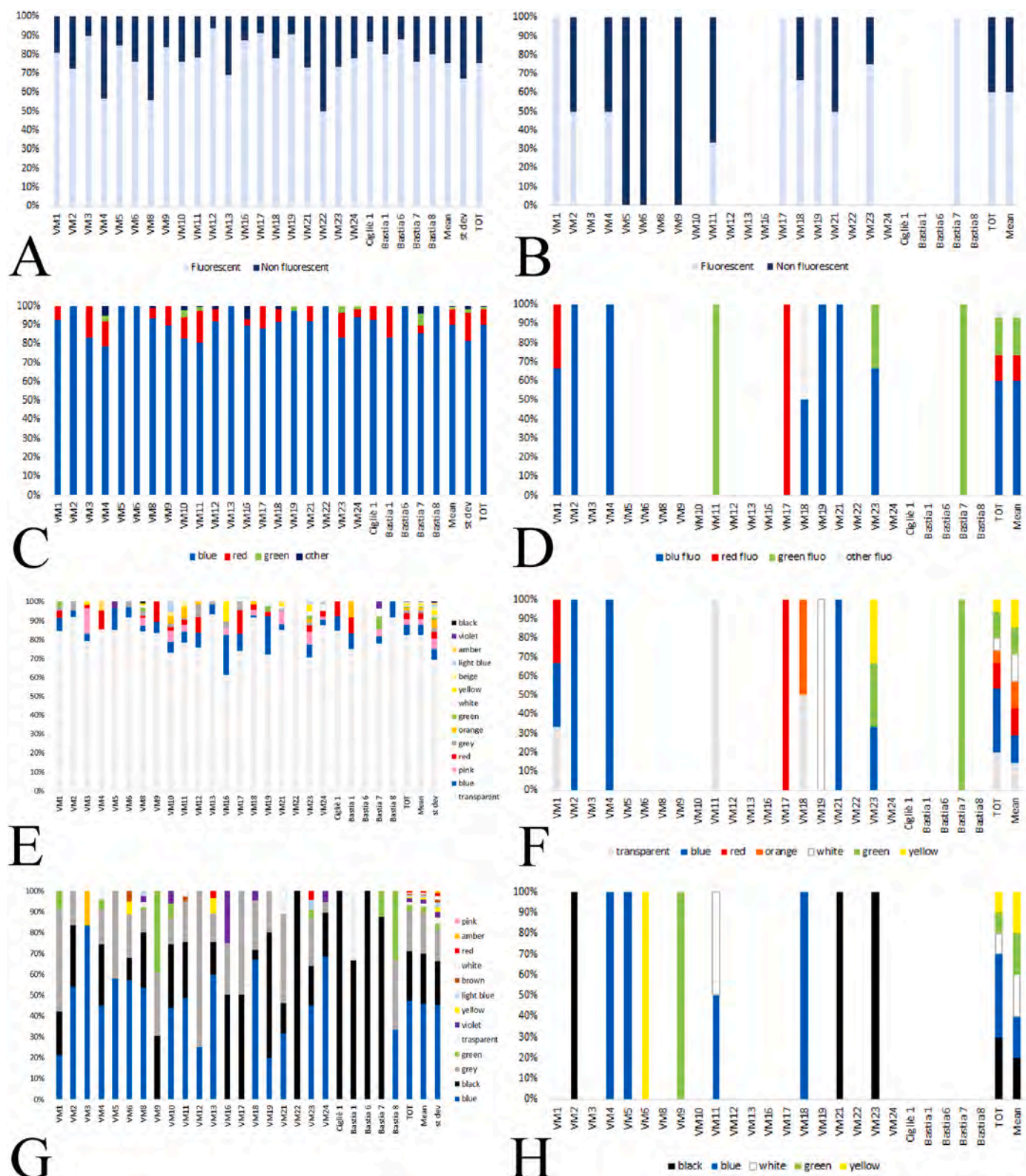


Fig. 4. Fluorescence and colour of anthropogenic microparticles (AMPs) and, in detail, microplastics (MPs) found in Italian confined aquifers. A: AMP fluorescence; B: MP fluorescence; C: AMP colour of fluorescence; D: MP colour of fluorescence; E: colours of fluorescent AMPs; F: colours of fluorescent MPs; G: colours of non-fluorescent AMPs; H: colours of non-fluorescent MPs.

Big MPs (5–1 mm) accounted for 16.0%, while 4.0% from 0.99 to 0.5 mm, and 80.0% from 0.49 to 0.10 mm, highlighting again the increase of MPs with the decrease in the size considered (Fig. 2H).

Shape and size of some microparticles are shown in Fig. 3.

3.3. Fluorescence and colour

The highest AMP abundance was fluorescent under UV light (75.7%) (Fig. 4A), showing especially a blue fluorescence (90.2%), followed by

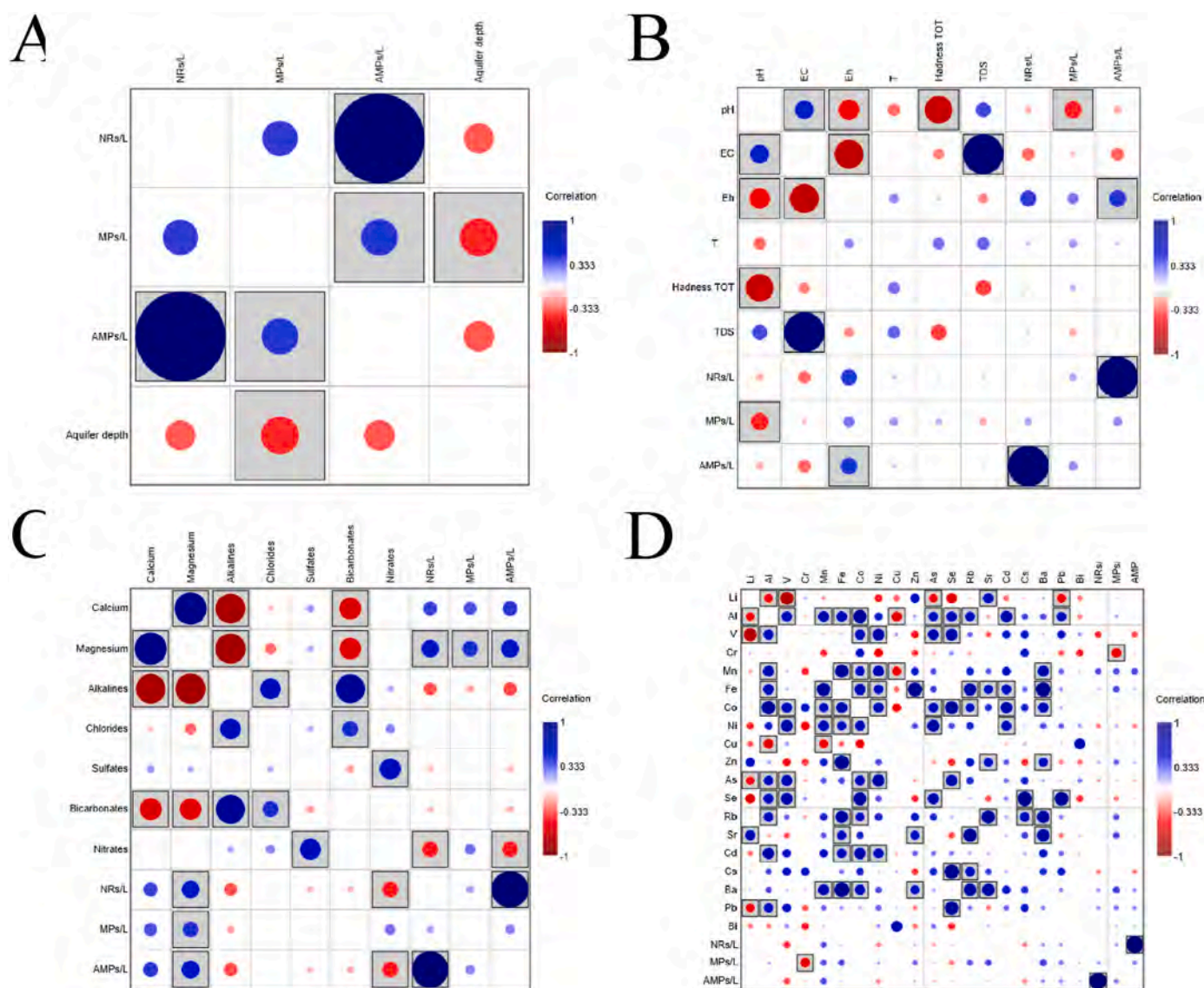


Fig. 5. Correlation between anthropogenic microparticle (AMPs), microplastic (MPs) and natural/regenerated materials (NRs) abundances and aquifer depth (A), water physical parameters (B), main ions (C) and metals (D).

the red one (8.0%) (Fig. 4C). Of the fluorescent particles (Figs. 4E), 82.4% were transparent/clear, followed by blue (5.6%); other colours accounted for less than 3.1% of the total fluorescent ones. Non-fluorescent AMPs (Fig. 4G) were mainly blue (47.3%), black (23.8%), and grey (19.5%); other colours accounted for less than 2.5% of the total non-fluorescent ones.

The highest MP abundance was fluorescent under UV light (60.0%) (Fig. 4B), showing especially a blue fluorescence (60.0%) (Fig. 4D). Of the fluorescent MPs, 33.3 % were blue, 20.0% transparent/clear, 13.3% red, and 13.3% green; other colours (white, orange, and yellow) accounted for 6.7% each (Fig. 4F). Non-fluorescent MPs were mainly blue (40.0%) and black (30.0%); other colours (white, green, and yellow) accounted for 10.0% each (Fig. 4H).

Colours and fluorescence of some particles were shown in Fig. 3.

3.4. Possible correlations

Before FDR correction, the following moderate statistically significant correlations were found (Fig. 5):

- Negative correlation between MP abundances and water aquifer depth ($r_s = -0.41563$, $p = 0.038799$), showing higher amounts of MPs in shallower aquifers
- Negative correlation between MP abundances and pH ($r_s = -0.41638$, $p = 0.038415$)
- Positive correlation between AMP abundance and Eh ($r_s = 0.4006$, $p = 0.047206$)
- Positive correlations between AMPs ($r_s = 0.47769$, $p = 0.015736$), NR (natural and regenerated materials only) ($r_s = 0.46615$, $p = 0.018838$) and MP ($r_s = 0.41113$, $p = 0.041181$) abundances and quantities of Magnesium ions
- Negative correlations between AMPs ($r_s = -0.42028$, $p = 0.036455$) and NR ($r_s = -0.42186$, $p = 0.035687$) abundances and Nitrates ions
- Negative correlation ($r_s = -0.53767$, $p = 0.031708$) between MP abundances and Cr (ppb)

However, after FDR adjustment, these correlations did not survive.

RDA analysis illustrated the relationships between AMP, MP and NR amounts and water chemical-physical parameters and environmental factors (Fig. 6).

AMPs group is strongly oriented to the right along the RDA1 axis,

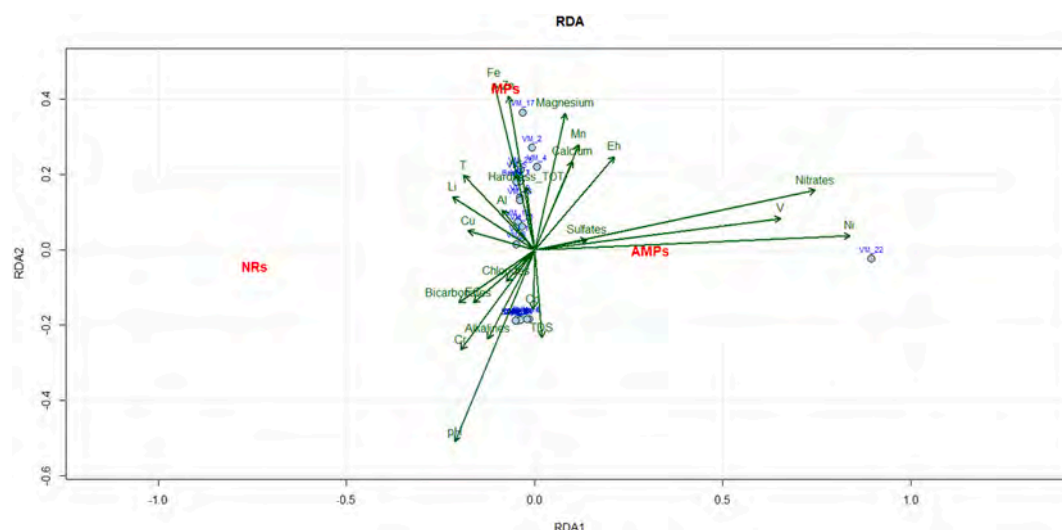


Fig. 6. Redundancy analysis (RDA) plot, illustrating the relationships between AMPs, MPs and NR amounts and water chemical-physical parameters and environmental factors. The arrow direction denotes positive and negative correlations between each factor and micropollutants amounts, while the length of the arrow indicates the strength of the correlation.

showing a strong positive correlation with Nitrates, Ni, V, and secondly to Sulfates. MPs group positioned upwards, along RDA2, presenting positive correlations especially with Fe, Zn, and Magnesium ions, but also with Total hardness, Eh, and T, and a negative correlation with pH. NRs group is positioned on the left of the graph along RDA1 in negative values, indicating an inversely related condition with the variables associated with AMPs, and, consequently, a negative correlation with Nitrates, Ni and V. pH is negatively correlated with most metal concentrations.

4. Discussion

MPs were found in 13 out of 25 confined aquifers, however, MPs were not found in the analyzed artesian aquifers, with the exception of Bastia 7, located near a provincial road. MPs ranged from 0 to 6.3 MPs/L. At the moment, a very limited number of studies have been carried out in groundwater and even fewer in confined and artesian aquifers (Severini et al., 2022). Some of the data obtained so far from groundwater studies were summarized in Table 4. Previous studies have found the most disparate values, from 0 to thousands items/L (Table 4), due to different geographical areas, surface anthropic activities and used methodologies for MP analyses. Our values are similar to those found in karst aquifers of China (An et al., 2022; Shu et al., 2023), coastal aquifers of India (Selvam et al., 2021), groundwaters of Germany (Mintenig et al., 2019), Hungary (Sa'adu and Farsang, 2022), or Poland (Tarasiewicz et al., 2025). However, the values found in these Italian confined aquifers were lower than those found in an alluvial unconfined aquifer in Australia (Samandra et al., 2022), in groundwater under a bedrock island in China (Gong et al., 2023), or in shallow and unconfined aquifer in India (Patterson et al., 2023). In previous work in cave groundwaters and alluvial aquifers in Italy, higher amounts of MPs were shown respect to those found in this study (Balestra et al., 2023, 2024b; Sforzi et al., 2024). However, how it is possible to see in Table 4, considered MP size vary from study to study, as well as method used, therefore, comparisons are hard. The need to harmonize methodologies is increasingly evident, as well as the effort required to obtain more information related to this type of pollution, especially in little studied environments.

Vinyl compounds and copolymers were the main types of MPs found in this study, followed by polyesters, polyamides, polyolefins, and other synthetics. PET, PA, PVC, EVA, ABS and PAC where the most present plastics in the analyzed aquifers, as reported in previous studies

(Table 4).

At the moment, there are still no studies dedicated exclusively to the presence and transport of MFs in confined aquifers. Natural and regenerated materials are much more present in environments than synthetic ones (Balestra, 2026; Balestra et al., 2024a; Finnegan et al., 2022; Stanton et al., 2019). The potential faster degradation of natural and regenerated MFs in comparison to synthetic ones may serve as a pathway for the release of toxic substances into the environment (Ladewig et al., 2015). These fibres are frequently treated and coated with various chemicals, which can substantially slow their degradation in natural environments (Li et al., 2010), persisting from months to decades, up to withstand more than 130 years in a deep-ocean environment (Athey and Erdle, 2022; Chen and Jakes, 2001). Moreover, cellulosic fibres could sink in the environment, due to the specific density of some material, which is higher than polyester, polypropylene, or nylon. Consequently, more studies need to be carried out in this direction.

Abundances of MPs and MFs found in this study were correlated with aquifers' depth, water physical parameters, ions and metals. However, no important correlations were found with most of the data analyzed. Correlations between the presence of MPs and heavy metals are known in literature, because MPs can adsorb some of them, thanks to their characteristics (Li et al., 2019; Selvam et al., 2021; Zhou et al., 2019). Instead, pH can influence both the solubility of certain metals and the surface charge of MPs. Although MPs are unlikely to directly affect Eh, they can affect some of the processes that control it, for example, providing colonizable surfaces for microorganisms that can modify the environment in which they live and the amounts of oxygen present. However, relations between AMP, especially MP, pollution and certain ions in water are currently unknown. From the chemical data, the waters of the Bastia Mondovì area resulted old, probably with an age that can be estimated at a few tens of year. MPs were not found in these waters, with the exception of Bastia 7, therefore, as well as validating the methodology used, these data could be a possible indicator for the estimate, assuming at least about thirty-forty years. However, it is very difficult to understand the real age of these waters even using stable isotope tests, because they may have infiltrated when Tritium activity was higher than today, due to the effects of nuclear tests in the atmosphere. In this case, taking into account that the activity of the Tritium has returned to being very low, the risk of finding waters with Tritium higher than that of the actual rains is high, confirming that these waters are old, but not the precise age.

Table 4
MP pollution comparison of groundwaters from different areas of the world.

Country	Abundance [items/L]	Considered size	Type	Sample type	Reference
Australia	16-97 Mean: 38 ± 8	18-491 μm	PP, PE, PVC, PS	Alluvial unconfined aquifer, capped groundwater monitoring bores (depth 2-29 m)	Samandra et al. (2022)
China	0-4	1-5000 μm	PS, PP, PET	Groundwater in Yulong River. Karst area	Shu et al. (2023)
China	2.33-9.50 Mean: 4.5	1 μm – 5 mm	PS, PE, PET, PA, PP, PVC, other	Karst cave groundwater in Guizhou Province	An et al. (2022)
China	3-23.5 Mean: 10.38	50-5000 μm	PE, PET, PVC, and PA	14 groundwater wells in Hainan, around municipal solid waste landfill	Li et al. (2025)
China	34-64 Mean: 47.5	500-5000 μm	PES, PP, rayon, PE, olefin, acrylic acid	Groundwater under a bedrock island	Gong et al. (2023)
China	4-7	-	PA	-	Ganesan et al. (2019)
China	4-72 Mean: 29	0.1-2500 μm	PA, PE, PP, PVC, PS	Groundwater, wells	Shi et al. (2022)
England	0.85 ± 1.98 (unconfined), 0.06 ± 0.09 (confined)	>25 μm	PP, PE, PA, CA	Unconfined and confined sandstone aquifers	Shockley (2024)
Germany	0-7 Mean: 5.6	20 μm – 5 mm	PA, PE, PES, PVC, EP	-	Minténig et al. (2019)
Hungary	0-5 Mean: 2.3	<5 mm	-	Groundwater (1 m perched depth)	Sa'adu and Farsang (2022)
India	9-39 Mean: 29.73 ± 3.27 Mean in bore wells: 32.9 ± 4 Mean in open wells: 23.9 ± 3.56	0.5-5 mm	PE, PP, PA, PS, PEU, PTFE, PES, CP	Shallow and unconfined aquifer of Tuticorin. 15 wells reaching the phreatic aquifer: 8 bore wells (3.7-6.1 m depth) and 7 open wells (4.3-7.3 m depth)	Patterson et al. (2023)
India	2-80	10-500 μm	PA, PVC, PE	Groundwater, 1 and 2 km distances from the municipal solid waste disposal sites. Corresponding borewell water depth ranges from 3 m to 30.48 m at the surrounding landfill sites	Manikanda et al. (2021)
India	Max: 10.1 Mean: 4.2	0.1-5 mm	PA, PE, PES	Costal aquifer, wells and bore wells	Selvam et al. (2021)
India	3.6-27.2 Mean: 12	<5 mm	-	Wells	Priya et al. (2023)
Indonesia	0.25-0.95	0.069-4.459 mm	-	Dug wells	Natsir et al. (2021)
Indonesia	1.8-2.3	-	-	Two sampling points in three caves. Underground river water in South Malang	Suprayogi et al. (2024)
Iran	0-1.3 Mean: 0.48	$\leq 500 \mu\text{m}$	PE, PET, PS	10 well samples obtained from an alluvial aquifer in the Shiraz semi-arid region	Esfandiari et al. (2022)
Italy	12-54 Mean: 28	0.1-5 mm	PE, PVA, PES, EVOH, PVC	Karst aquifer, Bossea cave, low-flow conditions	Balestra et al. (2023)
Italy	47.2-96	0.1-5 mm	PET, PES, EVOH, PVAc, PTFE, EP, copolymers	Karst cave waters in the Classical Karst Regione. Trebiciano cave, 214 cave, Mariano well	Balestra et al. (2024b)
Italy	26.88 ± 24.37	10 μm – 5 mm	-	Two sampling points in confined alluvial aquifers	Severini et al. (2022)
Italy	18-911	5 μm – 5 mm	EVA, PA, PAN, PE, PET, PP, copolymers, anthropogenic cellulose, polisaccharide gums	Waters from two cave and two alluvial aquifers	Sforzi et al. (2024)
Korea	Wet season: 0.014-0.554 Dry season: 0.042-1.026		PP, PET, PE	Shallow to deep aquifers (well depths: 3–120 m) and cave water of an agricultural region. Igneous fragmented rock, carbonate weathered rock, unconsolidated sediment, limestone cave	Jeong et al. (2023)
Korea	0.006-0.192	20-100 μm	PP, PE, PET, PVC, PS, PA, ABS, PU	Wells (13.7-143.2 m)	Kim et al. (2023)
Mexico	10-34 Mean: 18.3	63-1002 μm	HEC, iPP, PVC, LDPE	Highly permeable and affected by anthropogenic activities costal aquifer, capped boreholes	Alvarado-Zambrano et al. (2023)
Netherland	Groundwater: 0.231-1.584 Groundwater after riverbank filtration: 0.519-2.223	20 μm – 5 mm	PMMA, PP, PS, PTFE, polysulfone, silicone, rubbers, PVC, PET, PE, PE Chlorinated, PA, Polyacetal	Groundwater from one well, combined water from several wells	Bauerlein et al. (2022)
Poland	Max: 14.1 Mean: 1.3 ± 2.1	20-5000 μm	PU, PA, PE, PES	Groundwater in Biebrza Valley, one of Europe's largest and most ecologically significant wetland areas. The primary groundwater is related mainly to Quaternary deposits, consisting of alternating permeable sands and gravels, glacial tills, silts, and clays. 102 wells (1-11 m depth)	Tarasewicz et al. (2025)
Russia	2	30-570 μm	PE, PU, PC, PI, copolymers, phenol-formaldehyd (PF) resins, Polyterpene (TR) resins	Podolsk-Myachkovsky aquifer near the Zvenigorod Biological Station. Well 56 m deep, one sample	Filimonova et al. (2025)
Slovenia	<0.02	1-5 mm	PP, PET, PU, PAM, PE, ethylene propylene diene rubber (EPDM), polymethyl methacrylate. (PMMA), PA, EVA, other	Cave waters, Karst aquifers. Škocjan cave system, Postojna cave, Kačna cave	Valentić et al. (2022)

(continued on next page)

Table 4 (continued)

Country	Abundance [items/L]	Considered size	Type	Sample type	Reference
UK	0-113 Mean: 4.9	>25 µm	PE, PET, PP	Chalk and sandstone aquifer. Raw water	Johnson et al. (2020)
USA	9.2-81.3	4- >5000 µm	Acrylonitrile, PE, PS, PA, PP, anthropogenic cellulose	Waters from the spring issuing from the main entrance of Cliff Cave, Missouri	Baraza and Hasenmueller (2023)
USA	Max: 4.4 Mean: 2.8	0.5-5 mm	PE	Karst aquifer, wells, low-flow conditions	Panno et al. (2019)

Most of the analyzed waters are in agricultural or urban contexts (Fig. 1C), therefore, they could be polluted by agricultural activities and products, the presence of roads and urban human activities. Human-derived activities, atmospheric fallout, and the percolation of particles through soils and fractured rocks can introduce MP pollutants into deep aquifers too, threatening both water quality and the ecological integrity of these distinctive environments. High levels of MPs in agricultural soils were shown in previous studies, due to the extensive use of agricultural plastics (Corradini et al., 2019; Kim et al., 2021b). However, MP groundwater contamination in agricultural areas is still limited (Jeong et al., 2023; Samandra et al., 2022; Severini et al., 2022), highlighting the need to increase monitoring.

In addition, in some of the analyzed water intakes there is the presence of PE pipes or sheaths made of synthetic materials (VM1, VM3, VM5, VM6 and VM9) such as in the aqueduct water intakes. Therefore, possible sources of pollution could be linked to the water intake, complicating the water analysis in these aquifers. However, in VM3 no MPs were found. Analyzed MPs from VM1 resulted in PVC fragment, acrylic fragment and EVA fibre. The water of VM1 is taken from a PVC tank, highlighting a possible direct contamination from the tank, and some pipe sections are in PE. EVA and acrylic are not as common as PE or PVC in pipes; however, they can be present as sheaths, membranes, or joints. However, EVA MPs was fibre, therefore, only acrylic MPs should be considered among the possible direct sources of pollution from the pipelines. Polymers found in VM5, VM6 and VM9 are not generally associated with pipes by their type or shape.

Additional data would be required to test possible sources of pollution.

Once in groundwaters, MPs can be directly or indirectly ingested by organisms too. Research spanning a wide range of taxa has documented direct and indirect ingestion of MPs within aquatic environments (Devereux et al., 2021; Jemec et al., 2016; Pennati et al., 2022), including subterranean species (Kokalj et al., 2025; Sforzi et al., 2024). In addition, MPs present in groundwater may alter boundary zones between subterranean and surface environments, particularly sensitive transition areas like springs.

While groundwater flow processes are fundamental in controlling microplastic transport and distribution in subsurface environments, their detailed characterization was beyond the scope of this preliminary study; nevertheless, the present results provide a first empirical basis that can support future investigations integrating hydrogeological data and process-based interpretations.

Comprehensive studies are required to identify and characterize MP sources, dispersal routes, and accumulation processes within karst terrains, as well as to evaluate their ecological implications for aquatic biota. Long-term observation programs that include a broader range of both groundwater and surface-water sites will be vital for assessing the extent and persistence of MP contamination. Finally, the potential repercussions of MP pollution for groundwater safety - encompassing ecological functioning, biodiversity maintenance, ecosystem service provision, and human health - should be systematically explored.

5. Conclusions

These results improve knowledge on AMP pollution - including MPs and MFs - in groundwaters from confined aquifers, drawing attention on

water quality, and the potential risks that could affect to subterranean species and human health. This first investigation in the Italian confined aquifers documents the presence of MPs and MFs even in these particular aquifers, drawing attention on the potential exposition of species and humans. Possible sources of pollution could be linked to nearby human activities, especially agricultural ones, and water intakes, providing useful references for further research.

Surface and underground environments are closely connected, therefore, greater efforts should be made to establish more comprehensive measure of protection, especially for groundwater resources. Greater attention must be paid to the selection of materials for accessing aquifers, avoiding the use of plastics and implementing enhanced protective measures for the overlying soils, especially in agricultural or urban areas. AMP pollution monitoring in groundwaters must become a priority for the water resources management and ecosystems protection, implementing analyses on a larger number of aquifers, but also surface and subterranean habitats strictly linked to them.

CRediT authorship contribution statement

Valentina Balestra: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matteo Valle:** Writing – review & editing, Investigation, Data curation. **Rossana Bellopede:** Writing – review & editing, Resources. **Adriano Fiorucci:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Conceptualization.

Funding

This work was realized with internal fund, with the support of the Multimodal Analysis Laboratory (LAM) of DIATI – Politecnico di Torino.

Declaration of competing interest

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

Acknowledgements

This research is part of the PhD thesis of Valentina Balestra (2026). The authors are grateful to the reviewers for the critical review of the manuscript.

Data availability

Data will be made available on request.

References

- Allen, S., et al., 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. *Nat. Geosci.* 12, 339–344. <https://doi.org/10.1038/s41561-019-0335-5>.
- Alvarado-Zambrano, D., et al., 2023. First insight into microplastic groundwater pollution in Latin America: the case of a coastal aquifer in Northwest Mexico.

- Environ. Sci. Pollut. Control Ser. 30, 73600–73611. <https://doi.org/10.1007/s11356-023-27461-9>.
- An, X., et al., 2022. Preliminary study on the distribution, source, and ecological risk of typical microplastics in Karst groundwater in Guizhou Province, China. *Int. J. Environ. Res. Publ. Health* 19, 14751. <https://doi.org/10.3390/ijerph192214751>.
- Assas, M., et al., 2020. Bioaccumulation and reproductive effects of fluorescent microplastics in medaka fish. *Mar. Pollut. Bull.* 158, 111446. <https://doi.org/10.1016/j.marpolbul.2020.111446>.
- Athey, S.N., Erdle, L.M., 2022. Are we underestimating anthropogenic microfiber pollution? A critical review of occurrence, methods, and reporting. *Environ. Toxicol. Chem.* 41, 822–837. <https://doi.org/10.1002/etc.5173>.
- Balestra, V., 2026. The invisible problem of microplastics and microfibres in karst systems and aquifers: a multidisciplinary approach. Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Italy 256. <https://doi.org/10.13121/polito/porto/3006971>. PhD. Politecnico di Torino.
- Balestra, V., Bellopede, R., 2025. Explorations in the dark continent: did microplastics and microfibres get here before us? *Sci. Total Environ.* 977, 179328. <https://doi.org/10.1016/j.scitotenv.2025.179328>.
- Balestra, V., et al., 2024a. The problem of anthropogenic microfibres in karst systems: assessment of water and submerged sediments. *Chemosphere*, 142811. <https://doi.org/10.1016/j.chemosphere.2024.142811>.
- Balestra, V., et al., 2024b. Microplastic pollution calls for urgent investigations in stygobiont habitats: a case study from classical karst. *J. Environ. Manag.* 356, 120672. <https://doi.org/10.1016/j.jenvman.2024.120672>.
- Balestra, V., et al., 2024c. Microparticles of anthropogenic origin (microplastics and microfibers) in sandy sediments: a case study from Calabria, Italy. *Environ. Monit. Assess.* 196, 993. <https://doi.org/10.1007/s10661-024-13159-z>.
- Balestra, V., et al., 2023. Preliminary investigations of microplastic pollution in karst systems, from surface watercourses to cave waters. *J. Contam. Hydrol.* 252, 104117. <https://doi.org/10.1016/j.jconhyd.2022.104117>.
- Baraza, T., Hasenmueller, E.A., 2023. Floods enhance the abundance and diversity of anthropogenic microparticles (including microplastics and treated cellulose) transported through karst systems. *Water Res.*, 120204 <https://doi.org/10.1016/j.watres.2023.120204>.
- Barceló, D., et al., 2023. Microplastics: detection in human samples, cell line studies, and health impacts. *Environ. Toxicol. Pharmacol.*, 104204 <https://doi.org/10.1016/j.etap.2023.104204>.
- Bäuerlein, P.S., et al., 2022. Fate of microplastics in the drinking water production. *Water Res.* 221, 118790. <https://doi.org/10.1016/j.watres.2022.118790>.
- Carpanez, T.G., et al., 2025. Source, dynamics, and risks of microplastics and nanoplastics in agricultural groundwater systems. *An Acad. Bras Ciências* 97, e20241393. <https://doi.org/10.1590/0001-3765202420241393>.
- Chen, R., Jakes, K.A., 2001. Cellulolytic biodegradation of cotton fibers from a deep-ocean environment. *J. Am. Inst. Conserv.* 40, 91–103. <https://doi.org/10.1179/019713601806113076>.
- Chen, X., et al., 2023. Transport of micron-sized polyethylene particles in confined aquifer: effects of size, aging, and confining pressure. *Heliyon* 9, 1. <https://doi.org/10.1016/j.heliyon.2023.e18464>.
- Cheng, Z., et al., 2023. Combined effects of polyamide microplastics and hydrochemical factors on the transport of bisphenol A in groundwater. *Separations* 10, 123. <https://doi.org/10.3390/separations10020123>.
- Civita, M., et al., 2011. *Le Acque Sotterranee Della Pianura E Della Collina Cuneese*. Corradini, F., et al., 2019. Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. *Sci. Total Environ.* 671, 411–420. <https://doi.org/10.1016/j.scitotenv.2019.03.368>.
- Cox, K.D., et al., 2019. Human consumption of microplastics. *Environ. Sci. Technol.* 53, 7068–7074. <https://doi.org/10.1021/acs.est.9b01517>.
- Crawford, C.B., Quinn, B., 2016. *Microplastic Pollutants*. Elsevier, Amsterdam.
- Devereux, R., et al., 2021. The abundance of microplastics in Cnidaria and ctenophora in the North Sea. *Mar. Pollut. Bull.* 173, 112992. <https://doi.org/10.1016/j.marpolbul.2021.112992>.
- Dris, R., et al., 2016. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? *Mar. Pollut. Bull.* 104, 290–293. <https://doi.org/10.1016/j.marpolbul.2016.01.006>.
- Esfandiari, A., et al., 2022. Distribution and transport of microplastics in groundwater (Shiraz aquifer, southwest Iran). *Water Res.* 220, 118622. <https://doi.org/10.1016/j.watres.2022.118622>.
- European Commission, 2024. Commission Delegated Decision (EU) 2024/1441.
- Famiglietti, J.S., 2014. The global groundwater crisis. *Nat. Clim. Change* 4, 945–948.
- Filimonova, E., et al., 2025. Study of microplastic particles in a fissure–karst aquifer, Zvenigorod, Russia. *Water Resour.* 52, 517–527. <https://doi.org/10.1134/S0097807825700095>.
- Finnegan, A.M.D., et al., 2022. Man-made natural and regenerated cellulosic fibres greatly outnumber microplastic fibres in the atmosphere. *Environ. Pollut.* 310, 119808. <https://doi.org/10.1016/j.envpol.2022.119808>.
- Ganesan, M., et al., 2019. Fate and transport of microplastics from water sources. *Curr. Sci.* 117, 1879–1885. <https://doi.org/10.18520/cs/v117/i11/1879-1885>.
- Gong, X., et al., 2023. Microplastic pollution in the groundwater under a bedrock island in the South China sea. *Environ. Res.* 239, 117277. <https://doi.org/10.1016/j.envres.2023.117277>.
- Hammer, Ø., et al., 2001. *PAST: paleontological statistics software package for education and data analysis*. *Palaeontol. Electron.* 4, 9.
- Hasenmueller, E.A., et al., 2023. Cave sediment sequesters anthropogenic microparticles (including microplastics and modified cellulose) in subsurface environments. *Sci. Total Environ.*, 164690 <https://doi.org/10.1016/j.scitotenv.2023.164690>.
- He, X., et al., 2025. Groundwater and Public Health: Understanding the Links and Mitigating Risks. *Sustainable Groundwater and Environment: Challenges and Solutions*. Springer, pp. 77–96. https://doi.org/10.1007/978-3-031-82194-3_4.
- Hidalgo-Ruz, V., et al., 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. *Environ. Sci. Technol.* 46, 3060–3075. <https://doi.org/10.1021/es2031505>.
- Hoang, V.-H., et al., 2025. Microplastic characteristics, transport, risks, and remediation in groundwater: a review. *Environ. Chem. Lett.* 23, 817–837. <https://doi.org/10.1007/s10311-025-01825-8>.
- Houck, M.M., 2009. *Identification of Textile Fibers*. Woodhead Publishing in Textiles.
- International Organization for Standardization, 2023. *Textiles and textile products - microplastics from textile sources*. In: Part 2: Qualitative and Quantitative Analysis of Microplastics. ISO 4484-2:2023.
- Jahan, S., et al., 2019. Interrelationship of microplastic pollution in sediments and oysters in a seaport environment of the eastern coast of Australia. *Sci. Total Environ.* 695, 133924. <https://doi.org/10.1016/j.scitotenv.2019.133924>.
- Jemec, A., et al., 2016. Uptake and effects of microplastic textile fibers on freshwater crustacean *Daphnia magna*. *Environ. Pollut.* 219, 201–209. <https://doi.org/10.1016/j.envpol.2016.10.037>.
- Jeong, E., et al., 2023. Microplastic contamination in groundwater of rural area, eastern part of Korea. *Sci. Total Environ.* 895, 165006. <https://doi.org/10.1016/j.scitotenv.2023.165006>.
- Jin, R., et al., 2025. Research advances of micro/nanoplastics in groundwater: occurrence, environmental impacts and control strategies. *Environ. Pollut.*, 126899 <https://doi.org/10.1016/j.envpol.2025.126899>.
- Johnson, A.C., et al., 2020. Identification and quantification of microplastics in potable water and their sources within water treatment works in England and Wales. *Environ. Sci. Technol.* 54, 12326–12334. <https://doi.org/10.1021/acs.est.0c03211>.
- Kannan, K., Vimalakumar, K., 2021. A review of human exposure to microplastics and insights into microplastics as obesogens. *Front. Endocrinol.* 12, 978. <https://doi.org/10.3389/fendo.2021.724989>.
- Khan, A., et al., 2017. A review paper on textile fiber identification. *IOSR Journal of Polymer and Textile Engineering (IOSR-JPTE)* 4, 14–20. <https://doi.org/10.9790/019X-04021420>.
- Kim, D., et al., 2021a. Effects of synthetic and natural microfibers on *Daphnia magna*—Are they dependent on microfiber type? *Aquat. Toxicol.* 240, 105968. <https://doi.org/10.1016/j.aquatox.2021.105968>.
- Kim, S.-K., et al., 2021b. Abundance and characteristics of microplastics in soils with different agricultural practices: importance of sources with internal origin and environmental fate. *J. Hazard Mater.* 403, 123997. <https://doi.org/10.1016/j.jhazmat.2020.123997>.
- Kim, Y.-I., et al., 2023. Microplastic contamination in groundwater on a volcanic Jeju Island of Korea. *Environ. Res.* 226, 115682. <https://doi.org/10.1016/j.envres.2023.115682>.
- KIMO Sweden, 2007. *Small plastic particles in coastal Swedish waters*. N-Research Report, commissioned by KIM, Sweden. 1–11.
- Kokalj, A.J., et al., 2025. Above and in the underground: linking microplastic patterns in cave and surface crustaceans along a karst river stretch. *Environ. Pollut.*, 126939 <https://doi.org/10.1016/j.envpol.2025.126939>.
- Kumar, S., et al., 2025. Distribution, sources, and heavy metal interactions of microplastics in groundwater and sediment of semi-arid regions of Northwest India. *Land Degrad. Dev.* 36, 4031–4043. <https://doi.org/10.1002/ldr.5613>.
- Ladewig, S.M., et al., 2015. *Natural Fibers: a Missing Link to Chemical Pollution Dispersion in Aquatic Environments*. ACS Publications. <https://doi.org/10.1021/acs.est.5b04754>.
- Le Guen, C., et al., 2020. Microplastic study reveals the presence of natural and synthetic fibres in the diet of King Penguins (*Aptenodytes patagonicus*) foraging from South Georgia. *Environ. Int.* 134, 105303. <https://doi.org/10.1016/j.envint.2019.105303>.
- Li, J., et al., 2018. Adsorption of antibiotics on microplastics. *Environ. Pollut.* 237, 460–467. <https://doi.org/10.1016/j.envpol.2018.02.050>.
- Li, L., et al., 2010. Biodegradability study on cotton and polyester fabrics. *J. Eng. Fibers Fabrics* 5, 155892501000500406. <https://doi.org/10.1177/155892501000500406>.
- Li, X., et al., 2019. Enhancement in adsorption potential of microplastics in sewage sludge for metal pollutants after the wastewater treatment process. *Water Res.* 157, 228–237. <https://doi.org/10.1016/j.watres.2019.03.069>.
- Li, X., et al., 2025. Risk assessment of potentially toxic elements, microplastics, and microorganisms in groundwater around municipal solid waste landfill. *J. Hazard Mater.* 487, 137240. <https://doi.org/10.1016/j.jhazmat.2025.137240>.
- Liu, J., et al., 2019a. Microfibers: a preliminary discussion on their definition and sources. *Environ. Sci. Pollut. Control Ser.* 26, 29497–29501. <https://doi.org/10.1007/s11356-019-06265-w>.
- Liu, K., et al., 2019b. Source and potential risk assessment of suspended atmospheric microplastics in Shanghai. *Sci. Total Environ.* 675, 462–471. <https://doi.org/10.1016/j.scitotenv.2019.04.110>.
- Liu, X., et al., 2019c. Microplastics as both a sink and a source of bisphenol A in the marine environment. *Environ. Sci. Technol.* 53, 10188–10196. <https://doi.org/10.1021/acs.est.9b02834>.
- Lusher, A.L., et al., 2013. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. *Mar. Pollut. Bull.* 67, 94–99. <https://doi.org/10.1016/j.marpolbul.2012.11.028>.
- Malafeev, K.V., et al., 2023. Understanding the impact of biodegradable microplastics on living organisms entering the food chain: a review. *Polymers* 15, 3680. <https://doi.org/10.3390/polym15183680>.
- Maliva, R.G., 2016. *Aquifer characterization and properties*. In: *Aquifer Characterization Techniques: Schlumberger Methods in Water Resources Evaluation Series No. 4*. Springer, pp. 1–24. https://doi.org/10.1007/978-3-319-32137-0_1.

- Manikanda, B.K., et al., 2021. Spatial distribution of microplastic concentration around landfill sites and its potential risk on groundwater. *Chemosphere* 277, 130263. <https://doi.org/10.1016/j.chemosphere.2021.130263>.
- Margat, J., Van der Gun, J., 2013. *Groundwater Around the World: a Geographic Synopsis*. Crc Press.
- Martín-Gómez, B., et al., 2024. Recent applications of chromatography for determining microplastics and related compounds (bisphenols and phthalate esters) in food. *Microchem. J.*, 109903 <https://doi.org/10.1016/j.microc.2024.109903>.
- Miller, R.Z., et al., 2017. Mountains to the sea: river study of plastic and non-plastic microfibre pollution in the northeast USA. *Mar. Pollut. Bull.* 124, 245–251. <https://doi.org/10.1016/j.marpolbul.2017.07.028>.
- Mintenig, S., et al., 2019. Low numbers of microplastics detected in drinking water from ground water sources. *Sci. Total Environ.* 648, 631–635. <https://doi.org/10.1016/j.scitotenv.2018.08.178>.
- Natsir, M.F., et al., 2021. Analysis on microplastics in dug wells around Tamangapa landfills, Makassar City, Indonesia. *Gac. Sanit.* 35, S87–S89. <https://doi.org/10.1016/j.gaceta.2020.12.024>.
- Obbard, R.W., et al., 2014. Global warming releases microplastic legacy frozen in Arctic Sea ice. *Earth's Future* 2, 315–320. <https://doi.org/10.1002/2014EF000240>.
- Okyere, E.Y., et al., 2025. Assessing the global landscape of microfibre pollution: a systematic review. *Aquat. Ecol.* 1–12. <https://doi.org/10.1007/s10452-025-10199-6>.
- Panno, S.V., et al., 2019. Microplastic contamination in karst groundwater systems. *Groundwater* 57, 189–196. <https://doi.org/10.1111/gwat.12862>.
- Patterson, J., et al., 2023. Hydrochemical quality and microplastic levels of the groundwaters of Tuticorin, southeast coast of India. *Hydrogeol. J.* 31, 167–184. <https://doi.org/10.1007/s10040-022-02582-6>.
- Pauly, J.L., et al., 1998. Inhaled cellulosic and plastic fibers found in human lung tissue. *Cancer epidemiology, biomarkers & prevention: a publication of the American Association for Cancer Research, cosponsored by the American Society of Preventive Oncology* 7, 419–428.
- Pennati, R., et al., 2022. Mixotrophic flagellate ingestion boosts microplastic accumulation in ascidians. *J. Exp. Zool. Part A: Ecological and Integrative Physiology* 337, 639–644. <https://doi.org/10.1002/jez.2596>.
- Priya, K., et al., 2023. Implications of solid waste dumps on the microplastic abundance in groundwater in Kollam, India. *J. Environ. Manag.* 348, 119224. <https://doi.org/10.1016/j.jenvman.2023.119224>.
- Re, V., 2019. Shedding light on the invisible: addressing the potential for groundwater contamination by plastic microfibers. *Hydrogeol. J.* 27, 2719–2727. <https://doi.org/10.1007/s10040-019-01998-x>.
- Remy, F., et al., 2015. When microplastic is not plastic: the ingestion of artificial cellulose fibers by macrofauna living in seagrass macrophytodebris. *Environ. Sci. Technol.* 49, 11158–11166. <https://doi.org/10.1021/acs.est.5b02005>.
- Ren, Z., et al., 2021. Microplastics in the soil-groundwater environment: aging, migration, and co-transport of contaminants—a critical review. *J. Hazard Mater.*, 126455 <https://doi.org/10.1016/j.jhazmat.2021.126455>.
- Rochman, C.M., et al., 2013. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Sci. Rep.* 3, 1–7. <https://doi.org/10.1038/srep03263>.
- Romeo, T., et al., 2015. First evidence of presence of plastic debris in stomach of large pelagic fish in the Mediterranean Sea. *Mar. Pollut. Bull.* 95, 358–361. <https://doi.org/10.1016/j.marpolbul.2015.04.048>.
- Sa'adu, I., Farsang, A., 2022. Greenhouse farming as a source of macroplastic and microplastics contamination in agricultural soils: a case study from Southeast-Hungary. *Agrokém. Talajt.* <https://doi.org/10.1556/0088.2022.00120>.
- Saccò, M., et al., 2024. Groundwater is a hidden global keystone ecosystem. *Glob. Change Biol.* 30, e17066. <https://doi.org/10.1111/gcb.17066>.
- Saha, A., et al., 2025. Distribution characteristics of microplastics and potentially toxic elements as co-contaminants in groundwater in mid-Brahmaputra Valley, northeastern India. *Environ. Monit. Assess.* 197, 818. <https://doi.org/10.1007/s10661-025-14266-1>.
- Samandra, S., et al., 2022. Microplastic contamination of an unconfined groundwater aquifer in Victoria, Australia. *Sci. Total Environ.* 802, 149727. <https://doi.org/10.1016/j.scitotenv.2021.149727>.
- Selvam, S., et al., 2021. Hazardous microplastic characteristics and its role as a vector of heavy metal in groundwater and surface water of coastal South India. *J. Hazard Mater.* 402, 123786. <https://doi.org/10.1016/j.jhazmat.2020.123786>.
- Severini, E., et al., 2022. River-groundwater interaction and recharge effects on microplastics contamination of groundwater in confined alluvial aquifers. *Water* 14, 1913. <https://doi.org/10.3390/w14121913>.
- Sforzi, L., et al., 2024. (Micro-) plastics in saturated and unsaturated groundwater bodies: first evidence of presence in groundwater fauna and habitats. *Sustainability* 16, 2532. <https://doi.org/10.3390/su16062532>.
- Shi, J., et al., 2022. Groundwater antibiotics and microplastics in a drinking-water source area, northern China: occurrence, spatial distribution, risk assessment, and correlation. *Environ. Res.* 210, 112855. <https://doi.org/10.1016/j.envres.2022.112855>.
- Shockley, D.J., 2024. *Assessing Microplastic (> 25µm) Presence in Groundwater Systems in England*. University of Surrey. <https://doi.org/10.15126/thesis.901989>.
- Shruti, V., Kutralam-Muniasamy, G., 2023. Blanks and bias in microplastic research: implications for future quality assurance. *Trends in Environmental Analytical Chemistry*, e00203. <https://doi.org/10.1016/j.teac.2023.e00203>.
- Shu, X., et al., 2023. Spatial distribution characteristics and migration of microplastics in surface water, groundwater and sediment in karst areas: the case of Yulong River in Guilin, Southwest China. *Sci. Total Environ.* 868, 161578. <https://doi.org/10.1016/j.scitotenv.2023.161578>.
- Stanton, T., et al., 2019. Freshwater and airborne textile fibre populations are dominated by 'natural', not microplastic, fibres. *Sci. Total Environ.* 666, 377–389. <https://doi.org/10.1016/j.scitotenv.2019.02.278>.
- Suaria, G., et al., 2020a. Microfibers in oceanic surface waters: a global characterization. *Sci. Adv.* 6, 8493. <https://doi.org/10.1126/sciadv.aay8493>.
- Suaria, G., et al., 2020b. Textile fibres in mediterranean surface waters: abundance and composition. In: *Proceedings of the 2nd International Conference on Microplastic Pollution in the Mediterranean Sea*. Springer, pp. 62–66. https://doi.org/10.1007/978-3-030-45909-3_12.
- Sumam, S., et al., 2025. Understanding microplastic pollution in groundwater: pathways, health implications and solutions. *Water Environ. Res.* 97, e70132. <https://doi.org/10.1002/wer.70132>.
- Suprayogi, D., et al., 2024. Distribution and abundance of microplastics in underground rivers in the south Malang karst area: first evidence in Indonesia. *J. Environ. Health* 16. <https://doi.org/10.20473/jkl.v16i2.2024.101-109>.
- Taptiklis, P., et al., 2025. Microfibres and health: state of the evidence and research gaps. *J. Hazard. Mater. Adv.* 19, 100766. <https://doi.org/10.1016/j.hazadv.2025.100766>.
- Tarasiewicz, K., et al., 2025. A threat beneath the surface: microplastic contamination in the groundwater of one of Europe's largest wetland complexes. *Sci. Total Environ.* 976, 179329. <https://doi.org/10.1016/j.scitotenv.2025.179329>.
- Thompson, R.C., et al., 2004. Lost at sea: where is all the plastic? *Science* 304, 838. <https://doi.org/10.1126/science.1094559>.
- Valentić, L., et al., 2022. Microplastic pollution in vulnerable karst environments: case study from the Slovenian classical karst region. *Acta Carsologica* 51, 79–92. <https://doi.org/10.3986/ac.v51i1.10597>.
- Valle, M., 2025. *Caratterizzazione Geochimica Degli Acquiferi Profondi Del Piemonte Meridionale*. DIATI. Politecnico di Torino.
- Wanner, P., 2021. Plastic in agricultural soils—a global risk for groundwater systems and drinking water supplies?—a review. *Chemosphere* 264, 128453. <https://doi.org/10.1016/j.chemosphere.2020.128453>.
- Watts, A.J., et al., 2015. Ingestion of plastic microfibers by the crab *Carcinus maenas* and its effect on food consumption and energy balance. *Environ. Sci. Technol.* 49, 14597–14604. <https://doi.org/10.1021/acs.est.5b04026>.
- Wesch, C., et al., 2016. No microplastics in benthic eelpout (*Zoarces viviparus*): an urgent need for spectroscopic analyses in microplastic detection. *Environ. Res.* 148, 36–38. <https://doi.org/10.1016/j.envres.2016.03.017>.
- Woodall, L.C., et al., 2014. The deep sea is a major sink for microplastic debris. *R. Soc. Open Sci.* 1, 140317. <https://doi.org/10.1016/j.envres.2016.03.017>.
- Wright, S.L., et al., 2013. The physical impacts of microplastics on marine organisms: a review. *Environmental pollution* 178, 483–492. <https://doi.org/10.1016/j.envpol.2013.02.031>.
- Zambrano, M.C., et al., 2019. Microfibers generated from the laundering of cotton, rayon and polyester based fabrics and their aquatic biodegradation. *Mar. Pollut. Bull.* 142, 394–407. <https://doi.org/10.1016/j.marpolbul.2019.02.062>.
- Zhang, X., 2014. *Fundamentals of Fiber Science*. DESTech Publications, Inc.
- Zhao, B., et al., 2026. Impacts of phreatic aquifer leakage on confined groundwater quality degradation. *J. Environ. Manag.* 398, 128425. <https://doi.org/10.1016/j.jenvman.2025.128425>.
- Zhao, S., et al., 2016. Microscopic anthropogenic litter in terrestrial birds from Shanghai, China: not only plastics but also natural fibers. *Sci. Total Environ.* 550, 1110–1115. <https://doi.org/10.1016/j.scitotenv.2016.01.112>.
- Zhou, Y., et al., 2019. Characterization of microplastics and the association of heavy metals with microplastics in suburban soil of central China. *Sci. Total Environ.* 694, 133798. <https://doi.org/10.1016/j.scitotenv.2019.133798>.