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Limits, challenges, and opportunities of sampling groundwater wells with plastic casings for microplastic investigations

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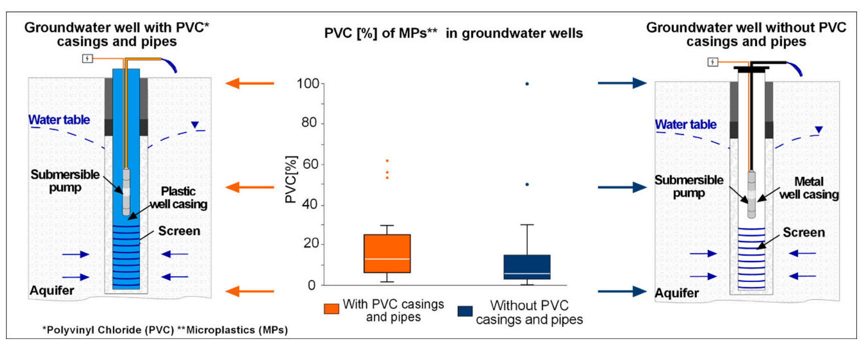
HIGHLIGHTS

- A strict correlation between PVC fragments and PVC well casings is not observed.
- Specific information on groundwater well construction is essential for MP research.
- Water wells with PVC casings can be included in MP analyses.
- Pollution sources should be investigated if PVC exceeds 6 % of the total MPs.

GRAPHICAL ABSTRACT



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ABSTRACT

Investigating microplastics (MPs) in groundwater suffers from problems already faced by surface water research, such as the absence of common protocols for sampling and analysis. While the use of plastic instruments during the collection, processing, and analysis of water samples is usually avoided in order to minimize unintentional contamination, groundwater research encompassing MPs faces unique challenges. Groundwater sampling typically relies on pre-existing monitoring wells (MWs) and water wells (WWs) that are often constructed with polyvinyl chloride (PVC) casings or pipes due to their favorable price-performance ratio. Despite the convenience, however, the suitability of PVC casings for MP research is questionable. Unfortunately, the specifics of these wells are often not detailed in published studies. Current literature does not indicate significant pollution risks from PVC casings, suggesting these wells might still be viable for MP studies. Our preliminary analysis of the existing literature indicates that if PVC exceeds 6 % of the total MP concentration, it is likely that casings and

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pipes made of PVC are a source of pollution. Above this threshold, additional investigations in MWs and WWs with PVC casings and pipes are suggested.

1. Introduction

Groundwater is a vital resource supporting ecosystem resilience and is strategic for the development of human activities (Saccò et al., 2024). Being hidden in the subsoil, this resource is often undervalued, mismanaged, and over-abstracted, and thus the importance of its preservation and protection is generally underestimated by most stakeholders (United Nations, 2022). The innovative research on groundwater urges us to assess the effects of climate change (Stigter et al., 2023) and contaminants of emerging concerns (Lapworth et al., 2023). Microplastics (MPs) are receiving a growing interest, due to their persistence and pervasiveness throughout the entire water cycle (Kumar et al., 2023; Lee et al., 2024; Re, 2019; Viaroli et al., 2022). The original MP classification includes plastic particles that are less than 5 mm in size (Thompson et al., 2004), distinguished from nanoplastics (NPs) that have a submicrometric size range (Gigault et al., 2018). The most recent definition of MPs embraces synthetic polymer particles that are insoluble in water and have at least one dimension between 1 μm and 1000 μm; fragments between 1 mm and 5 mm range are defined as large microplastics (ISO, 2023).

MPs can be classified as primary polymer particles found in personal care and industrial products. Additionally, secondary plastic fibers and fragments take origin upon the degradation of plastic items and products, during regular usage or after their disposal. Released fragments are prone to undergo further fragmentation down to the nanoscale, resulting in pollutants of increasing concern because of the possible ingestion by living organisms (Gündoğdu et al., 2023) and the release of toxic molecular degradation products (Lomonaco et al., 2020). Groundwater investigations on MPs suffer from problems already faced in surface water research, such as the absence of common protocols for sampling

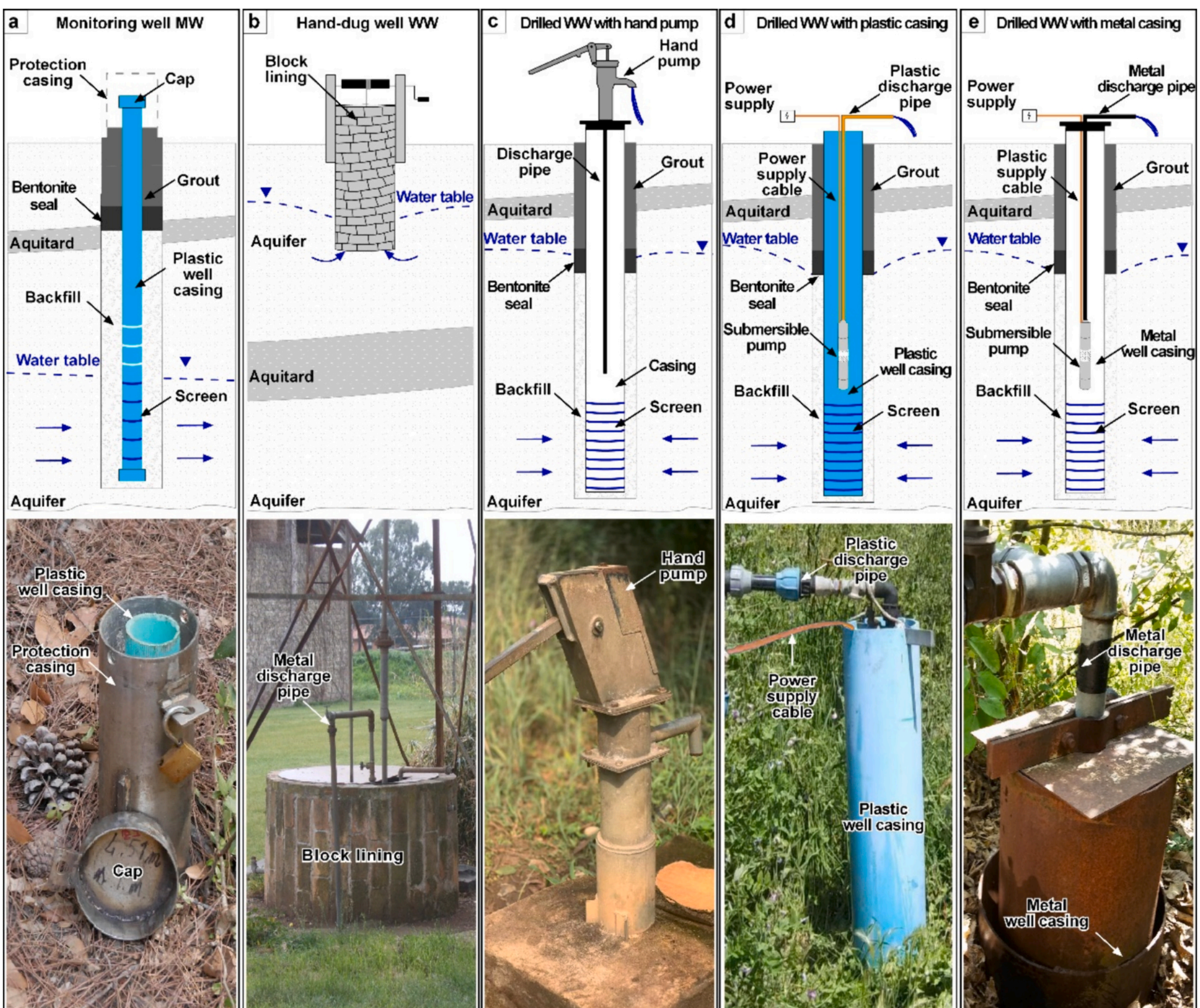

Fig. 1. Scheme and field photo of a monitoring well MW (a); hand-dug water well WW (b); drilled water-well WW with a hand pump (c); drilled water well WW with plastic casing (d); drilled water well WW with metal casing (e). Parts made of polyvinyl chloride (PVC) are represented in cyan, other synthetic polymer types in orange, and groundwater in dark blue. Photos (a,b,d,e) by S. Viaroli, photo (c) courtesy of P. Ucheaga Uchenna.

and analysis (Chia et al., 2022).

To ensure utmost caution, plastic instruments are refrained from being used in both field and laboratory activities. This is because they have the potential to release MPs, thereby compromising the accuracy of the results. Metal and glass instruments are preferred to maintain the consistency of the findings (Lee et al., 2022). Groundwater research is more complex as water is hidden in subsoil pores and fractures. Sampling points are constrained at water springs, monitoring wells (MWs), and water wells (WWs), reducing the range of investigations in space and time (Taylor and Alley, 2001). The collection of water spring samples is a practical way to assess groundwater quality without perturbating the natural aquifer dynamics. However, springs are often located in remote and pristine areas, where water quality is less impacted by human activities. In plains and coastal areas, groundwater interacts with surface water, limiting the opportunity to conduct hydrochemical investigations. In these areas, groundwater is sampled via MWs and WWs (Fig. 1).

MWs (Fig. 1a) are designed to record the water table oscillations and to sample groundwater at a certain depth. Water seeps from the aquifer to the well casing via a screened pipe made of polyvinyl chloride (PVC) and an outer backfill made of coarse soil. Screen locations are optimized based on the local hydro-stratigraphy. In response to the groundwater crisis that depleted numerous aquifers worldwide (Famiglietti, 2014), during the last decades national and local public authorities have built monitoring networks (He and Li, 2006; Lee et al., 2017; Onorati et al., 2006). PVC casings are popular for their convenient price-performance ratio and are valuable in environmental studies to investigate groundwater hydrodynamics as well as contaminant transport. However, PVC casings contrast with the MP research, which relies on the use of non-plastic instruments.

WWs have no standard in construction and are contingent upon the water table depth and the water demand. Shallow aquifers can be exploited with hand-dug wells (Fig. 1b). These wells have large diameters with lining walls or concrete rings that guarantee excavation stability. Pervious walls allow lateral groundwater seepage while wells with concrete rings only receive water from the bottom pit. These WWs are valuable for MP investigations, especially if head wells are capped and groundwater is not collected by buckets and pipes made of plastic.

Drilled WWs have a construction design similar to MWs but are furnished with pumping systems. Hand pumps guarantee water supply to rural areas that are not connected to the power network and are suitable with a static water depth over 60 m from the ground (Fig. 1c). They are widespread in Africa and South-East Asia (MacAllister et al., 2022). WWs with metal casings and metal hand pumps are strategic sampling points for MP investigations, due to the lack of plastic components.

Drilled WWs with submersible pumps (Fig. 1d, e) are more adaptable to the local hydrogeological context, potentially reaching hundreds of meters in depth, and exploiting deep aquifers. The diameter of the perforation is generally larger than MWs to allow the placement of a submersible pump. Due to the heavy price of perforations, casings and screens are often made of inexpensive and durable thermoplastic material (e.g., PVC or High-Density Polyethylene, HDPE). Discharge pipes, connecting pumps, and water supply points are generally made of HDPE. This setting (Fig. 1d) is the most popular as combines the manageability and effectiveness of a submersible pump with the added affordability offered by PVC pipes. Drilled WWs may also be realized with casings, screens, and pipes made of metals, such as iron or steel (Fig. 1e). The latter setting highly increases the construction costs, however, it is recommended in drinking water wells or when dealing with corrosive thermo-mineralized water. With these specifics, the lining of the electric wires is the only plastic component of the WWs.

MWs and WWs are complex systems, and their performance depends on construction features and interaction with the local stratigraphy. The old water wells frequently lack specific information about the exploited portion of the aquifer and can introduce pollutants from the head well, if the well cap is not professionally designed. In addition, leakages from shallow to deep aquifers, producing cross-contamination (Mayo, 2010; Sterling et al., 2005), is surely a major drawback of the old wells. Modern MWs and WWs are characterized by a large use of plastic in the well casings, screens, discharge pipes, and power supply wires that can release MPs, with impacts on environmental investigations. Metals have been utilized in certain studies to construct the MW casings that prevent the release of PVC in groundwater (Jeong et al., 2023). However, wells with PVC casing (e.g., Samandra et al., 2022) are also used but interpretations of the results might have limitations.

In general, the plastic-free approach is difficult to pursue in this kind of field activity. For example, purging operations in MWs and WWs are performed by pumping a volume of water to obtain truly representative groundwater samples, but are challenging without submersible pumps and plastic pipes. In environmental investigations, between 3 and 5 volumes of water are purged out from the well before the collection of the groundwater sample (Nielsen and Nielsen, 2007). On the contrary, a common protocol in MP research is still not defined, even if the benefits of purging to achieve consistent results are suggested (Cha et al., 2024).

The availability of MWs and WWs in a certain area poses a constraint when conducting MP investigations on groundwater. Adhering to stringent criteria for MP investigations, only MWs and WWs with metal casings should be considered. This practice significantly amplifies the expenses associated with environmental analyses or restricts the number of available sampling points.

In the following analysis of the available literature data on MWs and WWs, the occurrence of PVC and other plastic materials is discussed in order to: i) check whether the plastic casings release MPs; ii) propose the best practical compromise between plastic-free approach and field practice; iii) provide insights about the drinking safety of WWs with plastic casings, screens, and pipes.

2. Comparison of field data and discussion

Experimental field works on MPs in groundwater are few and often conducted in heterogeneous hydrogeological contexts, as already pointed out in the literature (Lee et al., 2024). Data from 29 studies, in both industrialized and developing countries, provide an overview of MP pollution in groundwaters (Table S1). Data are presented using identification codes (IDs), highlighting the country where the investigations were carried out (e.g., ITA, USA). In karst springs (An et al., 2022) (CHI2) and cave waters (Balestra et al., 2023, 2024) (ITA1, ITA4) the unintentional release of MPs from submersible pumps, casings, or other common instruments of the hydrogeological practice are avoided. Nevertheless, most of the studies are based on samples collected from MWs and WWs, underscoring the crucial need for integrating the specifics of the wells in the MP analyses.

Alvarado-Zambrano et al. (2023)(MEX1), Samandra et al. (2022) (AUS), and Severini et al. (2022) (ITA2) sample groundwater from two networks of MWs with PVC casings. Four studies carried out in China and India (Liu et al., 2022 - CHI3; Mu et al., 2022 - CHI5; Priya et al., 2023 - IND5; Xu et al., 2022 - CHI6) only focus on groundwater collected from hand-dug WWs. Several studies are based on groundwater collected from WWs with a metal casing (Brancaleone et al., 2024 - ITA3; Cha et al., 2024 - KOR4; Esfandiari et al., 2022 - IRA; Kim et al., 2023 - KOR2; Mendoza-Olea et al., 2022 - MEX2; Panno et al., 2019 - USA; Pittroff et al., 2021 - GER; Shu et al., 2023 - CHI1; Wu et al., 2022 - CHI4; Perraki et al., 2024 - GRE). In the remaining case studies (Cha et al., 2023 - KOR3; Gong et al., 2023 - CHI8; Jeong et al., 2023 - KOR1; Manikanda Bharath et al., 2021 - IND3; Patterson et al., 2023 - IND1; Selvam et al., 2021 - IND4; Shi et al., 2022 - CHI7; Srihari et al., 2023 - IND2; Sforzi et al., 2024 - ITA5), the groundwater is collected from MWs and WWs with casings and pipes made of PVC and other materials, depending on the available sampling points of the study site.

According to the results of the MP analysis, three main categories can be defined (Table 1): samples without PVC fragments (1), samples with

Table 1
Summary of the published MP analyses on groundwater samples. Results are divided into three major groups, based on thepresence of PVC in groundwater.

PVC not detected in groundwater		PVC detected in groundwater		No information about polymer type or concentration
Casings and pipes made of PVC	Casings and pipes made of other materials	Casings and pipes made of PVC	Casings and pipes made of other materials	
IND1	CHI1	AUS	CHI2	IND5
IND3[(a)]	CHI3	CHI7[(a)]	CHI3	ITA2
ITA5[(a)]	CHI4	KOR1[(a)]	CHI5	MEX2
KOR1[(a)]	CHI5	KOR3[(a)]	CHI6	
KOR3[(a)]	CHI8	MEX1	CHI7[(a)]	
	GER		IND2	
	GRE		IND3[(a)]	
	IND3[(a)]		ITA1	
	IND4		KOR1[(a)]	
	IRA		KOR2	
	ITA3		KOR3[(a)]	
	ITA4		KOR4	
	ITA5[(a)]			
	KOR1[(a)]			
	KOR3[(a)]			
	KOR4			
	USA			

[a] Studies comprising different types of MWs and WWs.

PVC fragments (2), and samples without information about polymer types and relative abundance (3). The first two categories are further subdivided, depending on whether PVC casings are present or not. Studies that fall into the third category (IND5, ITA2, MEX2) are not considered for further analyses.

From the available literature analysis, low-density MPs such as Polyethylene (PE) and Polypropylene (PP) are the most abundant polymers (Lee et al., 2024). The extensive use of PE and PP in agricultural and industrial practices justifies their abundance. On the other hand, PVC is predominantly employed in the construction of pipes and flooring owing to its durability, with only limited usage in packaging for customer goods that are more likely to end up as waste and eventually as microplastic fragments (Tian et al., 2023). Indeed, PVC is not always detected in the samples (Table 1). PVC fragments are not reported in 16 studies based on WWs with metal casings or lined with bricks, and 5 studies based on MWs with PVC casings (Table 1). Thus, the PVC casing does not necessarily represent a significant source of MPs. The heterogeneous release of PVC from the casing toward the water well might depend on the local hydrogeological conditions such as the water-well specifics or the friction forces occurring along the casing over time.

PVC fragments are reported in aquifers characterized by different land uses, like agriculture (KOR2, KOR3, MEX1), combined agriculture and industrial sites (CHI3), natural forests (KOR1), or a mixture of uses (AUS, CHI5, CHI7), as well as in other MWs and WWs with or without PVC casings and pipes. The heterogeneous results of KOR1 and KOR3 suggest the occurrence of local MP pollution which may also but not necessarily derive from casings and pipes. PVC is found in MWs and WWs constructed with metal and PVC casings. The presence of PVC fragments in WWs with metal cases confirms that PVC may derive from the aquifer, indicating MP transport occurring at the local or catchment scale. This statement is supported by the findings of IND1, KOR1, and KOR3, in which PVC was not detected in MWs.

PVC fragments in groundwater observed in MWs and WWs without PVC casings (Table 1) testify that pollution may occur from various sources other than the casing. 14 publications report the detection of PVC fragments (Table 2) with a wide concentration range of MPs, from less than 1 n/L to 2680 n/L using spectroscopic methods. When using Pyrolysis Gas Chromatography-Mass Spectrometry (CG-MS) (CHI6) the MP concentration is given as μg/L, since any information about the particle size and number concentration is lost.

Table 2
Total MPs, and PVC percentage on total MPs detected in groundwater. N.A.: relative percentage of polymer types not available.

Casings and pipes made of PVC			Casings and pipes made of other materials		
ID	Total MPs (number/L)	PVC (% total MNPs)	ID	Total MPs (number/L)	PVC (% total MPs)
AUS	16 to 97	6.7 to 53.6	CHI2	2.3 to 9.5	1.2
CHI7[a]	4 to72	N.A.	CHI3	0.25 to 25	6
KOR1[a]	0.1 to 0.5	1.8 to 62.7	CHI5	88 to 2680	~0 to 3.5
KOR3[a]	0.35 and 3.48	4 and 6.3	CHI6	0.003 to 0.01 μg/L[b]	3.1 to 12.8
MEX1	10 to 34	3.4 to 15.5	CHI7[a]	4 to 72	N.A.
			IND2	3 to 9	N.A.
			IND3[a]	42 and 80	3.8 and 26.2
			ITA1	11	9
			KOR1[a]	0.1 to 1	0.6 to 1.8
			KOR2	0.02 to 0.18	4 to 10
			KOR3[a]	0.04 to 2.56	0.2 to 36.4
			KOR4	0.06 to 17.7	0.6 to 18.3

[a] Study involving different types of MWs and WWs
[b] Mass-based analysis.

PVC concentration is expressed as a percentage of the total number of MPs to better compare the levels of pollution across the literature dataset (Table 2). This information is not retrieved for CHI7 and IND2 because the authors only focused on the detection of the polymer types presented in the samples, without their relative abundance. The collected dataset is built with results encompassing heterogeneous sampling techniques, sample preparation, and analytical methods (Table S2). To prevent biased results induced by different experiment setups, preliminary analyses are included to assess the quality of the statistical analysis (Fig. S1).

The percentage of PVC fragments in the analyzed studies spans the whole relative concentration range (Table 2 and Fig. 2). In total, 67 sampling points are considered, 19 of which correspond to MWs and WWs with PVC casings and the remaining 48 without PVC casings. The complete list of the points with the original details is reported in Table S2.

The visualization of the PVC percentage in MWs and WWs with or without PVC casings is shown through a box plot (Fig. 3a). The percentage of PVC fragments is higher in MWs and WWs with PVC casings (mean 18.5 %) than in MWs and WWs without PVC (mean 11.1 %). Both datasets show a wide dispersion of data, with minimum values close to 0 % and maximum values larger than 50 %. The two datasets overlap due to the larger interquartile range of the PVC casing dataset (Fig. 3a).

To identify a PVC threshold between the aquifer and casing pollution source, a statistical analysis is presented (Supplementary material). A two-sample Kolmogorov-Smirnov test (KS) (Massey, 1951) investigates whether the concentration of PVC particles differs, depending on the presence of casings and pipes made of PVC, at a significance level of 5 %. The results of the KS showed that the null hypothesis (the two datasets fall in the same distribution) must be rejected in favor of the alternative hypothesis (p-value = 0.03). Thus, varying the values of the threshold $\widehat{\theta}$, the optimal threshold requiring the maximum Matthews correlation coefficients is searched (Matthews, 1975). When searching for the optimal threshold, it is found an estimate of $\widehat{\theta} = 6$ % (Fig. 3b). The evaluation of the 95 % confidence interval reveals that its length, centered around $\widehat{\theta}$, is negligible (Fig. 3b). Around this percentage, the coefficient increases up to 0.34, while in the rest of the domain is firmly below 0.3.

If the amount of PVC fragments is lower than 6 %, a comparative analysis among the sampled wells of the same site is sufficient to check if there is any correlation between the casing type and the presence of PVC in groundwater. If the amount of PVC particles is higher than 6 %, the results should be critically discussed, and further investigation might be

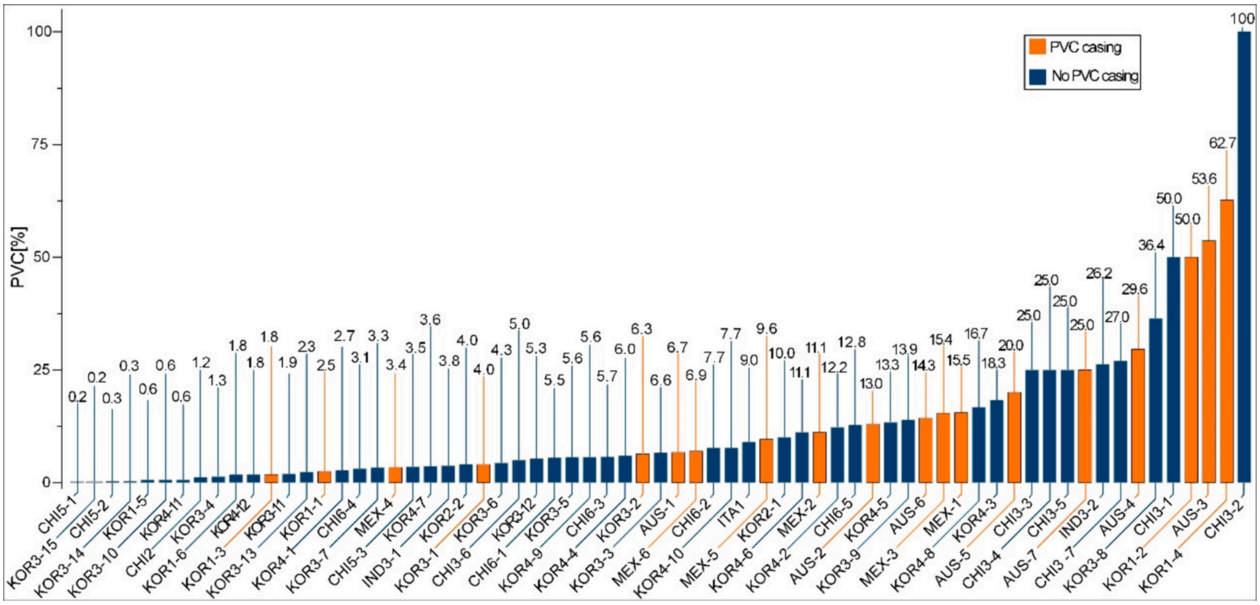

Fig. 2. Percentage of PVC in groundwater samples. Orange bars indicate MWs and WWs with casings and pipes made of PVC. Blue bars highlight MWs and WWs with casings and pipes made of other materials.

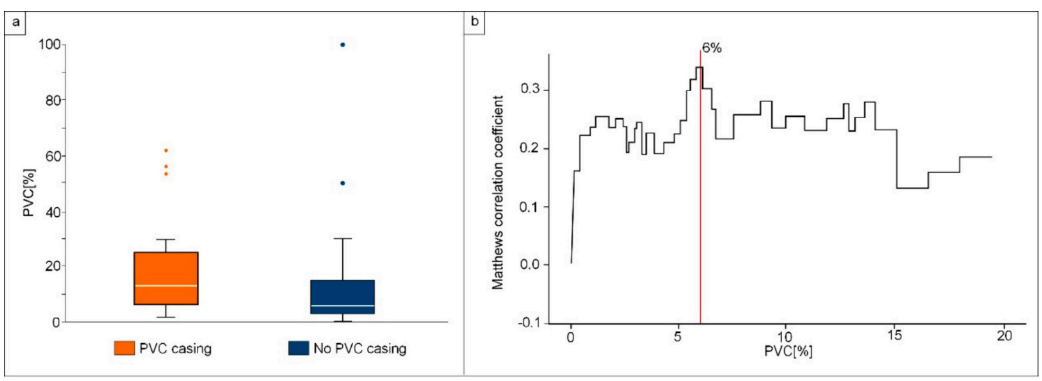

Fig. 3. Box plot of PVC [%] in the groundwater samples collected in MWs and WWs with (in orange) or without (in blue) PVC casing or pipes (a); analysis of the Matthews correlation coefficient versus PVC [%], the red line indicates the optimal threshold (b).

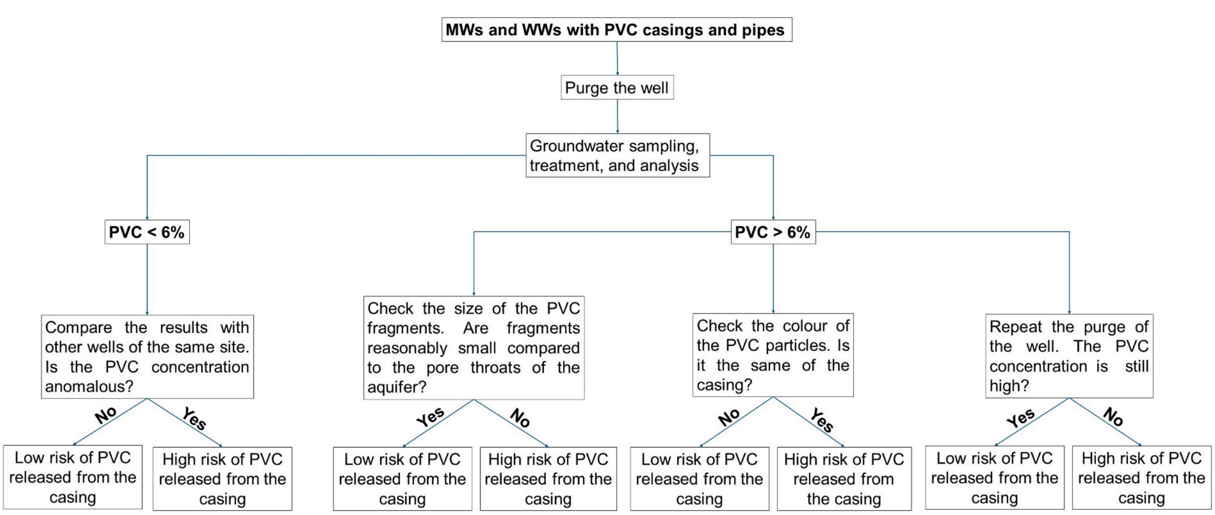

Fig. 4. Guideline proposal to investigate MPs in MWs and WWs with PVC casings.

required (Fig. 4). The PVC fragments should also be compared to the characteristics of the aquifer media. Large fragments may derive from the degradation of the plastic casing rather than the aquifer, especially if the particles exceed the estimated pore throat size of the soil. Analysis can be conducted considering the available geotechnical information (e.g., grain size, thickening) of the aquifer (Viaroli et al., 2022). Large fragments might also come from the head wells if the MWs and WWs are not adequately designed or sealed.

A visual inspection of the PVC particles, including a color comparison between fragments and well casing, may help to define the source of pollution. This analysis may reveal the release of PVC fragments from the well casing. An alternative method consists of repeating the well purge and the MP analysis. A consistent PVC concentration after repeated purging operations likely indicates pollution at the aquifer scale.

However, the overlap of local and regional pollution cannot be excluded. If pollution by PVC fragments from the well casing is probable, this result should be highlighted. The experimental data could later be reconsidered, and possibly discarded or omitted in case of studies aimed at assessing regional MP pollution. However, in (eco)toxicological studies these results might be worthy of note for WW users, also considering the possible contaminants that might be adsorbed onto the MPs (Fu et al., 2021; Gao et al., 2021; Li et al., 2018). Remarkable levels of PVC in groundwater could also suggest an advanced wear of the well casing.

Specific information on sampled MWs and WWs can highlight the MP sources. If available, additional information about the year of construction of the well, its regime of use, and the hydrochemical characteristics of the groundwater should also be reported. So far, based on the available data, there is no evidence suggesting an increased release of PVC with the age of the casing, although more information is needed to support these findings. On the other hand, intense pumping may induce a severe abrasion of the casing. Besides, saline or acid groundwater may increase the aging effect on the PVC casing. In the end, MWs and WWs with PVC casing may be used as monitoring points to assess the MP pollution, if data are critically analyzed. The same considerations concerning PVC may be applied to the detected HDPE fragments. However, polyolefins in groundwater are more frequent than PVC (Lee et al., 2024), that is, their release could hardly be from casings and pipes only.

Despite the preliminary MP analyses indicate that different protocols, sampling procedures, characterization techniques, and size range do not produce bias on PVC occurrence, future inconsistencies may emerge with the increment of the available data. In addition, attention should also be paid to the total number of particles detected and the lower detectable size threshold because, in case of low levels of pollution or of different size thresholds for the detection and identification of the MPs, some results could be subjected to a strong bias.

3. Concluding remarks and outlook

Based on the current data, we can assess that MWs and WWs constructed with PVC are valuable for MP investigation despite the possible presence of plastic components. They offer crucial sampling points, especially useful for catchment scale analyses. Additional attention needs to be considered according to the following general conclusions:

- Compared to water wells lined with metal or concrete, a higher average concentration of PVC fragments has been observed in water wells that utilize PVC casings and pipes.
- PVC casings do not necessarily represent a significant source of MPs as demonstrated by several groundwater samples free of PVC fragments collected in PVC-lined wells.
- The heterogeneous release of plastic fragments from PVC-lined wells may vary according to water-well specifics (construction design, age, wearing of the plastic components), local hydrogeological conditions, and the friction forces occurring along the casing.
- When the concentration of PVC fragments is below 6 %, it is more plausible that these originated from the aquifer itself rather than from the well casing.

Generally, MP studies can benefit from the additional information as groundwater well specifications details on plastic components like casings, discharge pipes, and the linings of power supply cables, as well as purging procedures conducted before sampling. Additional care in the characterization of MWs and WWs specifics would be fundamental when including nanoplastics in the investigation. Due to their smaller size, these particles are potentially more prone to seepage through the geological porous media. However, nanoplastics pose additional challenges as the current methods and techniques based on micro-spectroscopic detection are not suited for the sub-micrometric particles, requiring higher magnification as in electron microscopy or atomic force microscopy. On the other hand, these techniques are more complex and challenging to implement in environmental analysis, as well as result less effective in the characterization of the polymer type. Mass-based qualitative and quantitative analytical techniques such as Pyrolysis CG-MS may suffer from insufficient sensitivity due to the extremely low mass expected when nanoplastics are targeted. Future studies, with access to more extensive datasets and possibly dedicated sampling equipment as well as lab facilities with controlled levels of contamination by airborne particulate, may refine these initial conclusions. The current recommendations are based on a limited dataset and the absence of specialized sampling tools.

CRediT authorship contribution statement

Stefano Viaroli: Writing – original draft, Methodology, Data curation, Conceptualization. **Michele Lancia:** Writing – review & editing, Visualization, Formal analysis. **Jin-Yong Lee:** Writing – review & editing, Conceptualization. **Yujie Ben:** Writing – review & editing. **Roberto Giannecchini:** Writing – review & editing. **Valter Castelvetro:** Writing – review & editing, Funding acquisition. **Riccardo Petrini:** Supervision. **Chunmiao Zheng:** Writing – review & editing, Supervision, Funding acquisition. **Viviana Re:** Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.174259.

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