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Articles

Microplastics in groundwater of two rural communities in Mexico

Microplásticos en aguas subterráneas de dos comunidades rurales en México

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Abstract

Groundwater is used by almost two billion people worldwide. Microplastic (MP) pollution is found in every environment; however, studies on groundwater MP pollution are scarce. Therefore, the present study evaluated the amount and types of microplastics in ten rural wells where drinking water is extracted for two rural Mexican communities. In each well two samples were taken per month for 10 months; one to evaluate MP air deposition, of surface water (first 5 cm of depth) and another of water without contact with air (3 to 5 m depth). There were no differences between the communities in the average number of microplastics in both types of samples. MP measured 2 100 to 4 400 μm in length; 100 % of the MP found were fragments. In both communities, color abundance coincided: black > white > blue > green > gray. The polymers identified were nylon, HDPE, PP, PS, PVC, and PET. There were no differences in the abundance of MP by air deposition, between dry and rainy seasons; however, there was a highest abundance ($p < 0.05$) in the dry season (0.41 MP/l) in deep water, which indicates that rainwater dilutes this type of pollution (0.25 MP/l). Ixtacuixtla and Xocoyucan, Mexico, do not adequately manage their urban solid wastes and wastewater, generating

plastic pollution in the region's groundwater, which represents a risk to human health.

Keywords: Groundwater, water pollution, plastics, drinking water, rural areas, Mexico.

Resumen

El agua subterránea es utilizada por casi dos mil millones de personas en el mundo. La contaminación por microplásticos (MP) está presente en todos los ambientes, pero los estudios sobre MP en aguas subterráneas son escasos; por ello, este estudio evaluó la cantidad y tipos de MP presentes en diez pozos rurales de donde se extrae agua potable para dos comunidades rurales mexicanas. En cada pozo se tomaron dos muestras al mes por 10 meses: una para evaluar deposición aérea de MP, de agua superficial (primeros 5 cm de profundidad), y otra de agua sin contacto con el aire (de 3 a 5 m de profundidad). No hubo diferencias entre las comunidades en el número promedio de MP para ambos tipos de muestras. Los MP midieron entre 2 100 y 4 400 μm de longitud. El 100 % de los MP encontrados fueron fragmentos. En ambas comunidades la abundancia de colores coincidió: negro > blanco > azul > verde > gris. Los polímeros identificados fueron nailon, HDPE, PP, PS, PVC y PET. No hubo diferencias en la abundancia de MP por deposición aérea en secas y lluvias; sin embargo, en aguas profundas se presentó mayor abundancia ($p < 0.05$) en la época de secas (0.41 MP/l), lo que indica que el agua de lluvia diluye este tipo de contaminación (0.25 MP/l). Ixtacuixtla y Xocoyucan, México, no gestionan adecuadamente sus residuos sólidos urbanos y aguas residuales, lo que genera contaminación plástica en los

mantos acuíferos de la región, representando un riesgo para la salud humana.

Palabras clave: Agua subterránea, contaminación del agua, plásticos, agua potable, zona rural, México.

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Introduction

Pollution is one of the most critical environmental problems affecting people's and ecosystems' health. Environmental pollution arises when an imbalance occurs due to the addition of any harmful substance to the environment at doses that exceed acceptable levels in nature, which causes adverse effects on the health of humans, animals, and vegetables (Li, Karunanidhi, Subramani, & Srinivasamoorthy, 2021).

The most frequent sources of pollution are urban solid waste, industrial waste, and chemicals, like metals (Beltrán & Satuquina, 2024), hydrocarbons (Enamorado-Montes *et al.*, 2024) and plastics (Andrés-Bercianos, Martínez-Hernández, & Meffe, 2024). The indiscriminate use of plastics has grown as a packaging method for food, pharmaceuticals, cosmetics, detergents, and chemical products (Shah, Hasan, Hameed, & Ahmed, 2008; Wessel, Lockridge, Battiste, & Cebrian, 2016). Plastics are not the problem, but poor management when they become waste has contaminated practically all environmental compartments (Chen *et al.*,

2021; Mihai *et al.*, 2021; Rajmohan, Ramya, Viswanathan, & Varjani, 2019), and in different countries, efforts have begun to be directed towards their sustainable use and management (Teuten *et al.*, 2009). Plastics are synthetic organic polymers formed by polymerizing monomers extracted from petroleum (Lino-Tolentino, 2022). These are carbon-based polymers, usually synthesized from petrochemicals. They are lightweight, inexpensive, durable, strong, corrosion-resistant, and designed to be thrown away. Plastics are present in all environmental compartments, in the air when plastic burning occurs, and in the soil when plastic is thrown into the natural environment, resulting in animals ingesting plastic pieces and in the delayed degradation of this in the water component (Cárdenas & Vela, 2024).

Microplastics

The first definition of microplastics (MP) was made by Thompson *et al.*, (2004), those who described them as 20 μm residues. Later, Arthur, Baker and Bamford (2009) defined them as fragments less than 5 mm. These particles were first detected in bird stomachs in the sixties (Rothstein, 1973). However, it was not until the following decade that they were cited in the scientific literature (Carpenter, Anderson, Harvey, Miklas, & Peck, 1972). At the beginning of the millennium, they began to be given more importance thanks to the research of Thompson *et al.* (2004). Since then, studies have been increasing, which allows us today to know that microplastics are found in all types of environments, even in areas considered virgin, remote, and inhospitable, such as the Arctic (Cózar *et al.*, 2014).

Microplastics are divided into two categories: primary and secondary. Among the primary ones, microspheres stand out, smaller than 500 μm , used mainly in cosmetic products, medicines, and detergents, which end up in the ocean due to uncontrolled discharges of untreated sewage (Crespo-Sánchez, 2021). Secondary microplastics are derived from the degradation, in any environment, of macroplastics that are exposed to UV radiation and physical, chemical, or biological factors. Within this group, synthetic fibers are also derived from washing clothes. A study by Browne *et al.* (2011) concluded that in a single washing cycle of synthetic garments, more than 1 900 fibers can be released to reach rivers and oceans through drains.

On the other hand, when plastic waste (bags, packaging, bottles, etc.) enters the ocean, its degradation rate and persistence vary depending on the type of polymer, as well as specific conditions such as weathering, temperature, irradiation, and pH (Akbay & Özdemir, 2016). Over time, plastic particles contaminate marine ecosystems and the food chain, including food intended for human consumption.

According to Lithner (2011), plastic is processed with additives to modify its properties, including plasticizers, pigments, antimicrobial agents, heat stabilizers, UV stabilizers, fillers, and flame retardants such as polybrominated diphenyl ethers (PBDEs); these additives can represent 4 % of the weight of microplastics (Rubio-Armendáriz *et al.*, 2022). Once synthesized, plastic polymers are described as non-toxic because they are non-reactive and, generally, are not easily transported across biological membranes due to their size. However, non-polymeric substances, such as chemical additives or residual monomers, can be hazardous to human health and the environment when they leach from the plastic polymer matrix (Lusher, Hollman, & Mendoza-Hill, 2017). Over

time, plastics typically become smaller particles, and with this, it is expected that additives attached to microplastics will leach and may bioaccumulate (Teuten *et al.*, 2009).

In wastewater, during its journey to the ocean, an association often occurs between chemical additives, microplastics, and persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), organochlorine pesticides such as dichlorodiphenyltrichloroethane (DDT) or hexachlorobenzene (HCB). These POPs have a greater affinity for plastic than water, so they can remain adsorbed on the polymer and bioaccumulate in organisms once they have ingested the MP (Rochman, Hoh, Hentschel, & Kaye, 2013).

Microplastics in drinking water

Microplastics are found worldwide in freshwater systems (Zhang *et al.*, 2017). Their abundance varies greatly, from zero to millions of microplastics per cubic meter. For example, microplastics have been found in Lake Geneva, Switzerland, reaching 48,146 microplastics/km² (Eerkes-Medrano, Thompson, & Aldridge, 2015). Free *et al.* (2014) also detected microplastics in Lake Hovsgol, northern Mongolia; the average surface water presence was 20 246 microplastics/km². Eriksen *et al.* (2013) found that, in the surface water of the Great Lakes basin in the United States and Canada, the presence was 43 000 microplastics/km² (Eriksen *et al.*, 2013). In a research carried out by Lechner *et al.* (2014), they determined that the average concentration of microplastics in the surface water of the Danube was 0.316 microplastics/m³ (Lechner *et al.*, 2014). In another study, Di and Wang (2018) found concentrations ranging from 1 597 to 12 611 microplastics/m³ in surface waters of the

Three Gorges Reservoir in China. Likewise, Su *et al.* (2016) detected the presence of microplastics in Lake Taihu, China, at concentrations of 3.4 to 25.8 microplastics/l (Su *et al.*, 2016).

Groundwater

Groundwater is an essential resource used by various productive sectors and used by millions of people worldwide. It represents 33 % of worldwide freshwater consumption (De-Graaf *et al.*, 2017). One of the main reasons for its use is its higher quality than other sources because it filters naturally through the ground, reducing the risk of contamination compared to dams, rivers, lakes, or lagoons (Kayastha *et al.*, 2022). Globally, agriculture consumes around 70 % of freshwater, especially for irrigated agriculture, which ensures food security (Huo *et al.*, 2022).

Groundwater represents 25 % of the global drinking water supply (Singh & Bhagwat, 2022). It is also used for agricultural production, residential, and industrial use by almost two billion people worldwide (Panno *et al.*, 2019). Domestic demand includes the water needed for drinking, cooking, flushing the toilet, bathing, and garden watering. Agricultural water demand consists of irrigation water for crop growth, livestock feeding, and water directly needed for livestock, mainly drinking water. Industrial water demand consists of processed water for manufacturing and cooling water needed to support production processes. Water demand for processing animal products is included in industrial water demand (Flörke *et al.*, 2013). Breaking down groundwater extractions by sector of use, it is observed that 69 % of the total extracted volume is used in the agricultural sector, 22 % is for domestic use, and 9 % for industrial purposes. These percentages vary from continent to

continent (UN, 2022). In Mexico, consumptive uses of water are 76.3 % for agricultural, 14.8 % for public supply, 4.8 % for industry, and 4.1 % for electric energy excluding hydroelectricity (Conagua, 2023). Around 2.2 billion people worldwide do not have safe drinking water services, 4.2 billion people do not have safe sanitation services, and 3 billion people lack basic facilities for hand washing water (UNICEF, 2019). In 2023, the rural population in Mexico was 18.4 %, and worldwide it was 38.6 % (World Bank Group, n. d.). Groundwater presently provides half of the water withdrawn for domestic use by the global population, including drinking water for the vast majority of the rural population, which does not get its water delivered via public or private supply systems (UN, 2022).

Most research on groundwater pollution has focused on chemical contaminants such as heavy metals, nitrates, petroleum hydrocarbons, and pesticides (Toccalino, Gilliom, Lindsey, & Rupert, 2014). In recent years, microplastics have been discovered in groundwater, making it a novel topic that poses challenges to environmental and human health (Coffin, Wyer, & Leapman, 2021). There are different entry routes of microplastics into groundwater, including surface runoff, agricultural activities (fertilizers and compost), atmospheric deposition, and wastewater effluents. MPs travel considerable distances and infiltrate aquifers, causing their accumulation in underground environments (Goepfert & Goldscheider, 2021; Viaroli, Lancia, & Re, 2022). Upon reaching groundwater, MPs can persist for extended periods due to their inherent resistance to degradation, leading to long-term contamination and exposure risk (Chia, Lee, Jang, Kim, & Kwon, 2022).

The evaluation of groundwater contamination is essential since it is challenging to control underground processes; the situation becomes

more crucial when the sources of pollution are varied (Singh & Bhagwat, 2022). Groundwater now faces contamination by microplastics, and understanding the fate and transport of microplastics in groundwater is essential to evaluate the environmental distribution and the potential risks (Dong, Yu, Huang, & Gao, 2022).

Today, there are no standards to limit the concentration of microplastics in drinking water in any country, which translates into human exposure to microplastics and potential health risks. The effects on human health depend on the microplastics and their additive exposure concentrations; however, with the information available to date, only approximations can be made, and recent research has predicted that the total intake of microplastics can be up to 11 000 plastic particles per individual annually (Yang *et al.*, 2015). Microplastics can be dispersed through various exposure routes (oral, inhalation, dermal), with oral ingestion of seafood being the main route of human exposure. The potential toxicity caused by their leachable chemical additives (primarily bisphenol A) and their ability to combine with human body proteins allows them to diffuse and penetrate cells and organs, generating gastrointestinal toxicity, liver toxicity, neurotoxicity, and risk of carcinogenesis as microplastics are involved in mechanisms of oxidative stress and inflammation. Their ability to cross the placental barrier and interfere with breast milk secretion has even been demonstrated, demonstrating new routes of human exposure during pregnancy and lactation. Although there is still insufficient data to define plastics as an undeniable risk to human health, further epidemiological studies using new mammalian models are needed to delve deeper and properly detail all the information (Pat-Vázquez *et al.*, 2024). Microplastic contamination in underground drinking water has been less studied than in other natural

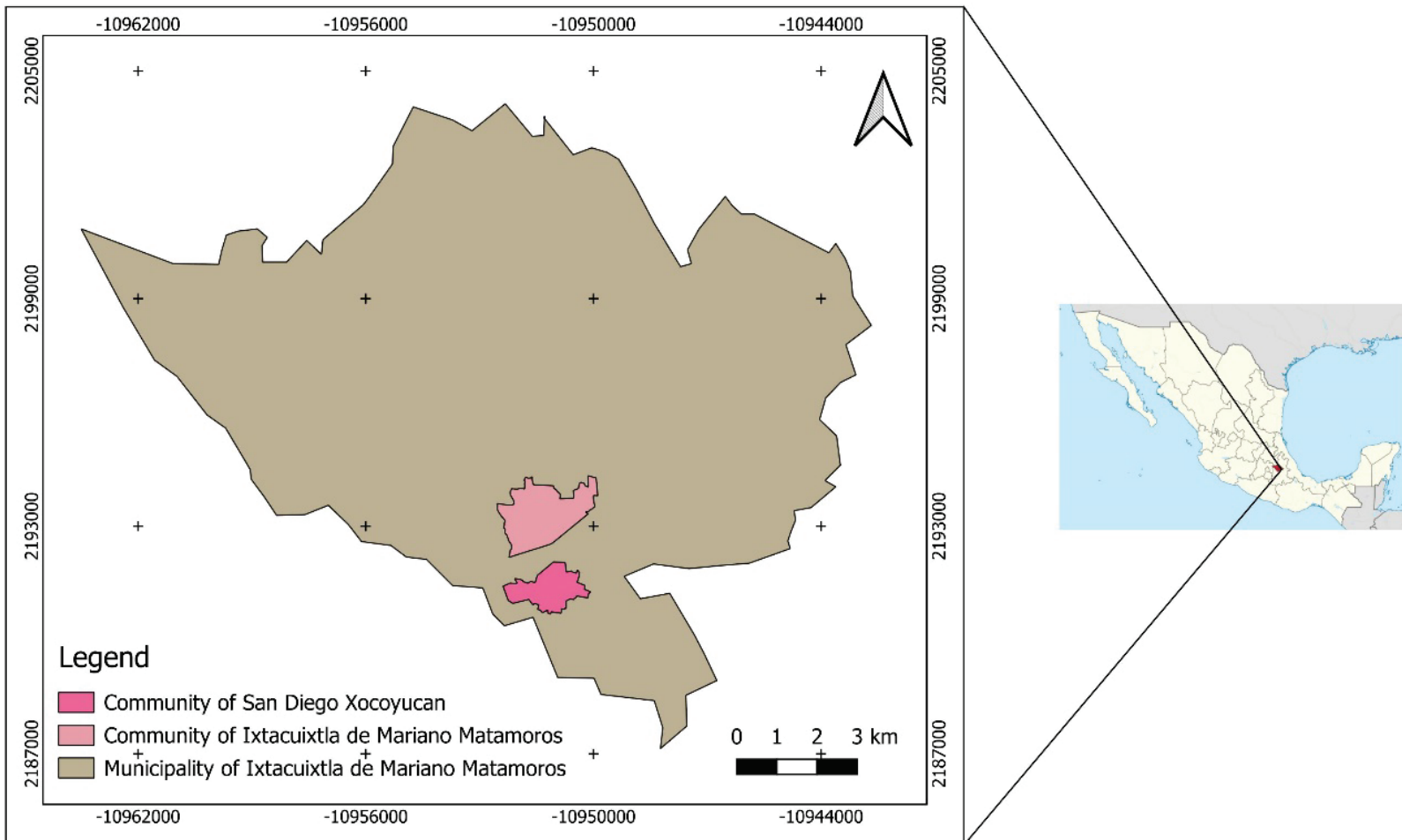
environments such as marine, riverine, raw drinking water, and soil (Mintenig, Loder, Primpke, & Gerdts, 2019). However, microplastic contamination in underground drinking water should not be underestimated, which is why the need arises to evaluate microplastics in this environmental compartment, especially in those communities in which groundwater is used as drinking water without any prior treatment, which directly exposes people to the contaminants that this water may contain, including microplastics.

Two small communities of Tlaxcala, Mexico (San Diego Xocoyucan and Ixtacuixtla De Mariano Matamoros, Mexico), were selected to study the presence and characterization of microplastic through groundwater because their inhabitants obtain their drinking water directly from wells and apply no treatment; the study of these communities represents the situation of many communities around the world.

Materials and methods

Study area

The rural communities studied were San Diego Xocoyucan and Ixtacuixtla de Mariano Matamoros Tlaxcala, Mexico. They are located in west Tlaxcala, Mexico (Figure 1), at 2 220 meters above sea level and a predominantly temperate sub-humid climate (Secretaría de Salud, 2013). The Municipality has a population of 38 970 inhabitants distributed in 23 communities (INEGI, 2020).



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Figure 1. Location of the Municipality of Ixtacuitla de Mariano Matamoros and the community of San Diego Xocoyucan, Tlaxcala, Mexico.

The sampling sites are shown on the map in Figure 1: San Diego Xocoyucan and Ixtacuixtla de Mariano Matamoros, Tlaxcala, Mexico.

Most rural communities are found in countries that base their economy on exploiting and exporting raw materials. When they are not technological, these activities require much labor. For this reason, most of the rural population has jobs linked to the agricultural, livestock, or

mining sectors (Manggat, Zain, & Jamaluddin, 2018). In this context and as previously analyzed, San Diego Xocoyucan and Ixtacuixtla de Mariano Matamoros, Mexico, are a clear example of rural communities.

The community of San Diego Xocoyucan, Tlaxcala, Mexico, does not have drinking water services; there is a pipeline, but it is not in operation. For this reason, residents dig wells inside their properties to satisfy their water needs. In the community's surroundings, there are rain-fed crop areas (corn, beans, pumpkin, tomato, cabbage, chard, tomato, tomato, etc.) for which fertilizers are used, specifically triple 17. On the other hand, domestic wastewater is carried through a defective drainage system to unused agricultural plots surrounding the community, so its contaminants are integrated into the soil and, therefore, into the water table.

The ten wells sampled are made of red brick used in construction; in fact, red brick is not directly related to microplastic contamination; however, the production of red clay bricks, like standard red brick, can generate polluting fumes and emissions during manufacturing (Carranza, Gutiérrez, & Martínez, 2023).

In the Municipality of Ixtacuixtla de Mariano Matamoros, Tlaxcala, Mexico, there is a drinking water service; however, there are still families who dig wells within their properties to satisfy their needs due to a cultural distrust in the water quality of the system. The wastewater generated in this community is disposed of in the Ixtacuixtla wastewater collector, which discharges with a deficient treatment in the Atoyac River, which nowadays presents high pollution (Conagua, 2022a; Conagua, 2022b). The Atoyac River is contaminated mainly by organic matter, suspended solids, nutrients, organic toxins, bacteria, chloroform, methyl chloride, cadmium, chromium, mercury, lead, cyanides, aluminum, copper, iron,

fats and oils, dissolved solids, sulfides, and zinc (Conagua, 2022a; Conagua, 2022b).

The aquifer that supplies water to the wells of San Diego Xocoyucan and Ixtacuixtla de Mariano Matamoros, Tlaxcala, Mexico, is the Alto Atoyac aquifer, defined with code 2901 in the Geographic Information System for the Management of Groundwater of the National Water Commission (SIGMAS), it is located in the central portion of the State of Tlaxcala, covering an area of 2 032 km² (Morales, Sánchez, Hoyos, & Esteller, 2015).

The Alto Atoyac aquifer is primarily karst and, therefore, contains areas of carbonate rocks that allow for the formation of this type of aquifer. Although there may be areas with siliciclastic rocks, the prevalence of carbonate rocks is what defines its karst nature (Conagua, 2022a; Conagua, 2022b).

The Alto Atoyac basin has many problems; it is one of the most polluted in the country and is among the ten most overburdened; the aquifer waters are used by more than one and a half million people (Zambrano, 2021a; Zambrano, 2021b); and there's been a reduction in rainfall and runoff. Another source of pollution in the Alto Atoyac aquifer is the poor solid waste management of the town of San Diego Xocoyucan, Mexico, and the Municipality of Ixtacuixtla, Mexico, where solid waste is deposited in the Panotla landfill (Tapia & Novelo, 2011). However, the collection is deficient, coupled with the fact that coverage in rural areas is low due to the spreading of homes, so part of the garbage is thrown into bodies of water and onto the ground (Tapia & Novelo, 2011). The landfill is located in the southwestern portion of Tlaxcala, northwest of Panotla, in Santa Cruz Techachalco (Secretaría del Medio Ambiente de Tlaxcala, n.d.). The land where the project was built belongs to a mining company;

the state government signed a bailment agreement to use the property as a sanitary landfill for five years. The landfill receives around 610 tons of solid waste daily from 23 municipalities of Tlaxcala, including those in this study (Secretaría del Medio Ambiente de Tlaxcala, n.d.).

Fieldwork

From February to November 2023, the sampling frequency was monthly. There were ten samplings in total, and ten wells were sampled. Sampling was carried out inside ten wells where drinking water is extracted for human consumption and to carry out domestic activities: five wells in the community of San Diego Xocoyucan, Mexico, and another five wells in Ixtacuixtla de Mariano Matamoros, Tlaxcala, Mexico. In both communities, the exact number of wells is unknown, as residents fear that municipal or state authorities will charge them money for having a well at home. In fact, during the sampling, residents were particular about not providing information about their wells. However, the main characteristic is that the ten wells sampled are between 3 and 5 meters deep, and all residents drink water from their wells without prior treatment.

For groundwater sampling, the possible air deposition of microplastics was considered, so in each well, two samples were taken, one of surface water (from the first 5 cm of depth) and another of water without contact with the air, the which was obtained with an EVANS brand fountain pump, model AQUA120W-F, entered into the deepest part of the wells; The pump was previously purged by operating it for 20 minutes before each sampling, to avoid plastic contamination coming from the pump. In both cases, 20 l of groundwater were filtered *in situ*, with a

number 35 sieve (500 pore size). This sieve was selected because the purpose was to collect MP particles bigger than 500 μm and smaller than 5 mm. The sieve was rinsed with filtered water before and after each sample was filtered. Furthermore, there is currently no standard procedure for MP sampling and analysis, and recent studies agree that there is an urgent need to standardize sampling and analysis protocols (Viaroli *et al.*, 2022). Consequently, studies assessing MP presence are difficult to compare since they use different sampling and analysis approaches (Colmenarejo-Calero, Kovač-Viršek, & Mali, 2024). The microplastics found were collected with tweezers and placed in previously labeled paper envelopes for transport to the laboratory.

Quality Control

Before and during sampling, all utensils were rinsed with filtered water, avoiding plastic contamination at all times. Participants entered the wells without outer clothing and wore only organic cotton underwear for the sample collection.

During laboratory work, only glass and metal materials were used. These materials were washed with filtered distilled water and dried at 70 °C in an oven. Cotton clothing was worn at all times. Nitrile gloves, previously rinsed with distilled water, were used. The extraction procedure was performed with bare, pre-washed hands, as recommended by Schymanski *et al.* (2021). Also, a control Petri dish was placed in the working area, which later was examined for MP presence.

Laboratory work

Characterization (shape, size, and color) of microplastics

The particles were observed and counted directly on the paper envelopes, subsequently photographed with a digital microscope (CE RoHS 640X - 480X), and classified into fibers, fragments, or granules, and their color was also recorded. Microplastics were measured in the photographs using ImageJ software (Digital-Microscope Suite 2.0). The data were stored in Excel for later statistical analysis.

Characterization of microplastic polymers

A PerkinElmer FT-IR Frontier spectrometer was used to characterize the microplastics, with a spectrum from 500 to 4 000 cm^{-1} and an accumulation of 16 scans. The samples provided data on transmittance. Samples spectra were compared with the catalogs of the microplastics library of the CIIEMAD-IPN research team to identify the polymers, with a correlation percentage of 95 %.

Statistical analysis

The Jamovi package version 2.4.14 was used. Normality in the data was determined using the Shapiro-Wilk test, and variances homogeneity was determined using the Levene test. Subsequently, it was decided to apply the Wilcoxon test of independent variables since they were two independent communities (San Diego Xocoyucan and Ixtacuixtla de Mariano Matamoros, Mexico) and two methods of obtaining microplastics (by air deposition and groundwater from the deepest wells).

Results and discussion

Abundance of microplastics

The average abundance of microplastics in both communities was 0.34 MP/l, the number is low compared to other natural environments such as marine, rivers, and lakes (Khant & Kim, 2022; Samandra *et al.*, 2022) and also to what was found in groundwater in Illinois, United States, in which the average concentration was 6.4 MP/l (Panno *et al.*, 2019) and in Victoria, Australia, where 38 MP/l were found (Samandra *et al.*, 2022). In contrast, groundwater in Holdorf, Germany (Mintenig *et al.*, 2019) reported an average concentration two orders of magnitude lower (0.0007 MP/l).

In Mexico, there are few studies on microplastics in groundwater. The results of our work were low compared to the karst aquifer of the Yucatán Peninsula, where an average concentration of 42.7 ± 37.3 particles l^{-1} was found in groundwater samples obtained from wells (Mendoza-Olea *et al.*, 2022). In the Laguna Agua Grande Aquifer (LAGA) in the Escuinapa Valley, Sinaloa, a range of 10-34 particles/l was found (Alvarado-Zambrano, Rivera-Hernández, & Green-Ruiz, 2023).

Table 1 shows the ranges of microplastics found in groundwater around the world. China and India have the lowest concentrations, with a lower range of 0.000 MP/l (Selvam, Jesuraja, Venkatramanan, Roy, & Kumari, 2021; Shu *et al.*, 2023), while France has the highest concentration, with an upper range of 106.70 MP/l (Ledieu *et al.*, 2023).

Table 1. Groundwater microplastic concentrations.

Site	Concentration MP/l	Citation
Korea	0.006-0.192	Kim, Jeong, Lee, Chia and Raza (2023)
Korea	0.02-3.48	Cha, Lee and Chia (2023)
China	0.00-4.00	Shu <i>et al.</i> (2023)
India	0.00-4.30	Selvam <i>et al.</i> (2021)
Mexico	0.1-0.7	Our article
Iran	0.10-1.30	Esfandiari <i>et al.</i> (2022)
France	0.71-106.70	Ledieu <i>et al.</i> (2023)
India	2.00-80.00	Natesan, Vaikunth, Kumar, Ruthra and Srinivasalu (2021)
China	11.00-17.00	Wan <i>et al.</i> (2022)
Italy	12.00-54.00	Balestra, Vigna, De Costanzo and Bellopede (2023)
China	4.00-72.00	Shi <i>et al.</i> (2022)
Australia	16.00-97.00	Samandra <i>et al.</i> (2022)

In the comparison between the communities monthly MP averages (from February to November 2023), there were no significant differences, neither by air deposition ($p = 0.939$) nor in deep water ($p = 0.719$). Therefore, we gathered all the data and obtained a general average for air deposition (0.25 MP/l) and deep water (0.41 MP/l). A Wilcoxon test of the monthly averages (from February to November 2023) was performed, resulting in a $p < 0.001$; therefore, it was concluded that there are significant differences in the average MP between the communities (Table 2).

Table 2. Average number (\pm SD) of MP from 10 groundwater samples from San Diego Xocoyucan and Ixtacuixtla de Mariano Matamoros, Mexico, and MP average (\pm SD) by climatic season. Different letters indicate significant statistical differences.

	Xocoyucan	Ixtacuixtla	Xocoyucan		Ixtacuixtla	
	MP/I $\bar{x} \pm SD$	MP/I $\bar{x} \pm SD$	Rainy MP/I $\bar{x} \pm SD$	Dry MP/I $\bar{x} \pm SD$	Rainy MP/I $\bar{x} \pm SD$	Dry MP/I $\bar{x} \pm SD$
Air deposition	0.25 \pm 0.08 ^a	0.25 \pm 0.09 ^a	0.21 \pm 0.05 ^a	0.29 \pm 0.09 ^a	0.20 \pm 0.04 ^a	0.30 \pm 0.10 ^a
Deep water	0.41 \pm 0.08 ^a	0.42 \pm 0.08 ^a	0.34 \pm 0.02 ^b	0.47 \pm 0.07 ^c	0.36 \pm 0.04 ^b	0.49 \pm 0.07 ^c

The Shapiro-Wilk Normality analysis showed no normality in the data ($p = 0.001$), and the Levene test showed homogeneity of variances ($p = 0.677$); thus, to compare the number of microplastics obtained in deep well water vs. those in surface water that resulted from air deposition. Letters a and b show that there is a significant difference (Figure 2).

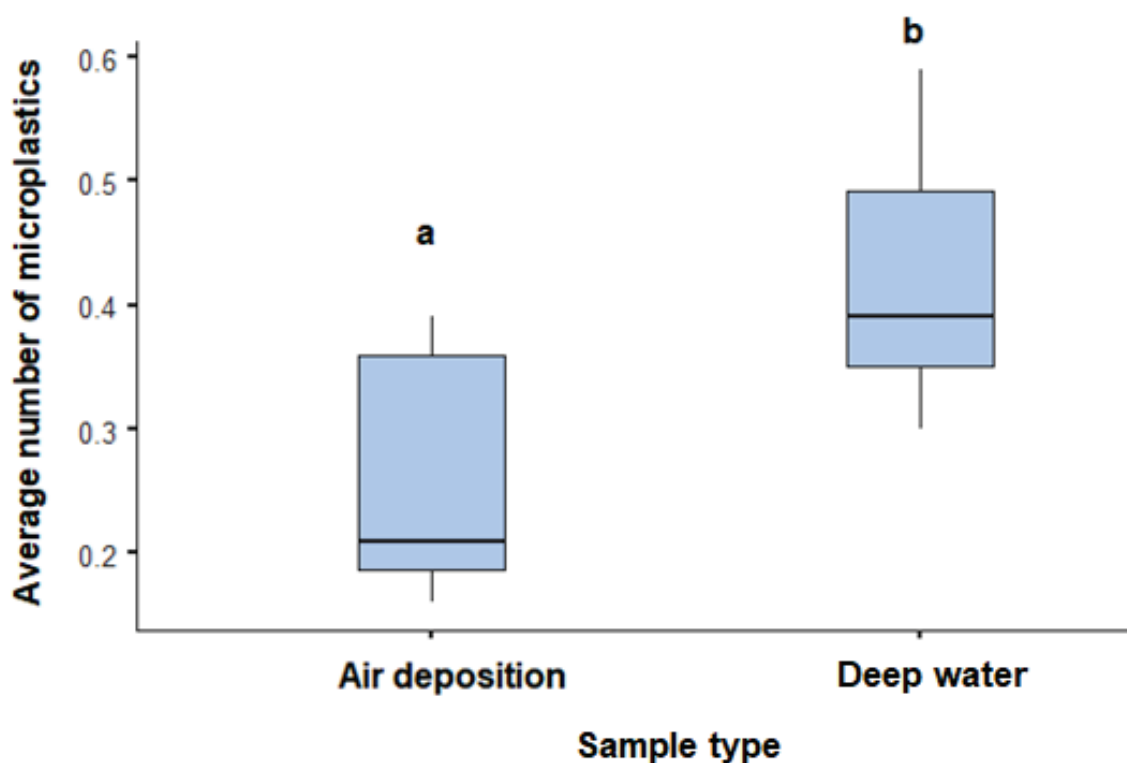


Figure 2. Microplastics in groundwater samples from deep water and air deposition.

Physical characteristics of microplastics

The MP measured 2 100 to 4 400 μm in length, averaging $2\,995 \pm 437$ μm ; 100 % of the MP found were fragments (Figure 3). This shape coincides with what was reported in groundwater samples from Chennai, India (Khant & Kim, 2022; Kumar & Sharma, 2021; Natesan *et al.*, 2021); from Krakow, Poland (Połec, Aleksander-Kwaterczak, Wątor, & Kmiecik, 2018); from Tamil Nadu, India (Ganesan, Nallathambi, & Srinivasalu, 2019; Selvam *et al.*, 2021); from Victoria, Australia (Samandra *et al.*, 2022); from Holdorf, Germany (Mintenig *et al.*, 2019); from Rüsselsheim, Germany (Weber, Kerpen, Wolff, Langer, & Eschweiler, 2021); from 17 sites in Denmark (Strand, Johnson, Nathanail, MacNaughtan, & Gomes,

2018), and from Skåne, Sweden (Kirstein *et al.*, 2021). In other studies, fibers and fragments have been found in groundwater, the two most common forms (Khant & Kim, 2022). In the Yucatan Peninsula groundwater, three forms were found: fragments, fibers, and spheres (Mendoza-Olea *et al.*, 2022); and in Sinaloa (Northern Mexico) foams, fragments, and films were identified (Alvarado-Zambrano *et al.*, 2023).

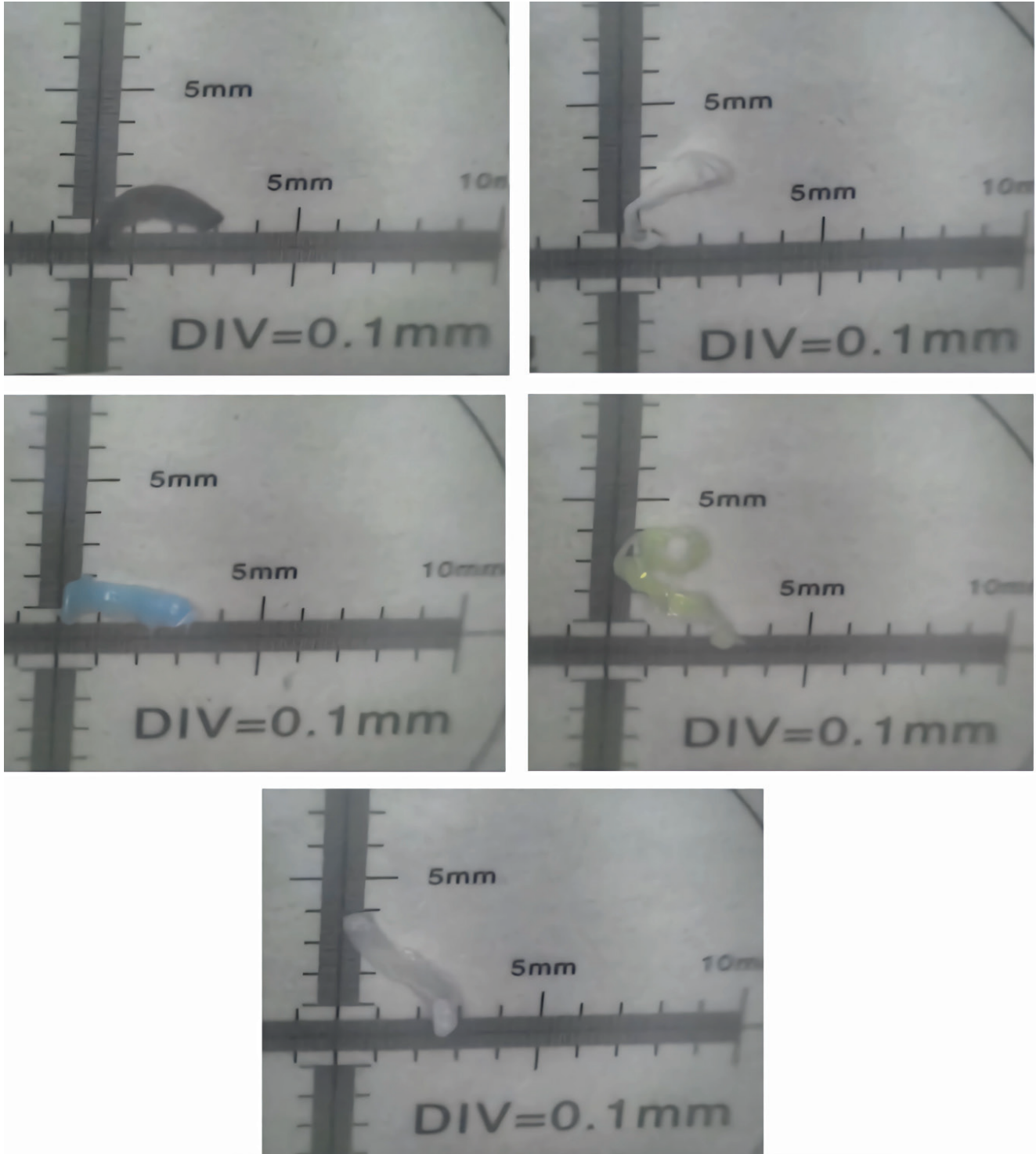


Figure 3. Photographs of microplastics extracted from groundwater samples in San Diego Xocoyucan and Ixtacuixtla de Mariano Matamoros, Tlaxcala, Mexico.

Regarding the color distribution, MP of black > white > blue > green > gray were recorded in both communities (Figure 4).

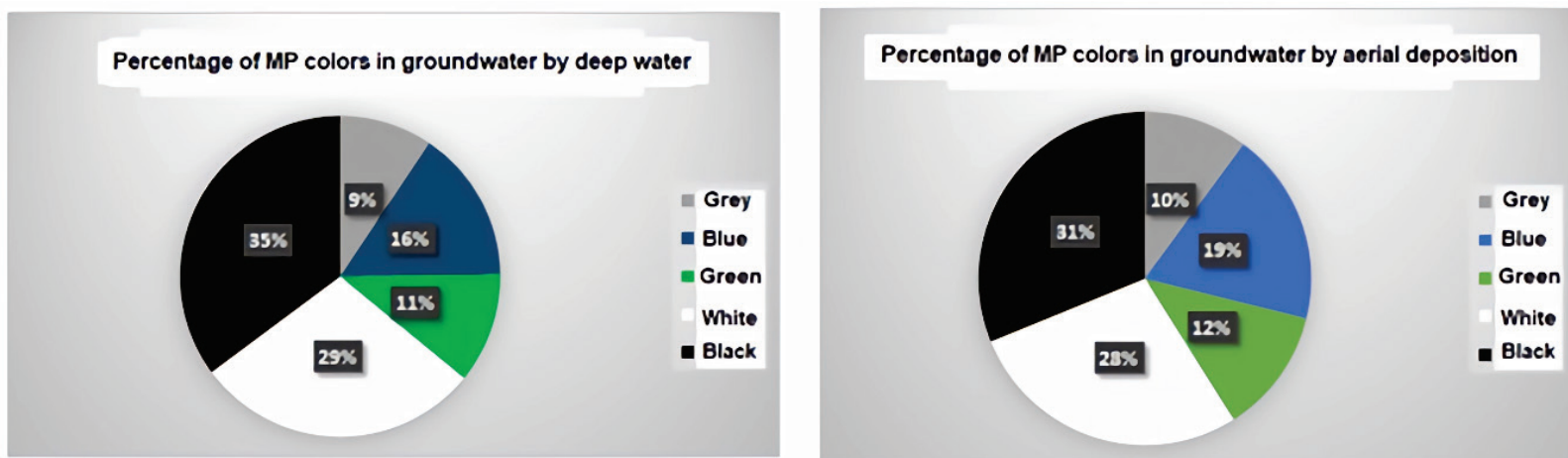


Figure 4. Percentage of the different colors of MP in groundwater from deep wells and in groundwater by air deposition in the ten wells sampled at the San Diego Xocoyucan and Ixtacuixtla site of Mariano Matamoros, Mexico, from February to September 2023.

The communities of San Diego Xocoyucan and Ixtacuixtla de Mariano Matamoros, Tlaxcala, Mexico, generate domestic, agricultural, and industrial waste. Even more, urban solid waste and wastewater are not efficiently managed. All of the above generates plastic pollution in the region and its groundwater. Black-colored MP mainly come from tires and plastic bags (Ding *et al.*, 2023; Huang & Xu, 2022; Lenaker *et al.*, 2019; Nogo *et al.*, 2021); MP of other colors derive from the degradation of commonly used plastic products, textiles, and packaging products (Kabir, Wang, Luster-Teasley, Zhang, & Zhao, 2023; Wang, Lin, & Chen, 2020). The color of MP can provide data on the composition of solid waste and

the level of plastic degradation. White plastics may indicate that the degradation process in situ takes a long time, turning other colors into white (Matthews *et al.*, 2021; Natesan *et al.*, 2021; Sun *et al.*, 2021).

Nearly forty tons of garbage are produced daily in the 23 communities of Ixtacuixtla, Mexico, where the majority is plastic (Lima, 2018). Of the 23 communities, the municipal seat and San Diego Xocoyucan, Mexico, are the ones that produce the most garbage. Although there are compactor trucks, the Municipality must implement a waste separation campaign and make people aware of waste management (Lima, 2018). Awareness is essential because residents throw garbage in a ravine located in Trinidad Tenexyecac, Municipality of Ixtacuixtla, located on the San Martín Texmeluca-Tlaxcala highway, which has been used as a garbage dump since approximately 2017 (Padilla, 2018).

From our results, it is clear that groundwater can be a source of exposure to microplastics in rural communities worldwide. However, there is still a lack of studies calculating the health risks of these practices; nevertheless, this study is a first step in calculating exposure for rural communities that drink groundwater without any treatment.

Polymer characterization

The polymers found were Nylon, High-Density Polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET), the latter, along with polyethylene (PE) are the materials most found in groundwater (Huang *et al.*, 2021; Mintenig *et al.*, 2019; Rillig, Ziersch, & Hempel, 2017; Samandra *et al.*, 2022; Weber *et al.*, 2021). PET is used to produce trays, jars, reusable

food containers, glasses, or bottles due to its physic and chemicals properties that promote food and beverage conservation (Nisticò, 2020; Benyathiar, Kumar, Carpenter, Brace, & Mishra, 2022).

PET/Polyester can also be used in textiles, especially with materials such as cotton (Forrest, 2019). PET/Polyester fabrics are firm, flexible, and prevent shrinkage compared to cotton. In addition, the materials are light and resistant to dragging and tearing, which allows quality products to be manufactured. The PET/Polyester helps improve the performance and durability of the products. Therefore, it has become a popular material for plastic processors to make more profits in manufacturing (Park & Kim, 2014).

Conclusions

In the present work, MP contamination was characterized in groundwater used for human consumption in two rural communities in Tlaxcala, Mexico. The results showed that the dry season presents more MP than the rainy season, possibly due to a dilution effect. Statistically, there are no significant differences in the average number of MP between the communities. The most representative color was black, possibly derived from the degradation of tires and plastic bags. The primary sources of plastics in the region are waste from agricultural, industrial, and domestic activities that move between different environmental compartments until groundwater is reached, either by air deposition or infiltration. Both communities need adequate management of urban solid waste and water treatment plants to counteract plastic pollution. Groundwater from wells can contain microplastics, and people who use that water without prior treatment may consume MP. The findings of this work provide information

on the scarce study of MP in groundwater and will help calculate MP exposure for rural populations worldwide.

Different ways have been applied to prevent pollution in the community as alternatives for pollution prevention. The president of the Ixtacuixtla, Mexico Municipality, called neighbors to report any person who litters on public roads to authorities to sanction them and thus instill the culture of caring for the environment, to benefit the environment and to avoid pollution and flooding during the rainy season (Padilla, 2017; Lima, 2018).

Population growth, poorly planned industrial development, and uncontrolled production processes have left a significant footprint of environmental deterioration in the Atoyac basin (Estrada-Rivera *et al.*, 2022). The Atoyac basin pollution exceeds Official Mexican Water Quality Standards (LFD) and International Standards (Estrada-Rivera *et al.*, 2022; Montero-Montoya *et al.*, 2020); therefore, human activities are positively correlated with the degradation of water quality in the world's rivers; our results show that groundwater microplastic pollution can result from the same unsound practices.

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