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Sheza Khalil Ahmad

College of Earth and Environmental Sciences, University of the Punjab, Lahore 54590, Pakistan.

Muhammad Asim Imran

School of Resources and Safety Engineering, Chongqing University, Chongqing, China.

Muhammad Safdar

m.safdar@xust.edu.cn

College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China. <https://orcid.org/0009-0006-1779-6967>

Aamir Raza

Precision Agriculture Center, Department of Soil, Water and Climate, University of Minnesota, St. Paul, MN 55108, USA.

Imran Shauket

Department of Structures and Environmental Engineering, University of Agriculture, Faisalabad 38000, Pakistan

Uswa Zahid

College of Earth and Environmental Sciences, University of the Punjab, Lahore 54590, Pakistan.

Muhammad Aqib Javed

College of Earth and Environmental Sciences, University of the Punjab, Lahore 54590, Pakistan.

Israr Khan

Fuzhou University School of Environment and Resources: Fuzhou University College of Environment and Safety Engineering

Saffi Ur Rehman

College of Agricultural Science and Engineering, Hohai University, Nanjing, 210024, China

Rehan Mehmood Sabir

National Centre of GIS and Space Applications (NCGSA)-Agricultural Remote Sensing Lab (ARSL), University of Agriculture, Faisalabad 38000, Punjab, Pakistan.

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Microplastics in Drinking and Irrigation Groundwater of Kasur District, Pakistan: Abundance, Polymer Composition, and Source Identification

Sheza Khalil Ahmad¹, Muhammad Asim Imran², Muhammad Safdar^{3,4*}, Aamir Raza⁵, Imran Shaukat⁶, Uswa Zahid¹, Muhammad Aqib Javed¹, Israr Khan², Saffi Ur Rehman⁷, Rehan Mehmood Sabir⁴

¹College of Earth and Environmental Sciences, University of the Punjab, Lahore 54590, Pakistan.

²School of Resources and Safety Engineering, Chongqing University, Chongqing, China.

³College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China.

⁴National Centre of GIS and Space Applications (NCGSA)-Agricultural Remote Sensing Lab (ARSL), University of Agriculture, Faisalabad 38000, Punjab, Pakistan.

⁵Precision Agriculture Center, Department of Soil, Water and Climate, University of Minnesota, St. Paul, MN 55108, USA.

⁶Department of Structures and Environmental Engineering, University of Agriculture, Faisalabad 38000, Pakistan

⁷College of Agricultural Science and Engineering, Hohai University, Nanjing, 210024, China

Corresponding Author: *Muhammad Safdar; Email: m.safdar@xust.edu.cn

Abstract

Groundwater supplies most drinking and irrigation water in Punjab, Pakistan. The extent of microplastic (MP) contamination in the aquifer is still largely unknown. This study presents the first tehsil-level survey of MPs in the groundwater of Kasur District, a semi-urban district with intensive farming and a large textile and leather-processing sector. We collected 50 groundwater samples (200 mL each) in glass bottles from hand pumps, tube wells, motor pumps, municipal taps, filtration plants, and drain water across four tehsils: Kasur, Chunian, Pattoki, and Kot Radha Kishan. We digested samples with 30% H₂O₂ and vacuum-filtered them through 4 µm gridded filters. We counted and classified the particles under an optical microscope and confirmed a subset by ATR-FTIR spectroscopy. MPs were present in all 50 samples. Mean concentrations ranged from 5.08 to 5.61 particles per 200 mL ($\approx 25\text{--}28$ particles L⁻¹). Kasur was highest (5.61 ± 2.81) and Chunian lowest (5.08 ± 2.31). Fibres dominated ($\approx 70\%$), followed by fragments ($\approx 28\%$) and filaments ($\approx 2\%$). Transparent and white particles were the most common colour class (58–64% per tehsil). ATR-FTIR identified polyisobutylene as the most abundant polymer ($\approx 53\%$), followed by cellulose ($\approx 26\%$), polyethylene and ethylene-vinyl copolymers, polyester, fibreglass, and trace amounts of polyvinyl compounds, polyphenylene sulfide, and ethylene vinyl alcohol. The mix of fibres, PIB, and cellulose suggests domestic sewage, textile effluent, and plastic packaging as the main sources. These results provide a first baseline for drinking-water safety and irrigation exposure in Punjab. The district depends entirely on this shallow aquifer for drinking water and crop irrigation. The findings therefore underscore a widespread, ongoing exposure pathway for residents.

Keywords: Microplastics; Groundwater; Drinking-water quality; ATR-FTIR spectroscopy; Polyisobutylene; Source identification; Punjab, Pakistan.

1. Introduction

Global plastic production has risen sharply since the 1950s. About 8,300 million metric tons of virgin plastic have been produced to date, and roughly 79% has ended up in landfills or the environment (Geyer et al., 2017). Microplastics (MPs) are plastic particles smaller than 5 mm (Thompson et al., 2004; Hartmann et al., 2019). They form through mechanical abrasion, UV photo-oxidation, and thermal cycling of larger plastic debris. Each year, mismanaged waste streams carry them from land into rivers and oceans (Jambeck et al., 2015). MPs were once treated as a marine issue (Andrady, 2011; Cole et al., 2011). They are now recognized as widespread pollutants of freshwater, soil, air, and human food chains (Eerkes-Medrano et al., 2015; Dris et al., 2016; Allen et al., 2019; Brahney et al., 2020).

Most people depend on groundwater for drinking. As a result, drinking water is a major route of human exposure to microplastics. MPs have been found in bottled water (Mason et al., 2018; Oßmann et al., 2018; Schymanski et al., 2018; Kankanige and Babel, 2020), in raw and treated supplies at conventional treatment plants (Pivokonsky et al., 2018), in distribution networks (Kirstein et al., 2021), and in municipal tap supplies on several continents (Kosuth et al., 2018; Mukotaka et al., 2021). Reviews agree that contamination is widespread. Reported concentrations, however, vary by several orders of magnitude. The main reasons are differences in sampling volume, lower size cut-off, and analytical verification (Koelmans et al., 2019; Danopoulos et al., 2020). The World Health Organization has called for better occurrence data, especially from source waters, to support human health risk assessment (WHO, 2019).

Groundwater is the least studied part of the drinking-water cycle. Aquifers were long assumed to be protected by soil filtration. Recent field studies have challenged that view. MPs have been detected in groundwater in the United States (Panno et al., 2019), in unconfined alluvial aquifers in Australia (Samandra et al., 2022) and Iran (Esfandiari et al., 2022), in coastal aquifers of south India (Selvam et al., 2021), on volcanic Jeju Island, Korea (Kim et al., 2023), and in groundwater-derived drinking water in Bangladesh, where mean concentrations reached 24.63 ± 16.13 items L^{-1} (Paray et al., 2024; Sangkham et al., 2023). In well-managed, protected European aquifers, concentrations are orders of magnitude lower (Mintenig et al., 2019). This contrast shows that sanitation infrastructure, waste management, and land-use pressure, not aquifer geology alone, drive groundwater vulnerability (Re, 2019; Kim and Lee, 2020). Likely entry routes include septic and sewer leakage, landfill leachate, wastewater-irrigated soils, effluent-fed drains, and atmospheric fiber deposition (Carr et al., 2016; Ziajahromi et al., 2017; Dris et al., 2016). Wastewater treatment plants act as key collection and release points for fibers and fragments.

The health case for closing this data gap is growing. Hazard frameworks now separate physical particle effects, chemical effects from monomers and additives, and biological effects linked to biofilms on plastic surfaces (Vethaak and Legler, 2021; WHO, 2019; Wright and Kelly, 2017).

Conservative estimates put human MP intake in the tens of thousands of particles per year, with drinking water as a major contributor (Cox et al., 2019). Plastic particles have been found in human blood (Leslie et al., 2022) and placental tissue (Ragusa et al., 2021), and have been linked to cardiovascular disease in clinical cohorts (Marfella et al., 2024). Inhalation of airborne fibres is another concern (Prata, 2018; Barboza et al., 2018). In groundwater-dependent farming regions such as South Asia, risk increases through two routes: direct ingestion of drinking water and indirect exposure through soil–crop uptake. Researchers are only beginning to study the long-term effects (Esfandiari et al., 2022; Paray et al., 2024).

Pakistan combines high exposure potential with almost no data. Groundwater is the main source of domestic and agricultural water in Punjab, the country's most populous and industrially developed province. However, no published study has described MPs in Punjab's aquifers. Related work has reported MPs in peri-urban agricultural soils near Lahore (Luqman et al., 2023) and in freshwater fish from the Punjab Barrage, South Punjab (Raheel et al., 2025). MPs are therefore already widespread in Punjab's land and surface-water systems. The groundwater pathway remains the only unstudied link in this chain.

Kasur District, which borders India southeast of Lahore, concentrates the risk factors noted above: intensive year-round irrigated agriculture, one of Pakistan's largest clusters of textile and leather-processing industry, densely settled rural communities reliant on hand pumps and shallow tube wells, and long-standing weaknesses in solid-waste and effluent management.

This study addresses that gap. It provides the first systematic, spectroscopically verified assessment of MPs in groundwater of Kasur District. It aims to (i) quantify MP abundance in 50 groundwater samples from the four tehsils of Kasur, Chunian, Pattoki, and Kot Radha Kishan; (ii) describe particle shape and colour as source-related traits; (iii) determine polymer composition by ATR-FTIR spectroscopy; and (iv) evaluate likely sources and transport pathways through an integrated morphotype–colour–polymer analysis, compared with global groundwater and drinking-water studies.

2. Materials and Methods

2.1. Study area

Kasur District lies in central Punjab, Pakistan (31.12–31.55°N, 73.50–74.45°E; $\approx 3,995$ km²), on the alluvial plain (Fig. 1). It has four tehsils: Kasur, Chunian, Pattoki, and Kot Radha Kishan. The district is one of the province's most fertile and productive agricultural areas. It has flat topography, year-round cultivation across two crop seasons, canal and fresh groundwater resources, and fertile alluvial soils. The climate is semi-arid subtropical, with long hot summers (often 40–45 °C), cool winters (3–7 °C), and annual rainfall of 300–500 mm. The shallow

unconfined alluvial aquifer is heavily abstracted, especially during the July–September monsoon. Several factors may raise the aquifer's vulnerability to plastic contamination: high evaporation, intensive irrigation, a dense rural population, and a large textile, hosiery, and leather-processing sector, much of which discharges to open drains.

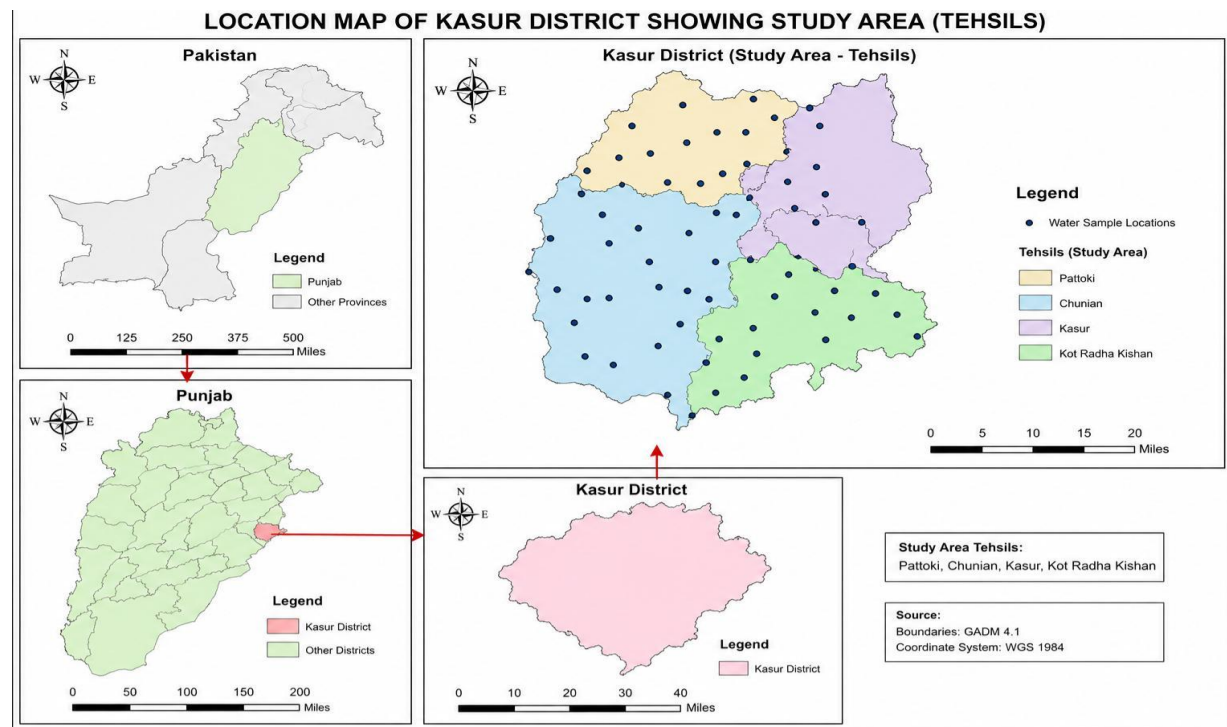


Figure 1. Study area map of (a) Pakistan, (b) Punjab Province, and (c) Kasur District and its tehsils.

2.2. Sampling design and collection

We collected samples from the main local groundwater sources: hand pumps, tube wells, motor pumps, municipal taps, and household or commercial filtration plants. We also collected drain water as an end-member source. In total, we collected 50 samples across the four tehsils, with 12–13 per tehsil (Table 1, Fig. 2).

To avoid container contamination, we collected all samples in pre-cleaned glass bottles. We triple-rinsed bottles with distilled water and then with sample water. We collected about 200 mL at each site. We sealed the bottles immediately and labelled them with the sample ID, GPS location, tehsil, and source type. We transported them under clean, cool conditions to the Toxicology Laboratory, College of Earth and Environmental Sciences, University of the Punjab.

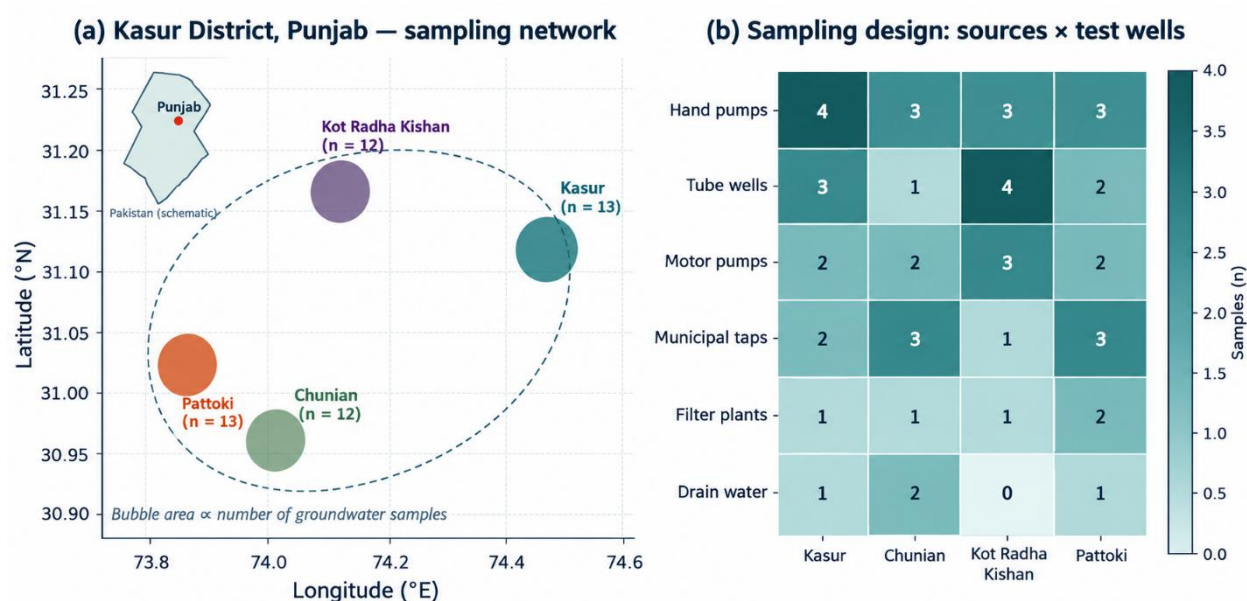


Figure 2. (a) Location of the four sampled tehsils of Kasur District, Punjab, Pakistan, with sample intensity (bubble area $\propto$ number of samples; inset: schematic position of Punjab within Pakistan). (b) Sampling design matrix showing the indicative allocation of the 50 groundwater samples across source categories and tehsils, consistent with the tehsil totals in Table 1.

Table 1. Sampling design: groundwater sampling effort and dominant source types across the four tehsils of Kasur District.

Tehsil	Approx. coordinates	Samples (n)	Major sampled sources
Kasur	31.12°N, 74.45°E	13	Tap water, tube wells, hand pumps, filtration units
Chunian	30.96°N, 73.98°E	12	Hand pumps, municipal taps, groundwater
Kot Radha Kishan	31.17°N, 74.10°E	12	Tube wells, motor pumps, filtration plants
Pattoki	31.02°N, 73.85°E	13	Groundwater, hand pumps, municipal supply
Total	—	50	—

2.3. Analytical methodology

2.3.1. Sample digestion, filtration, and preservation

Each 200 mL sample was oxidized with 1.5 mL of 30% hydrogen peroxide (H_2O_2) under continuous magnetic stirring and gentle heating for about 10 min. This follows the principles of wet peroxide oxidation used for water matrices (Hidalgo-Ruz et al., 2012; Koelmans et al., 2019). Digested samples were vacuum-filtered through 4 μm gridded filter paper, which retained small fibers and fragments. Rinse filter units and retained material with distilled water to improve recovery. Loaded filters were placed in a sterile glass Petri dish, air-dried at room temperature for 24 h, and then analyzed

2.4. Optical microscopy and particle classification

Dried filters were examined under an optical microscope. Suspect MPs were identified using standard visual criteria: absence of cellular structure, uniform colour, and, for fibres, uniform thickness without tapering (Hidalgo-Ruz et al., 2012). Particles were classified by morphotype (fibers, filaments, fragments), estimated size, colour (transparent/white, blue, red, black, brown), and surface texture. All counted particles were recorded per sample, tehsil, and source type.

2.5. ATR-FTIR polymer identification

Suspect MPs identified under the microscope were then verified by attenuated total reflectance Fourier-transform infrared (ATR-FTIR) spectroscopy. We pressed each particle against the ATR crystal, recorded infrared absorption spectra, and compared them with a polymer reference library. This method is now standard for polymer verification in MP research (Shim et al., 2017; Primpke et al., 2018; Ivleva, 2021). The sample set included spectra matching polyisobutylene, polyethylene, polyester, ethylene vinyl alcohol (EVOH), and polyvinyl-type polymers. We recorded cellulose separately and report it as an anthropogenic cellulosic fibre, distinct from synthetic polymers. Fiberglass was also detected. Because fibreglass is inorganic, we reported it separately from synthetic polymers.

2.6. Quality assurance and quality control

We collected all samples in glass bottles to avoid plastic container contamination. We further limited contamination by using cotton laboratory coats, rinsing all apparatus with distilled water, covering samples with aluminium foil between steps, and processing procedural blanks (distilled water controls). Five procedural blanks were processed. No particles were detected in any blank, so counts were not blank corrected. This approach follows emerging best practice for MP analysis (Koelmans et al., 2019; Kirstein et al., 2021).

2.7. Data analysis

We collated particle counts by tehsil, source type, morphotype, and colour. Means and standard deviations (SD) are reported per 200 mL sample. For international comparison, data were normalized to particles L^{-1} ($\times 5$ factor). We summarized colour composition in each tehsil with a semi-quantitative dominance matrix (dominant/common/minor/absent), anchored to the measured share of transparent particles. We normalized relative polymer abundances from ATR-FTIR to 100% per tehsil and compiled them into a district profile. We then combined morphotype shares and polymer profiles with district land-use data in a conceptual source-identification matrix linking emission sources, particle forms, and polymer families. The overall workflow is summarized in Fig. 3.

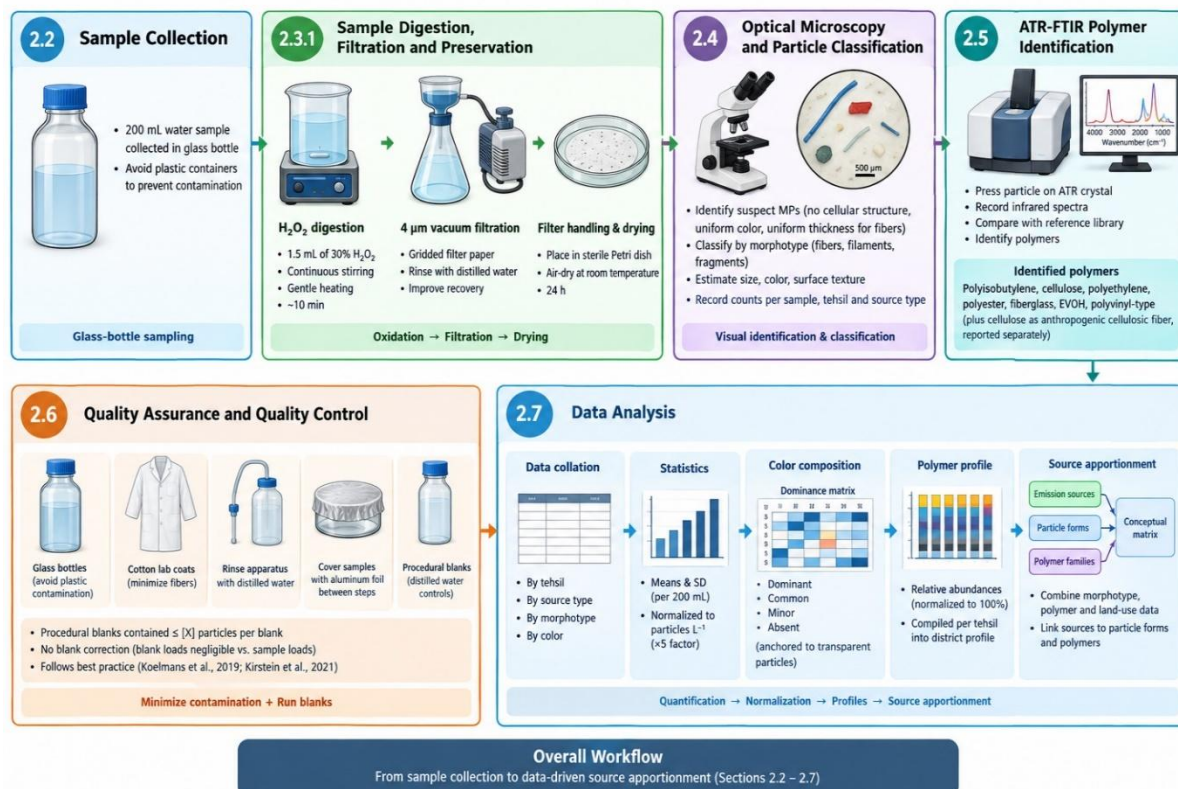


Figure 3. Methodology flowchart: summary of sample collection, digestion, filtration, optical/ATR-FTIR characterization, and data-analysis steps described in Sections 2.2–2.7.

3. Results

3.1. Occurrence and magnitude of MP contamination

MPs were found in all 50 samples (100% occurrence). This shows that MP contamination of the shallow aquifer is not localized. Mean loads were highest in Kasur (5.61 ± 2.81 particles per 200 mL), followed by Kot Radha Kishan (5.33 ± 3.05), Pattoki (5.15 ± 3.80), and Chunian (5.08 ± 2.31) (Table 2, Fig. 4a). After normalization, these values equal about 25–28 particles L⁻¹ (district mean ≈ 26.5 particles L⁻¹).

The narrow inter-tehsil range (5.08–5.61) points to a broad background of contamination. The highest values in Kasur, the most urbanized and industrialized tehsil, align with greater pressure from urban runoff, wastewater discharge, and industry. Large standard deviations indicate real differences between source types.

Table 2. Microplastic abundance by tehsil and morphotype (mean $\pm$ SD, particles per 200 mL sample)

Tehsil	Total MPs	Fibers	Filaments	Fragments
Tehsil	Total MPs	Fibers	Filaments	Fragments
Kasur	5.61 ± 2.81	4.23 ± 2.05	0.23 ± 0.43	1.79 ± 0.98

Tehsil	Total MPs	Fibers	Filaments	Fragments
Kot Radha Kishan	5.33 ± 3.05	3.50 ± 2.77	0.00 ± 0.00	1.83 ± 1.27
Pattoki	5.15 ± 3.80	3.76 ± 2.62	0.31 ± 0.48	1.08 ± 1.55
Chunian	5.08 ± 2.31	3.67 ± 2.18	0.00 ± 0.00	1.42 ± 1.24
District mean	5.29	3.79	0.14	1.53

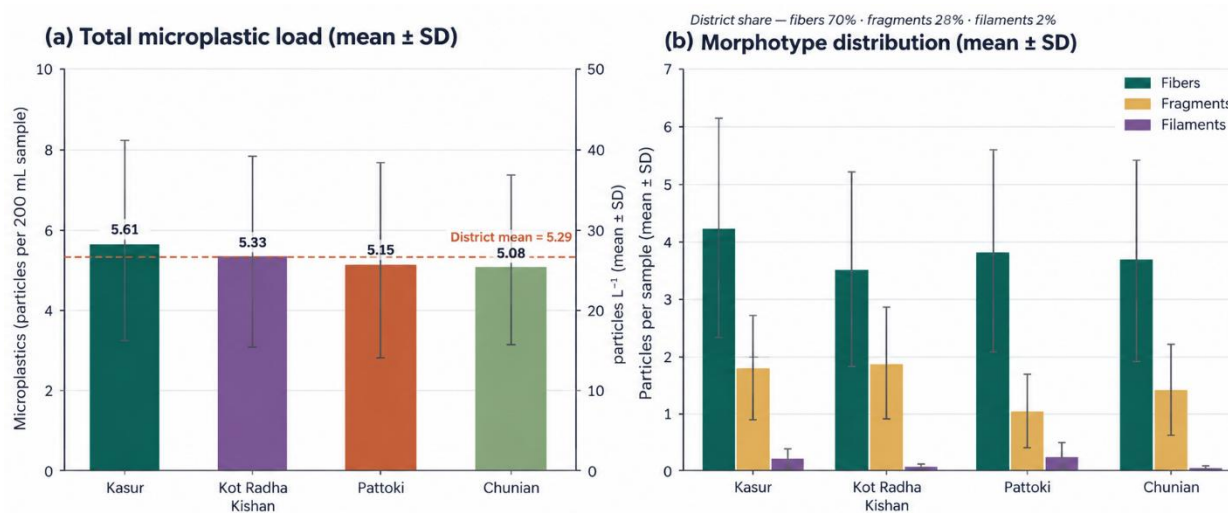


Figure 4. (a) Total microplastic load per tehsil (mean ± SD; dashed line = district mean; right axis shows volumetric normalization to particles L⁻¹). (b) Morphotype distribution (mean ± SD) showing district-wide dominance of fibers.

3.2. Morphotype distribution

Fibers were the most abundant morphotype in every tehsil (Fig. 4b). Counts were highest in Kasur (4.23 particles per sample) and lowest in Kot Radha Kishan (3.50). District-wide, fibers made up about 70% of all particles. Fragments ranked second ($\approx 28\%$), with the highest mean in Kot Radha Kishan (1.83 ± 1.27) and the lowest in Pattoki (1.08 ± 1.55). Filaments were rare ($\approx 2\%$) and appeared only in Kasur and Pattoki. This suggests local inputs of synthetic monofilament material in those two tehsils. The order fibers > fragments > filaments match the pattern seen in sewage- and textile-affected water (Carr et al., 2016; Ziajahromi et al., 2017).

3.3. Color composition

Transparent and white particles predominated in all tehsils, ranging from 58.20% in Pattoki to 63.51% in Kasur (Table 3, Fig. 5). Blue and red particles were consistently present. Black and brown particles were minor and tehsil-specific: black was a secondary color in Kasur, and brown was a secondary color in Pattoki. The high share of transparent and white particles may reflect

weathering and bleaching of older plastic waste. Colored particles may come from packaging, consumer goods, and dyed textile fibers (Dris et al., 2016; Paray et al., 2024).

Table 3. Dominant, secondary, and minor color classes of microplastics by tehsil, with the quantified share of transparent/white particles.

Tehsil	Dominant color	Secondary colors	Minor colors
Chunian	Transparent (62.29%)	Blue, red	Black, brown
Kasur	Transparent (63.51%)	Red, black	Blue, brown
Pattoki	Transparent (58.20%)	Red, brown	Blue, black
Kot Radha Kishan	Transparent (62.50%)	Blue, red	Brown, black

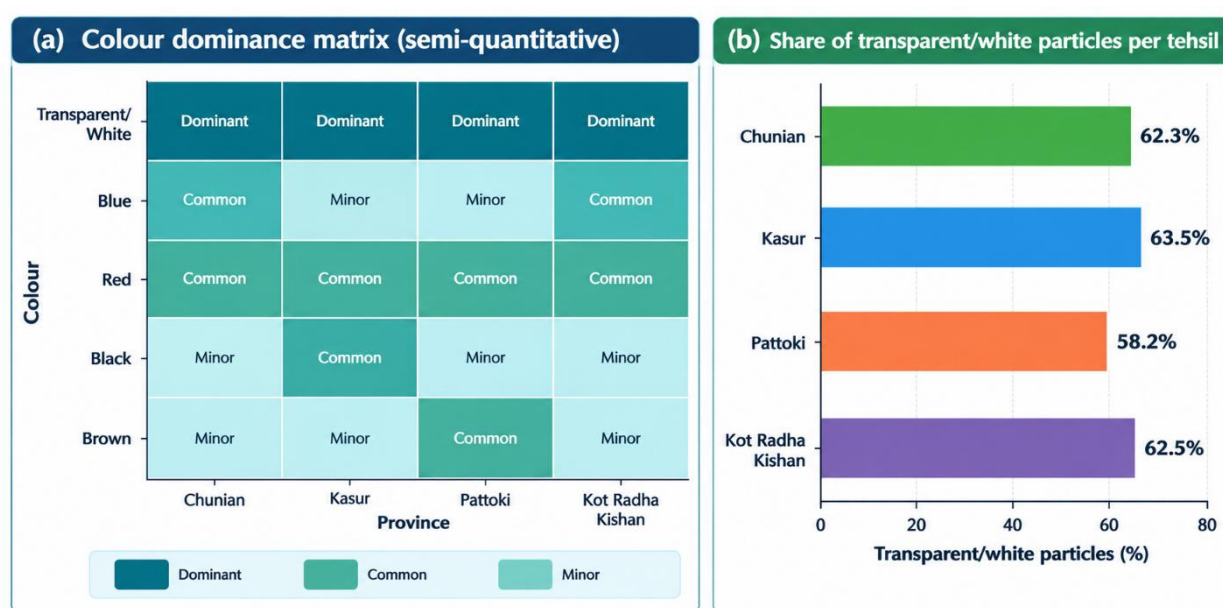


Figure 5. (a) Semi-quantitative color-dominance matrix across tehsils. (b) Quantified share of transparent/white particles per tehsil.

3.4. Polymer composition from ATR-FTIR

ATR-FTIR confirmed five synthetic polymer families, plus cellulose and fiberglass, across the district (Table 4, Fig. 6). Polyisobutylene (PIB) was the most abundant in all four tehsils: 76.9% in Kasur, 50.0% in Chunian, 46.1% in Pattoki, and 41.6% in Kot Radha Kishan (district aggregate $\approx 53\%$ after normalization). Cellulose was second (district $\approx 26\%$; 33.3–38.4% in Kot Radha Kishan, Chunian, and Pattoki; 7.6% in Kasur), reflecting natural textile fibers and cellulosic debris.

The remaining profile included polyethylene and ethylene-vinyl copolymers (including EVOH), polyester, fiberglass, and traces of polyvinyl compounds and polyphenylene sulfide. Polymer diversity was highest in urbanized Kasur and at the agriculture–industry interface in Kot Radha Kishan. It was lowest in Chunian, where emission sources are fewer.

Table 4. Relative abundance of ATR-FTIR-confirmed polymers by tehsil (% of identified polymers; dash = not detected).

Polymer	Kasur	Kot Radha Kishan	Chunian	Pattoki
Polyisobutylene	76.9	41.6	50.0	46.1
Cellulose	7.6	33.3	33.3	38.4
Polyethylene/ethylene–vinyl	7.6	8.3	0.1	—
Polyester	7.6	—	—	—
Fiberglass	—	8.3	16.6	—
Other / trace (polyvinyl, PPS, EVOH)	0.3	8.5	—	15.5

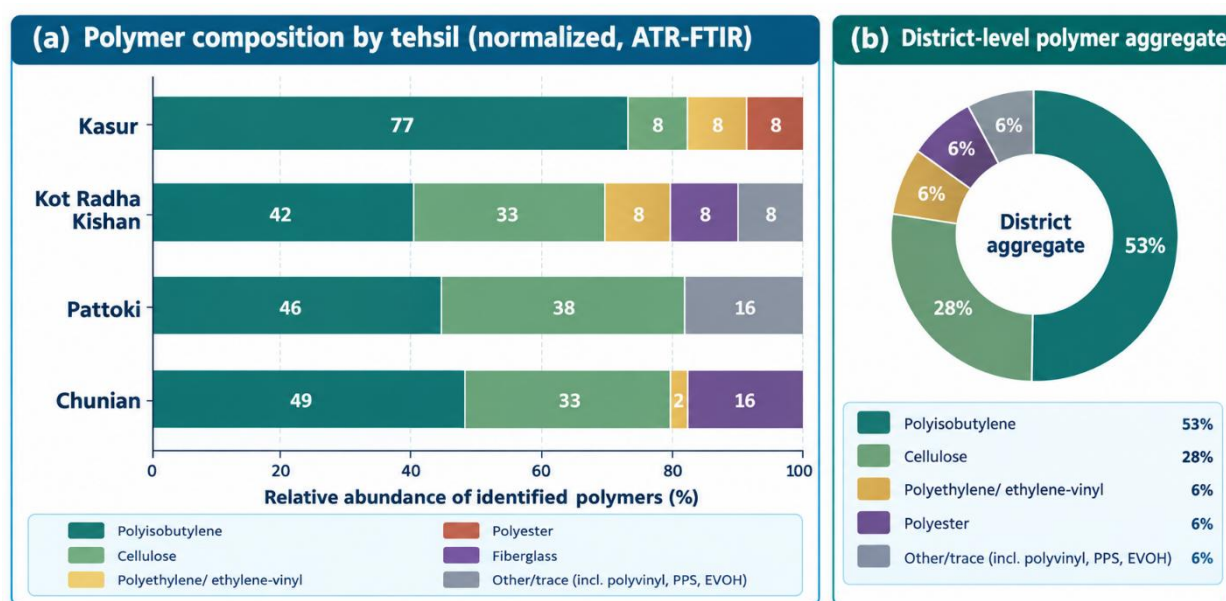
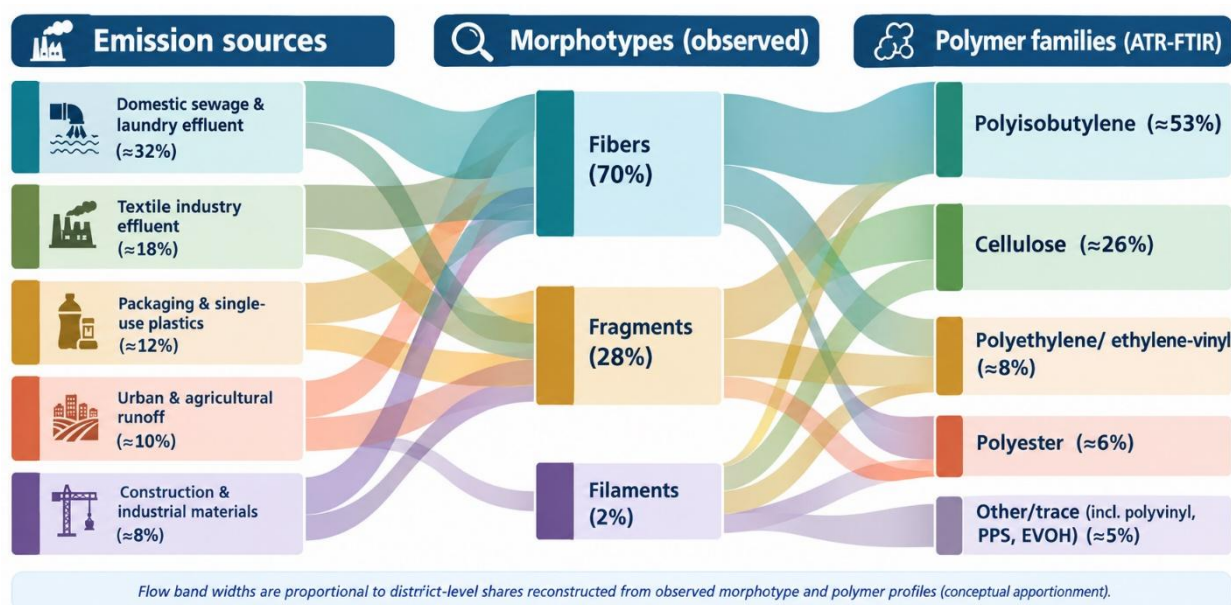


Figure 6. (a) Normalized polymer composition by tehsil from ATR-FTIR confirmation. (b) District-level aggregate polymer profile. PPS = polyphenylene sulfide; EVOH = ethylene vinyl alcohol.

3.5. Integrated source apportionment

Combining morphotype ($\approx 70\%$ fibers), color (mostly transparent/white, with steady red and blue fractions), and polymer fingerprint (PIB- and cellulose-dominated, with minor polyester, PE/ethylene-vinyl, and fiberglass) gives a consistent source picture for the district (Fig. 7). Fiber dominance points to domestic sewage and laundry greywater, which carry high loads of cellulosic and synthetic fibers, plus the district's large textile and hosiery industry. PIB, used in adhesives, sealants, and lubricants, suggests construction, automotive, and industrial inputs. PE and vinyl fragments indicate packaging and single-use plastic degradation. Fiberglass points to insulation, composites, and construction materials. Urban Kasur combines the most diverse mix of these inputs. Chunian's profile is simpler and dominated by agriculture.



microscopy-only surveys. Kasur's values should therefore be read as a baseline a minimum, not a maximum.

Table 5. Reported microplastic abundances in groundwater and drinking water worldwide, benchmarked against the present study.

Location	Water type	Abundance (items L ⁻¹)	Dominants morphotype / polymers	Reference
Kasur, Pakistan	Shallow alluvial groundwater	≈25–28 (mean 26.5)	Fibers ≈70%; PIB, cellulose, PE, polyester, fiberglass	Present study
Coastal Bangladesh	Groundwater wells	24.63 ± 16.13	Fibers (97.6%); LDPE, HDPE, EVA, PETE	Paray et al. (2024)
Victoria, Australia	Unconfined aquifer	≈38	PET, PP, PE, PS	Samandra et al. (2022)
Mexico	Public drinking fountains / kiosks	18 ± 7	Fibers, fragments; PTT, epoxy resin	Shruti et al. (2022)
Illinois, USA	Karst wells and springs	≤15.2 (mean ≈6.4)	Fibers (100%); PE	Panno et al. (2019)
South India	Wells and borewells	≈4.2	Fibers, foam, film; PA, PE, PET	Selvam et al. (2021)
Denmark	Tap water	≈0.3	Fibers (82%); PET, PP, PS	Strand et al. (2018)
Sweden	Treated tap water	0.174	Fragments; PA, PET, acrylates	Kirstein et al. (2021)
Germany	Groundwater-fed supply	≈0.0007	Fragments; PE, PA, polyester, PVC	Mintenig et al. (2019)

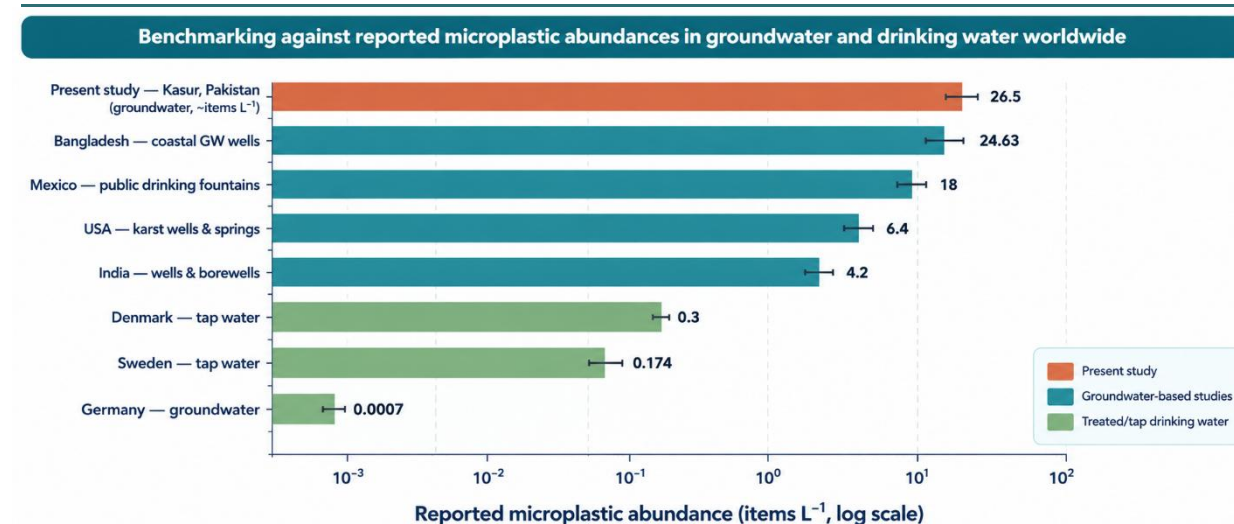


Figure 8. Benchmarking of the present study against reported microplastic abundances in groundwater and drinking water worldwide (log scale; values as compiled in Table 5).

4.2. Sources and pathways into the aquifer

The combined morphotype, colour, and polymer evidence points to multiple sources, summarized in Fig. 9. Domestic sewage and greywater are the most likely primary sources. Fibres dominated every tehsil and are typical of laundry effluent and municipal wastewater. In Kasur,

most of this wastewater is discharged untreated to open drains that recharge the shallow aquifer (Carr et al., 2016; Ziajahromi et al., 2017).

Second, the textile and hosiery sector, concentrated in Kasur city, releases synthetic (polyester) and cellulosic fibers. This aligns with the co-dominance of cellulose, higher fibre counts, and greater polymer diversity in Kasur tehsil.

Third, packaging and single-use plastics break down into the PE and vinyl fragments observed. Formal waste collection is limited across the district. Construction materials, adhesives, and sealants provide a plausible local source for the district-wide PIB signal, since PIB is produced in large amounts for sealants and adhesives (Andrady, 2017).

This PIB result deserves close attention. PIB is not the dominant polymer in any comparable groundwater or drinking-water study identified here. Fiber-forming polyethylenes (LDPE/HDPE) and EVA dominate Bangladesh's coastal aquifers (Paray et al., 2024). Polyethylene dominates Illinois karst wells (Panno et al., 2019). Polyamide, polyethylene, and PET dominate south Indian wells (Selvam et al., 2021). PET, PP, PE, and PS dominate the Victorian unconfined aquifer (Samandra et al., 2022). The district-wide PIB dominance in Kasur is therefore unusual. It strengthens the case for a distinct, spatially concentrated source possibly the district's sealant, adhesive, rubber, and tyre-related industries.

We therefore treat the PIB finding as provisional. To strengthen it, future work should confirm a subset of PIB-classified particles against a certified reference library or by a complementary technique such as Raman spectroscopy or pyrolysis-GC/MS. Future work should also test whether PIB-classified samples cluster near specific industrial sites, which would help identify point sources.

Fourth, agricultural practices can move particles into the unsaturated zone and recharge. These include irrigation with drain water, degradation of plastic mulch, and application of sludge or wastewater to fields (Esfandiari et al., 2022; Sangkham et al., 2023). Atmospheric fiber deposition adds a diffuse background, even in remote catchments (Dris et al., 2016; Allen et al., 2019; Brahney et al., 2020). Finally, abstraction and distribution infrastructure PVC or PE pipes, pump seals, storage tanks, and household filters may contribute directly (Mukotaka et al., 2021; WHO, 2019).

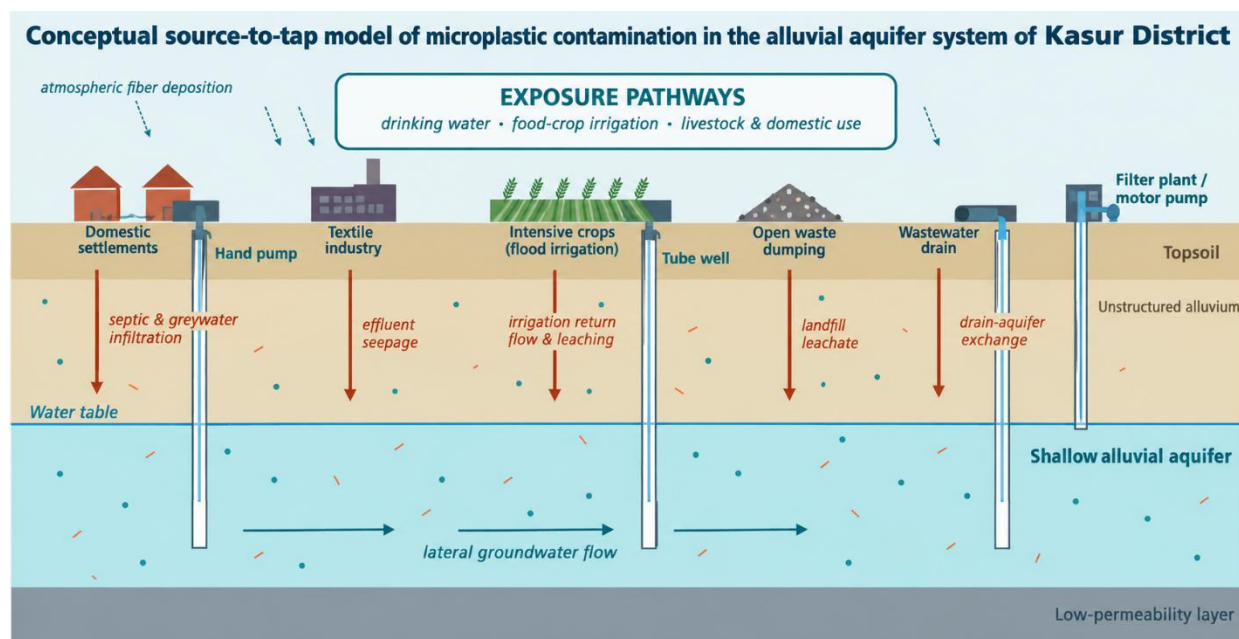


Figure 9. Conceptual source-to-tap model of microplastic contamination in the shallow alluvial aquifer system of Kasur District: surface emission sources, vadose-zone and drainage-mediated infiltration pathways, lateral groundwater transport, abstraction points, and human exposure routes.

4.3. Implications for drinking-water safety and irrigated agriculture

MPs were present in every Kasur groundwater sample. This has two implications. For drinking-water safety, nearly every resident who draws water from hand pumps, tube wells, or small filtration units is chronically exposed. At the observed district mean, and assuming a daily intake of about 2 L, this equals roughly 50 particles per person per day ($\approx 19,000$ per year). This is broadly comparable to exposure estimates for similarly contaminated supplies (Cox et al., 2019; Paray et al., 2024). It is far above the estimated exposure of <1 particle per year for high-performance European drinking-water treatment (Kirstein et al., 2021). No acute toxicity has been shown at these levels (WHO, 2019; Vethaak and Legler, 2021). Still, researchers have found plastic particles in human blood, placenta, and cardiovascular tissue (Leslie et al., 2022; Ragusa et al., 2021; Marfella et al., 2024). MPs can also carry additives, sorbed pollutants, and pathogens (Barboza et al., 2018; Selvam et al., 2021). These findings support a precautionary approach.

For irrigated agriculture, MPs in groundwater mean that irrigated soils receive a continuous MP input. This can affect soil structure, soil microbial communities, and crop uptake. It also means groundwater is moving urban and industrial contamination into the food system (Esfandiari et al., 2022). Household filter plants are common in the district but are not designed for MP removal, so they cannot be assumed to be protective. Conventional treatment trains also remove MPs only partially (Pivokonsky et al., 2018; Shannon et al., 2008). The main near-term option is source control: intercepting and treating wastewater, regulating textile effluent, and formalizing solid-waste collection. Global policy momentum is moving toward stricter classification and regulation of plastic waste (Rochman et al., 2013; UNEP, 2018).

4.4. Limitations and future research

This study has five main limitations. (i) The 200 mL aliquots are small compared with recommended volumes for drinking-water MP assessment (Koelmans et al., 2019), so heterogeneous particle distributions may be undersampled. (ii) Microscopy-based counting can misclassify particles, even with spectroscopic confirmation of a subset (Kirstein et al., 2021; Mukotaka et al., 2021). (iii) The 4 μm cut-off excludes sub-4 μm particles, which dominate counts in μFTIR or Raman studies (Oßmann et al., 2018; Schymanski et al., 2018). (iv) Single-campaign sampling cannot capture seasonal dynamics, monsoon recharge, or dry-season abstraction. (v) No mass-based quantification (pyrolysis-GC/MS) or formal polymer-hazard and dietary-intake indices were computed. Priority extensions include larger-volume and seasonal campaigns, Nile Red or μFTIR imaging workflows, soil–crop co-sampling along irrigation gradients, source fingerprinting of drains and effluents, and quantitative risk characterization for drinking-water and food-chain exposure.

5. Conclusions

This study provides the first spectroscopically verified baseline of microplastic contamination in groundwater of Punjab, Pakistan. MPs were present in all 50 samples from the four tehsils of Kasur District, with mean loads of 5.08–5.61 particles per 200 mL ($\approx 25\text{--}28$ particles L^{-1}). Loads were highest in the urbanized tehsil of Kasur. Fibers were the dominant morphotype ($\approx 70\%$). Transparent and white particles were most common (58–64%). ATR-FTIR showed a polymer profile dominated by polyisobutylene, with substantial cellulose and minor polyethylene/ethylene-vinyl, polyester, fiberglass, and traces of vinyl, PPS, and EVOH.

Domestic sewage, textile-industry effluent, packaging waste, and construction materials appear to be the main sources. These enter the shallow aquifer through drainage, irrigation return flow, landfill leaching, and failing waste infrastructure. Kasur's groundwater ranks among the most MP-contaminated drinking-water sources reported to date, like coastal drinking-water aquifers in Bangladesh, and is orders of magnitude above protected European sources.

The district depends entirely on groundwater for both drinking water and irrigation. We therefore recommend four actions: (i) routine MP monitoring of groundwater sources; (ii) interception and treatment of domestic and textile effluents; (iii) formal solid-waste collection and a ban on open dumping; and (iv) polymer-specific exposure and hazard assessment for the region's drinking water and irrigated food systems.

Authorship contribution statement

Sheza Khalil Ahmad: Investigation, Formal analysis, Writing – original draft. Muhammad Asim Imran: Methodology, Investigation. Imran Shaukat, Muhammad Safdar: Conceptualization, Supervision, Writing – review & editing, Corresponding author. Aamir Raza: Methodology, Data Curation. Uswa Zahid: Investigation, Formal analysis. Muhammad Aqib Javed: Investigation. Israr Khan: Formal analysis, Visualization. Rehan Mehmood Sabir, Saffi Ur Rehman: Writing – review & editing.

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