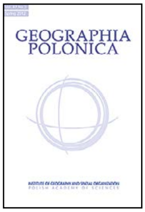

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APPLICATION OF OPTICAL MICROSCOPY TO ASSESSMENT OF SOLID WASTE CONTAMINATION OF SOILS

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Abstract

Solid waste contamination in soils is an extremely important and relevant problem for recreational areas and sports centers. Solid wastes, such as glass, plastics, and metals, do not degrade quickly and accumulate in the soil at shallow depths or remain on the surface. This is a particularly dangerous situation for recreational area users and may lead to cuts, which can cause severe infections. In the analyzed case, pollutants were present at the junction of a beach and a nearby area that was covered with a small amount of grassy vegetation, which further limited the visibility of solid wastes. A microscopic analysis method was used to assess the presence of hazardous waste in the soil qualitatively and quantitatively. Petrographic analysis revealed the presence of glass and metals in the examined material, as well as other solid components. In addition, areas where the concentration of these hazardous pollutants had increased and those where they had not been identified.

Keywords

soil pollution • petrography • hazardous waste • hazards at recreation areas and sports centers

Introduction

Determining the quantity and quality of solid waste contaminants in soils is an extremely important task for facility administrators of recreational areas and sports centers. The presence of solid waste in soils can be harmful to both the environment and the users of these facilities. Therefore, it is extremely important to regularly monitor the amount and type of waste accumulated at facilities and the infiltration of this waste into the soil. The accurate determination of the degree of soil contamination requires appropriate steps to reduce soil contamination and protect the environment. To maintain cleanliness and safety in recreational and sports facilities, administrators should take measures to minimize the amount and effects of soil contamination by solid waste. In the analyzed area, contamination occurred at the interface between the beach and the nearby ground covered with little vegetation, which is a particularly dangerous situation. The area beyond the beach is also used by people using the facility; however, unlike beach sand, the soil in this area is not thoroughly cleaned, such as through screening. Surface collection of waste in grassy areas is usually limited to the removal of large, clearly visible elements. The analyzed brown soil varies in structure (grain size and mineral-to-organic ratio) and thickness (Medne & Krišāns, 2021), creating a potentially friendly environment for the absorption of various solid contaminants, most of which originate as waste from the beach or are left by recreational visitors using the area directly adjacent to the beach. Contaminants such as glass, plastics, and metals do not degrade quickly (LeBlanc, 2017) and are often buried in soil at shallow depths after being shredded. Sharp fragments of such waste, even in small quantities, pose a major safety hazard to users of the area. These fragments, partially protruding or lying under several centimeters of soil, can contribute to cuts that can lead to dangerous fungal or bacterial infections (Spichler-Moffarah et al., 2016; Marina & Popa, 2020) (tetanus, abscesses, and hard-to-heal wounds).

In addition, solid waste generated during thermal food processing (Jelonek et al., 2021), such as long-term industrial emissions (Grodzińska, 1994), can adversely affect the study area, i.e., the Sosina Reservoir catchment area, through rainwater leaching of polycyclic aromatic hydrocarbons (PAHs) and accumulation of heavy elements in the soil, which are then deposited in the reservoir.

Mechanical sifting of sand on sandy beaches enables the detection of contaminants that contribute to cleanliness and safety in these areas. This process allows for the elimination of small trash, glass, or other hazardous objects, and by regularly sifting sand, it is possible to keep beaches clean and minimize the risk of biological and mechanical contamination by trash (Zamora et al., 2021). Compared with loose soil, areas of compact soil, especially those with shallow-rooted vegetation, require special attention in terms of visual assessment and identification of solid contaminants. They are not only characterized by greater challenges in detecting potential hazards but also present difficulties in cleanup processes. Thus, a precise approach and specialized methods are required to effectively clean these areas and accurately assess the degree of soil contamination. In addition, decision-making for both sandy beaches and adjacent areas involves significant costs in terms of both mechanical and manual cleanup of recreational areas. An improper assessment of the degree of sand or soil contamination can lead to disregarding the threat or incurring unnecessary costs for cleaning the areas (Shankar & Shikha, 2017). Therefore, the precise and accurate determination of the level of contamination is crucial for the effective management of environmental hazards and the rational expenditure of funds for necessary cleanup work.

In addition to current physical and chemical analysis methods for the presence and concentrations of toxic compounds and elements in soils (Buchardt Boyd et al., 1999; Matthew et al., 2014; Kowalska et al., 2018), new methods for determining the amount of accumulated solid waste in beach sands are being introduced (Pervez et al., 2020). However, the currently available methods for laboratory analysis do not guarantee precise determination of the amount and characteristics of accumulated solid waste in soils.

Study area

The study site was located in a recreational area near the Sosina Reservoir (50.2052800° N, 19.2749800° E; WGS 84) in the eastern part of the Upper Silesian Industrial District in Jaworzno, Poland (Fig. 1). The artificially created lagoon, with second-class water purity, is surrounded by a forest–meadow complex with two sand beaches adjacent

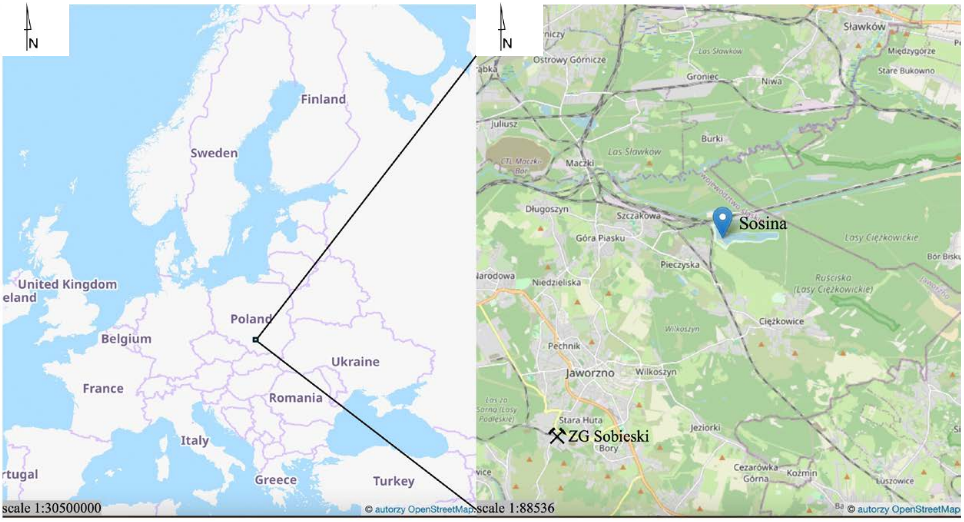

Figure 1. Location of the study site against the background of Europe and in the administrative area of Jaworzno city

to the waterline. The creation of the reservoir is related to the activities of the Szczakowa sand mine in the Jaworzno plant to obtain filler sands, and the sand extracted here was used to fill pits in Silesian coal mines. The original 17 ha of the reservoir was built in the late 1960s and the early 1970s. Over the years, the reservoir expanded to approximately 50 ha. Its shape resembles an elongated letter "L," and its average depth is approximately 2 m. There is also a large island in the middle of the reservoir that was created when the lagoon expanded (Bednarczyk et al., 2015; Machowski & Rzętała, 2022). This facility has become a popular summer recreational spot for Jaworzno residents and people from neighboring towns. Unfortunately, the popularity of this facility and the large number of visitors are associated with the generation of large amounts of anthropogenic waste. As the number of visitors increases, so does the amount of garbage, which cannot always be located and collected in appropriate containers. If left behind, it adversely affects the surrounding area and environment.

This study identified an area of 500 m^2 (Fig. 2) bordering a sandy beach with sparse, grassy, and woody vegetation. The area forms a combination of two different environments with varying absorption of waste generated by recreational visitors. It also provides an attractive place for relaxation owing to trees overgrowing the slope, which provides pleasant shade during hot days, in contrast to the open sandy beach. For these reasons, the selected study area was mostly used for leisure and recreational purposes by visitors to sites beyond the beach during the season (from June to the end of September).

Materials and methods

Soil samples were collected from a rectangular area measuring 10 m × 50 m, in which the highest concentration of vacationers at the resort was observed during the summer season, in addition to sandy beaches. Materials were collected in October after the end of the holiday season. During this period, atmospheric conditions effectively limited the number of visitors to the facilities. An additional convenience during the collection of research material after the season was that the grasses overgrowing the hills were almost completely trampled. As a result, material collection occurred with minimal contamination

Figure 2. The selected study area of 500 m^2 (50.239374°N, 19.327454°E; WGS 84)

of the samples by herbaceous materials. Eight soil samples were collected using a 20 cm × 20 cm frame driven into the ground to a depth of approximately 15 cm (Fig. 3). The samples were taken at equal intervals in both vertical and horizontal orientations, considering the acreage of the 10 × 50 m test field.

Nondestructive energy-dispersive X-ray fluorescence (XRF) was used to determine the elemental composition of the samples. Energy-dispersive X-ray fluorescence was used to identify the elements in the test object by detecting their characteristic XRF emission energies (Skupio, 2014). Individual samples were analyzed in the field using a handheld Vanta XRF spectrometer (EPA 6200, ISO/DIS13196, SOPs). Before taking the measurements, an application dedicated to soil analysis was installed on the device, which was calibrated using a standard (Q0201457) provided by the measurement equipment manufacturer. Each sample was placed in dedicated containers from Olimpus and then in a field-shielded Vanta station and analyzed using a basic parameter algorithm for soils measured with three scanning beams (Beam1 – 20s: 50.0 kV – Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Mo, Cd, Sn, Sb, Hg, Pb, LE., Beam2 – 20s: 40.0 kV – Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Mo, Cd, Sn, Sb, Hg, Pb, LE., Beam3 – 10s: 10.0 kV – P, S, Cl, Ca, Ti, V, Cr, Mn, Fe, LE). For the light elements (H, Na, O, and C), a computational method in the form of an estimation algorithm that summed these elements in a percentage data format (LE = light elements) was used. Other values for the individual elements detected are expressed in ppm.

The moisture content of the soil was determined to be 38% using a moisture analyzer RADWAG MA50/1. R. Before preparing the specimens for microscopic analysis, each sample was individually and evenly spread on an absorbent cardboard substrate in a layer approximately 1 cm thick. The samples were left in this state for 72 h at room temperature to reduce the moisture content. For petrographic analysis of the soils, the collected material was ground to a grain size of approximately 1 mm in accordance with ISO 7404-2:2009 and then sieved through 1 mm and 0.5 mm sieves. From the sieved material that remained on the 0.5 mm mesh sieve, approximately 8 g of the mixed sample was collected and prepared for microscopic observation by encapsulating the sample in epoxy resin and sanding and polishing the surface in accordance with ISO 6344-3:2021. The deposits had a diameter of 4 cm to create a sufficient field for petrographic analysis. The deposits were made of discs with a diameter of 4 cm to provide a sufficient field for the petrographic analysis. Identification

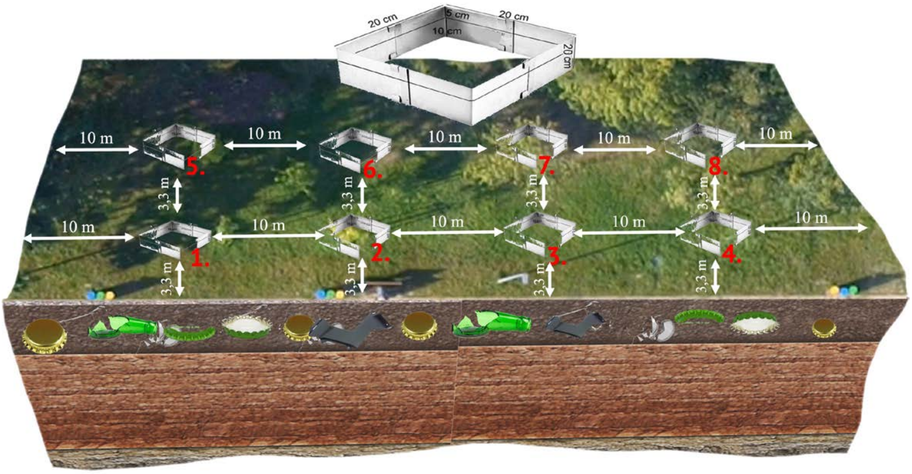

Figure 3. Approximate distribution of sites for collection of research material

of the solids was performed using a ZEISS AxioImager M2m automated optical microscope under white-reflected light using the oil immersion method at 500 × magnification with an attachable table. Quantitative and qualitative analyses were carried out using the visible-solid counting technique, with 1000 observed points counted at the intersection of the cross nickels mounted on the microscope eyepiece, in accordance with PN-EN 1860-2:2023-11. This analytical process was repeated separately for each sample in terms of both specimen preparation and petrographic analysis. The resulting specimens were subjected to petrographic analysis to determine the presence of solid components such as mineral matter, organic matter, glass, plastics, metals, ashes, charcoal, and fossil coals, and were statistically recalculated in terms of quantity using calculating software (Labikon, software KS Run No. 0500324, Ihnatowicz J., Manufacture of computers and peripherals – 6310106641).

Analysis and results

A Vanta X-ray fluorescence (XRF) analyzer was used to evaluate the elemental content of the soil, and the analysis was performed in accordance with ISO 13196:2013 at a soil moisture content of 38%. The concentrations of each element revealed by the abovementioned analysis are presented in Table 1.

Analysis of the presence of arsenic (4-6 ppm) and bismuth (2-28 ppm) in the soil revealed trace amounts of these elements, whereas the calcium content varied slightly over a small area and ranged from 1038 to 5230 ppm. Copper was present in the tested samples at concentrations ranging from 8 to 24 ppm, conforming to the Regulations of the Minister of the Environment of September 1, 2016. This element, typically present at concentrations from 100 to 600 ppm, depending on the soil class, can also be treated as a trace element. The iron content in the samples averaged 1080 ppm with a high of 4620 ppm, exceeding the reference value of 3800 ppm. The presence of Hg in the samples was recorded at levels ranging from 2 to 10 ppm, which can be considered as values that slightly exceed the standards for each soil class of 30 ppm, assuming that this type of recreational area, where visitors are in direct contact with the ground, would have to be assigned to soil group II. Similarly, the potassium content of the tested soil and iron content oscillated between medium and high levels of 318-4620 ppm. Mn was detected in the samples in the range

Table 1. Summary of results from the XRF analysis for the presence and concentration (ppm) of identified elements in the soil samples tested

Sample number	1	2	3	4	5	6	7	8
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
As	6	4	0	0	5	5	0	0
Bi	28	23	22	23	22	0	2	0
Ca	5230	4800	3575	1720	1152	1122	1200	1038
Cu	24	14	17	12	11	8	10	8
Fe	4620	3802	3630	1519	1055	1202	1326	1080
Hg	6	0	10	8	4	8	0	4
K	3790	4620	2600	550	320	404	318	426
Mn	126	239	127	410	51	110	108	100
Mo	286	289	420	225	194	244	208	196
Nb	13	18	14	10	6	0	4	0
Pb	75	54	85	46	34	11	28	10
Sn	41	19	81	37	16	31	32	27
SO_4	5070	4270	4010	1290	1750	1580	1465	1510
Sr	52	36	19	18	0	31	20	0
Ti	706	677	505	117	121	45	57	95
Zn	253	169	175	133	51	91	83	79
Zr	75	117	34	54	30	26	18	20

of 51-410 ppm, and these amounts did not exceed those of Mo. The amount of this element in the soil should not exceed 50 ppm, and its content at the minimum level was 194 ppm, reaching 420 ppm in extreme cases. A content standard for titanium in soils has not yet been established; however, we can assume that concentrations above 500 ppm are not inert to the environment. Other elements, such as niobium (4-18 ppm), lead (10-85 ppm), tin (19-81 ppm), strontium (0-52 ppm), zirconium (18-117 ppm), and zinc (51-253 ppm) did not exceed the designated concentrations specified in the regulations and recommendations of both the Polish (Dziennik Ustaw, 2016) and EU legislation (Soil Strategy for 2030). The final parameter recorded during the analysis of the collected soil samples using XRF was the sulfate level. This analysis revealed high levels of SO_4^{2-}, ranging from high (1290 ppm) to very high (5070 ppm).

As a result of the oil-immersion petrographic analysis, the reflected light of the collected soil samples showed the presence of glass fragments, plastics, metals, and organic matter that were not thermally altered, as well as charcoal, hard coal, slag, and ash. The names of each identified solid component are listed in column one. In the columns containing samples 1, 2, 3, 4, 5, 6, 7, and 8, the number of observed solid components assigned to each component group is given, and in the next column, the percentage content of each component in the subsequent samples is given (Tab. 2).

The analyzed samples had similar mineral contents, ranging between 92.2% and 94.5% of the mineral matter. The organic matter contents were also similar, ranging between 5.2% and 5.5%. These values also characterize the studied soil, allowing it to be classified as an organic–mineral soil (Vanyushina & Travnikova, 2003). Glass was identified

Table 2. Summary of results from petrographic analysis for solids in the ground

Component	Sample No. 1		Sample No. 2		Sample No. 3		Sample No. 4	
	quantity	%	quantity	%	quantity	%	quantity	%
Mineral matter	922	92.2	928	92.8	930	93	929	92.9
Organic matter	55	5.5	52	5.2	54	5.4	55	5.5
Glass	3	0.3	4	0.4	3	0.3	1	0.1
Plastic	6	0.6	4	0.4	2	0.2	2	0.2
Metals	4	0.4	3	0.3	5	0.5	2	0.2
Ashes and slags	2	0.2	2	0.2	1	0.1	3	0.3
Charcoal	6	0.6	5	0.5	3	0.3	6	0.6
Coal	2	0.2	2	0.2	2	0.2	2	0.2
Total	1000	100	1000	100	1000	100	1000	100

Component	Sample No. 5		Sample No. 6		Sample No. 7		Sample No. 8	
	quantity	%	quantity	%	quantity	%	quantity	%
Mineral matter	942	94.2	943	94.3	942	94.2	945	94.5
Organic matter	54	5.4	54	5.4	55	5.5	53	5.3
Glass	1	0.1	2	0.2	1	0.1	0	0
Plastic	1	0.1	0	0	1	0.1	1	0.1
Metals	2	0.2	1	0.1	1	0.1	1	0.1
Ashes and slags	0	0	0	0	0	0	0	0
Charcoal	0	0	0	0	0	0	0	0
Coal	0	0	0	0	0	0	0	0
Total	1000	100	1000	100	1000	100	1000	100

in seven samples (1-7), and its content ranged from 0.1% to 0.4%. However, in sample 8, no residual glass waste was detected during the petrographic analysis. In all analyzed samples, with the exception of sample 6, microplastic contents ranging from 0.1% to 0.6% were detected. Subsequently, solid metal impurities were detected in the analyzed material, with contents ranging from 0.1% to 0.5%. All analyzed samples showed the presence of impurities. Ash and slag residues were detected in samples 1-4 at concentrations ranging from 0.1 to 0.3%. In contrast, no residues from the solid fuel combustion processes were detected in samples 5-8. Petrographic analysis also revealed the presence of charcoal at levels ranging from 0.3 to 0.6% in samples 1 to 4 and fossil coals at a constant level of 0.2% in samples 1 to 4. In samples 5-8, neither fossil coal nor charcoal were found. The metal content ranged from 0.1 to 0.2%; the glass content ranged from 0% (sample 8) to 0.1% (sample 7) and 0.2% (sample 5); the plastic content was 0.1% in samples 5, 7 and 8; plastic content was detected in only small amounts in sample 6 (Tab. 2).

Discussion

Organic-mineral soils (Mocek & Drzymała, 2010) are characterized by a rich organic composition and a high content of inorganic fractions, especially clay-sand. According to previous studies, the organic matter content of organic mineral soils has a positive effect on soil biological activity by increasing the bioavailability of nutrients to plants (Smith et al., 2018). In addition, chemical analyses have shown that soils of this type have an optimal pH and excellent water retention and permeability (Sridhar et al., 2020). Both characteristics contributed to the concentration of both elements and solid contaminants in the lower layer of the studied slice (samples 1, 2, 3, and 4) from the area adjacent to the beach and the lower contents in the upper part (samples 5, 6, 7, and 8). This type of distribution of contaminants in the soil is also not significant because of the slight slope of the area (approximately 150°C), which favors the movement of both macro- and micro-elements to the lower parts of the hill.

In terms of concentration, low levels of both toxic elements and heavy metals were detected in the studied section of the area adjacent to the beach. The higher the location in the area, the more markedly the concentration decreased (Figs. 4 A, B, C, D). A significant exceedance of the reference values was recorded only for Mo, whereas a slight exceedance of the reference values was recorded for Hg. In contrast, the recorded high sulfate content indicates high acidification of the studied land (Pietrzak, 2015), with SO_4 levels also higher in the lower part of the study area and much lower in the upper part (Fig. 4A).

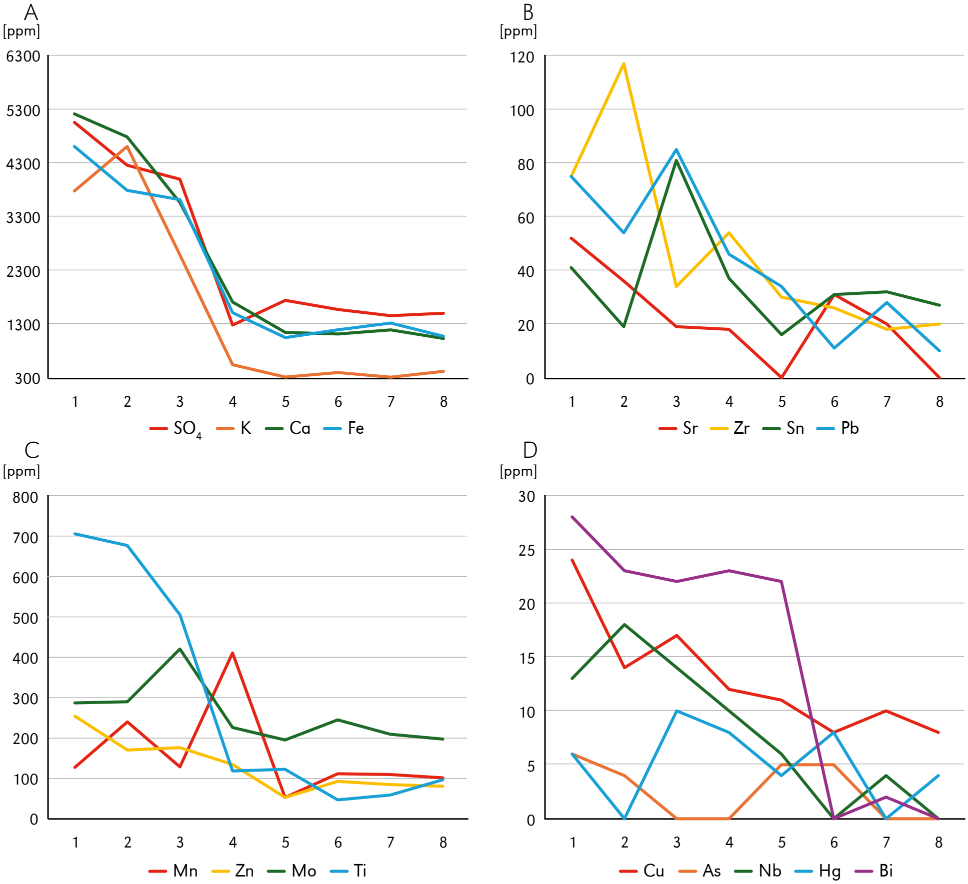

Figure 4. Concentrations of identified elements and SO_4 in individual soil samples
A – sulfate, potassium, calcium, and iron, B – strontium, zirconium, tin, lead, C – manganese, zinc, molybdenum, titanium, D – copper, arsenic, niobium, bismuth

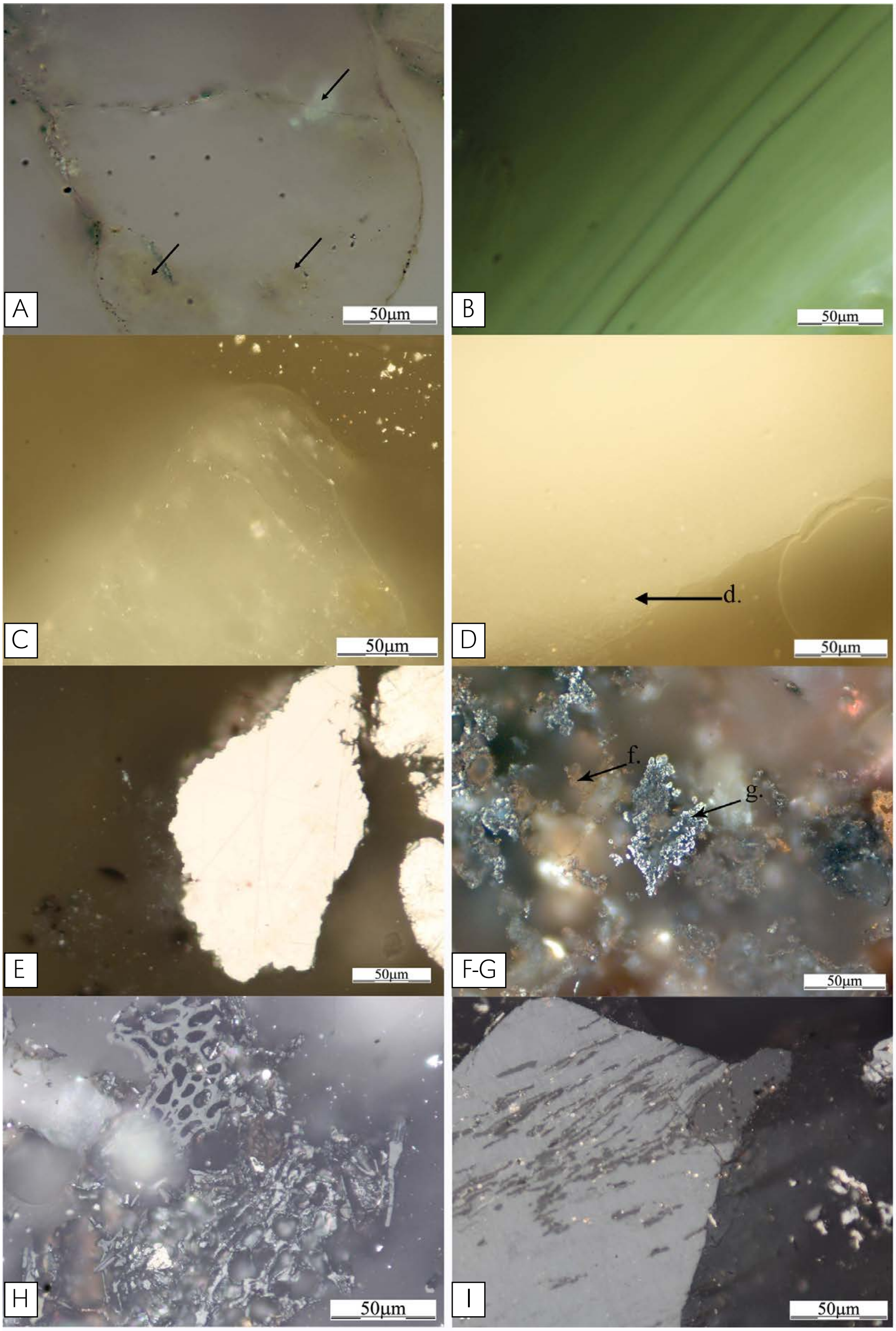

Figure 5. Microscopy images of identified solids in the samples
A – mineral matter, B – organic matter, C – glass, D – plastic, E – metals, F–G – ash and slag, H – charcoal, I – coal

A methodology for the petrographic analysis of beach sands, developed and tested at two independent research centers, was used to study land contamination by solid components (Drobniak et al., 2021a). With the aim of verifying the results during the development of analytical assumptions in Poland, screening, petrographic, and visual methods were used to determine the quantitative and qualitative content of individual solid components accumulating in beach sands (Kuś et al., 2023). However, foreign studies have usually focused on identifying one soil component and its percentage in the studied medium (Suárez-Ruiz et al., 2023). It should be noted that in the analyzed area, no macroscopically visible larger fragments or whole waste on the surface, such as bottles, packaging, plastic containers, or cups, were observed. However, in the investigated soil layer, reaching up to 15 cm in depth, microscopic analyses revealed the presence of waste residues (Suárez-Ruiz et al., 2012). Microscopy images (Drobniak et al., 2021b) revealed both the basic components of the soil, i.e., mineral matter (Fig. 5A) and organic matter (Fig. 5B), as well as the following solid contaminants: glass (Fig. 5C), plastic (Fig. 5D), both ferrous (Fig. 5E) and nonferrous (Fig. 5F) metals, ash and slag (Fig. 5G), charcoal (Fig. 5H) and coal (Fig. 5I).

It was also found that the accumulation of waste gradually decreased as it moved away from the shoreline, as was the case for the chemical elements described above. Samples taken from Sites 1, 2, 3, and 4 were characterized by an increased content of all detected solid contaminants, and the predominant contaminants were charcoal, metals, and plastic (Fig. 6).

This condition may not necessarily be attributed to the greater number of people staying at the sand–grass interface, especially because the area above is shaded more by trees, which is the main factor attracting recreational visitors to the site. This is probably due to the near-zero slope of the land and not the number of people on it, which is responsible for the accumulation of these materials. This type of ground leveling, for example, is conducive to the establishment of popular food preparation equipment. The use of both plastic and glass packaging, as well as aluminum and metal packaging, is related to the transportation and thermal preparation of food or its storage before grilling, as well as the sealing of beverage bottles with metal or plastic caps. Another indication of the accumulation of post-grilling waste is the presence of charcoal and coal, which are contaminants found in charcoal briquettes. Ashes and slag were also identified in the samples, which are indicative of the combustion processes carried out at the site for fuels such as wood, charcoal, and charcoal briquettes, both in the form of bonfires and in the form of bonfires.

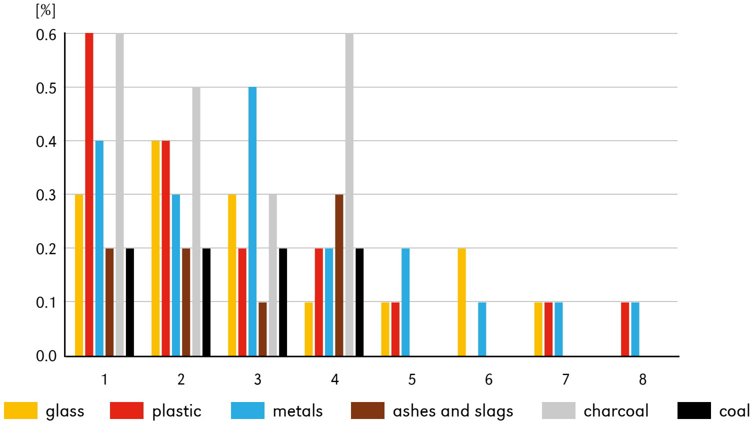

Figure 6. Share of individual solids in the analyzed samples

Summary

In the field of protecting recreational areas from the accumulation of solid waste in soil, the key aspect is the continuous improvement and development of new analytical methods and the systematic testing of innovative solutions. Constant monitoring of soils in this area will allow for effective prevention of and solutions to the growing pollution problem. By implementing new solutions, recreational areas can be effectively protected from the adverse effects of solid waste accumulation in soils, ensuring their continued integrity and accessibility for facility users. The applied research method of optical analysis in reflected light in oil immersion can be a complementary and, in some cases, sufficient technique for analyzing soils in the context of commonly used tests aimed at identifying solid contaminants from anthropogenic waste. Although the results of this analysis did not provide information on soil chemistry, they allowed us to obtain data on the physical composition of the soil. Unlike other methods currently in use, especially physical–chemical methods, which do not tell us what the solid components of the soil are, quantitatively and qualitatively, petrographic analysis allows us to determine these parameters precisely. In addition, because of the quantification of the ratio of mineral matter to organic matter, we could classify the studied soil into mineral soils, organic-mineral soils, or organic soils. Petrographic studies of soils also enable the determination of the migration of solid contaminants, which is analogous to tracking the movement of chemical elements. Consequently, it is possible to monitor the solid waste transport processes in the soil environment and assess the impact of this phenomenon on the ecosystem. Such monitoring will enable facility administrators to take appropriate steps to protect and optimize the condition of the soil, which will contribute to both the safety of the users and the protection of the environment.

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Authors' contribution

ZJ: conceptualization, data curation, formal analysis, project administration, visualization, writing, original draft, and writing review and editing; **IJ**: conceptualization, data curation, and review and editing; **DK**: writing original draft and writing review and editing.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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