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Microplastics in Landfill Bodies: Abundance, Spatial Distribution and Effect of Landfill Age

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Abstract: Almost a quarter of the plastic produced in Europe still ends up in landfills. In addition to the loss of valuable resources, this leads to the generation and accumulation of microplastics in landfills. The microplastics abundance in the refuse and their spatial distribution in the landfill body have not been practically studied. In the current work, changes in the abundance and characteristics of microplastics in landfill refuse from 3 age sections of the Lapės regional landfill, Lithuania, to a depth of 10–20 m were studied. A microplastics abundance of up to 55 particles/g or 52.8 g/kg was found. The lowest microplastics abundance was found in the old section, while the highest in the young (numerical) and the middle-aged (mass) sections. Moreover, microplastics abundance increased with the age of landfilled waste and depth, which may reflect the fragmentation of microplastics and their transport. Polyethylene and polypropylene were the dominant polymer types in all sections, while films were the dominant shape. The carbonyl index of PE microplastics was calculated to monitor microplastics oxidation. The analysis showed an increase of carbonyl index with landfill depth and landfill age, proving the intensive degradation of microplastics. Thus, landfills are large reservoirs of microplastics and their potential sources.

Keywords: microplastics; landfill; MSW; carbonyl index; landfill age; spatial distribution

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1. Introduction

Proper waste management is an important part of achieving sustainable development. The Waste Framework Directive introduced a five-step hierarchy of waste management options that range from best to worst for sustainability. Despite waste disposal having been given the last place in the hierarchy, 23% of the municipal solid waste (MSW) is still landfilled in Europe [1]. Waste disposal leads to a constant increase in the number of landfills, of which there are nearly 500,000 in Europe [2]. Landfills have recently been considered holders of anthropogenic resources [3]. At the same time, however, they are also reservoirs for pollutants, such as heavy metals, organic compounds [4] and microplastics (plastic particles of 0.001–5 mm) [5].

The extent of microplastic pollution, its sources and long-term effects on the environment and human health are still poorly understood. However, initial studies show the global nature of the problem, the presence of microplastics in different environmental compartments [6], their constant migration [7] and potential accumulation even in our bodies [8,9]. In addition, microplastics can absorb and transport organic pollutants, trace elements such as heavy metals and other harmful agents such as pharmaceuticals and pathogenic organisms [10].

The problem of microplastic pollution is a concern among the population and, accordingly, regarded as a high political priority [11]. However, effective policies to reduce and control microplastic pollution require a complete understanding of their sources. Landfills

can potentially be a significant source of microplastics [12–14]. Microplastics can enter the landfill along with the landfilled waste. In Europe, landfills mainly receive microplastics together with a stabilised organic waste (SOW) output after mechanical-biological treatment (MBT) of MSW [15,16] since the disposal of untreated MSW is prohibited by the Landfill Directive. Other possible sources of microplastics are ash [17,18] and sewage sludge [14,19]. In addition, microplastics can also be generated in the body of the landfill following the fragmentation of large plastic waste. Plastic fragmentation can be caused by different processes, including waste compaction, photodegradation on the surface of the landfill, physicochemical degradation and biodegradation [5,20].

The study of landfills as a source of microplastics has recently begun [5]. Previous studies found high concentrations of microplastics in landfill leachate [13,21,22]. Microplastics abundance in landfill bodies has only been undertaken by Su [12], Zhang [22] and Puthcharoen and Leungprasert [23]. Zhang [22] found up to 113 microplastics/g in landfill refuse in China, and Puthcharoen and Leungprasert [23] found up to 23 microplastics/g in Thailand. According to Su [12], the average microplastics abundance in landfill refuse significantly exceeded the abundance in the leachate with 62 $\pm$ 23 items/g and 8 $\pm$ 3 items/L, respectively. The high abundance of microplastics in refuse makes landfills a major sink of microplastics [14]. The potential of landfills to store, generate and release microplastics with leachate makes their study as a source of microplastics particularly important. Primary studies provide an initial insight into microplastic abundance in landfills but cover only the upper layers of landfills, so there is no data on microplastic concentration at other depths, its spatial distribution, migration and degradation.

Therefore, the aim of this article is to investigate changes in the abundance of microplastics and their characteristics with the depth and age of the landfill. The article provides an insight into this source of microplastics as well as initial data on microplastics degradation based on carbonyl index calculations. Such data can be useful for regulating landfill management and policy formulation to reduce microplastic release from landfills. In addition, this data should be taken into account before planning landfill mining activities to prevent the leakage of microplastics.

2. Materials and Methods

2.1. Sampling Site and Sample Collection

Refuse samples were obtained from Lapės landfill, a regional non-hazardous waste landfill in Kaunas County, Lithuania. It was opened in 1973 and reconstructed in 2009 in accordance with the EU Landfill Directive. Rotary-spoke drilling was carried out by Wamet MWG-6 (small size caterpillar drilling rig) in three main cells of the landfill: the old (years 1973–2000), middle-aged (years 2000–2008) and young (2008–present). Sampling was conducted at the old section (54°59′53″ N 24°01′22″ E) from 11 am to 3 pm on 19 July 2021; at the middle-aged (54°59′48″ N 24°01′50″ E) from 11 am to 2 pm on 20 July 2021; and at the young section (54°59′52″ N 24°01′38″ E) from 10 am to 2 pm on 27 September 2021. Sampling points are presented in Figure 1. Three replicate samples were taken every 2 m to a depth of 10 m on the old, up to 20 m on the middle and up to 14 m on the young sections [24]. Altogether, a total of 66 samples were obtained. The depth of drilling depended on the layer of landfilled waste and the difficulty of drilling (the presence of strong impenetrable zones). Since the samples are heterogeneous and waste can be large-sized, 2–5 kg of samples were sieved at the site, and only a fraction $\leq$20 mm was taken to the laboratory for further analysis. In each sample, during the morphological analysis, the content of macroplastics $\geq$20 mm was also determined. Sample descriptions are presented in Table S1. After sieving, fractions $\leq$20 mm were collected with a stainless-steel spatula, placed into containers, transported immediately into the laboratory and stored at 4 °C until processing.

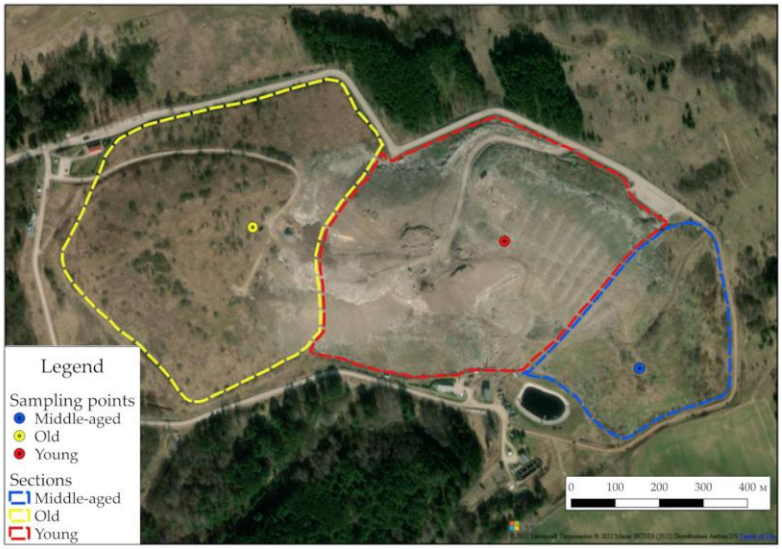

Figure 1. Sampling points and main sections of Lapes landfill.

2.2. Microplastics Extraction

Microplastics from the landfill samples were extracted according to the protocol for treated organic waste samples, as described in detail in a previous article [25]. Dried samples were sieved into 3 fractions: >5 mm, 1–5 mm and <1 mm. Since microplastics are polymer particles from 1 µm to 5 mm, only the last 2 fractions were analysed. Large microplastics from the 1–5 mm fraction range were manually separated by visual inspection, washed gently with distillate water to remove adhering organic matter, then subjected to density separation, dried and some were checked with Fourier Transform Infrared Spectroscopy (FTIR) analysis.

Organic matter was removed from the fraction < 1 mm using Fenton's reagent according to the "Laboratory Methods for the Analysis of Microplastics in the Marine Environment: Recommendations for quantifying synthetic particles in waters and sediments" [26]. Heavy particles such as sand and stones were removed by density separation with a potassium formate solution (1.5 g mL^{-1}). Samples were mixed with the solution, shaken vigorously by hand for 30 seconds and left for 2 hours. The floating particles were vacuum-filtered onto a glass fibre filter, stained with a Nile Red solution at a concentration of 10 µg mL^{-1} as in Maes [27] and then examined under a fluorescence microscope Optika B-353FL in blue excitation scale.

The efficiency of Fenton's reagent for organic removal was validated by establishing organic loss through the loss-on-ignition method (550 °C for 4 h) and accounted for 80.5 ± 2.5%. The recovery rate of a density separation method for 10 0.2–0.5 mm particles of each common polymer—polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), polyvinyl chloride (PVC) and polystyrene (PS)—was analysed and varied from 93.3 ± 5.8% for PP to 100% for PS. The efficiency of Nile Red dye staining was analysed in a previous article [25] and confirmed by Prata [28].

All chemicals and filters used for the microplastics extraction protocol were ordered from Sigma-Aldrich. For filter staining, Nile Red, suitable for fluorescence, ≥97.0% was used.

2.3. Microplastic Analysis

Based on the images obtained from a fluorescent microscope, the size and shape of the microplastics were determined. The size was determined by measuring the longest dimension with ImageJ 1.48 software. All microplastics were divided according to length into categories such as 1–5 mm, 0.5–1 mm, 0.2–0.5 mm, 0.1–0.2 mm and 0.05–0.1 mm. According to their shapes, microplastics were divided into fragments, films, fibres, spheres,

foams and undefined, where the shape was difficult to attribute exactly to one of the above categories. Examples of each shape are presented in Figure S1.

Twenty large microplastics from each depth were examined by the attenuated total reflection (ATR) mode of FTIR. The spectra were obtained with a Bruker Alpha FTIR Spectrometer as the average of 64 scans in the wavenumber range of 4000–600 cm^{-1} with a resolution of 4 cm^{-1}. The polymer types were determined by comparing obtained spectres with the Open Specy (openanalysis.org) database. The example of spectra identification by Open Specy is presented in Figure S2. To study the ageing and oxidation of microplastics, the carbonyl index was calculated based on the FTIR spectra. Since PE was the most common polymer type in the landfill samples, 3–5 PE microplastics were randomly selected from each depth for carbonyl index calculation.

The carbonyl index calculation is the most common analytical technique to monitor oxidation reactions for polyolefins. It is used to specifically monitor the absorption band of the carbonyl species formed during oxidation in the range of 1850–1650 cm^{-1} by measuring a ratio of the carbonyl peak relative to a reference peak [29]. In the current article, the carbonyl index was calculated based on Almond [29] from the ratio between the integrated band absorbance of the carbonyl peak from 1850 to 1650 cm^{-1} and that of the methylene scissoring peak from 1500 to 1420 cm^{-1} (Equation (1)). The area under the band was calculated through the Spectragryph 1.2.15 software options using the peak analysis tool.

$$\text{Carnonyl index} = \frac{\text{Area under band 1850–1650 cm}^{-1}}{\text{Area under band 1500–1420 cm}^{-1}} \quad (1)$$

The weight of large microplastics was measured, while the weight of small microplastics was calculated theoretically by multiplying the density and volume of microplastics based on Simon [30] and Braun [31]. However, instead of the minimum and maximum density of polymers, the weight average density for each sample was calculated based on the distribution of polymer types in the samples. The volumes of each particle were calculated as the volume of a cylinder for fibres and as the volume of an ellipsoid for other shapes. The width and longitude of the microplastics were measured on fluorescent images, and the ratio of width to thickness was taken as the same as the ratio of longitude to width.

2.4. Data Analysis

Statistical analysis was performed using SPSS statistics 27.0.1.0 (IBM, Armonk, NY, USA) software. The abundance of microplastics was expressed as mean ± 95% confidence interval. The normality test was performed using the Shapiro–Wilk test, and results showed that all data sets were not normally distributed ($p < 0.05$). Therefore, the Mann–Whitney test was used to analyse the difference in the abundance of microplastics among different sections. A p-value < 0.05 was used to indicate statistical significance. The relationship between the plastic content and the microplastics abundance at different depths was estimated using a Spearmen correlation analysis.

3. Results

3.1. Microplastics Abundance in Landfill Refuse

The numerical abundance of microplastics at different depths in the old, middle-aged and young sections of the landfill is shown in Figure 2a. Since the drilling depth was different for each section, for comparison, the average abundance of microplastics for depths of 0–10 m was calculated and presented in Figure 2b. The average microplastics abundance (0–10 m) in the old section of the landfill was 6 ± 1 particles/g; in the middle age, 18 ± 3 particles/g; and in the young, 19 ± 3 particles/g. A Mann–Whitney test showed that there is a significant difference ($p < 0.05$) between old and young and between old and middle-aged, but there is no ($p > 0.05$) between young and middle-aged sections.

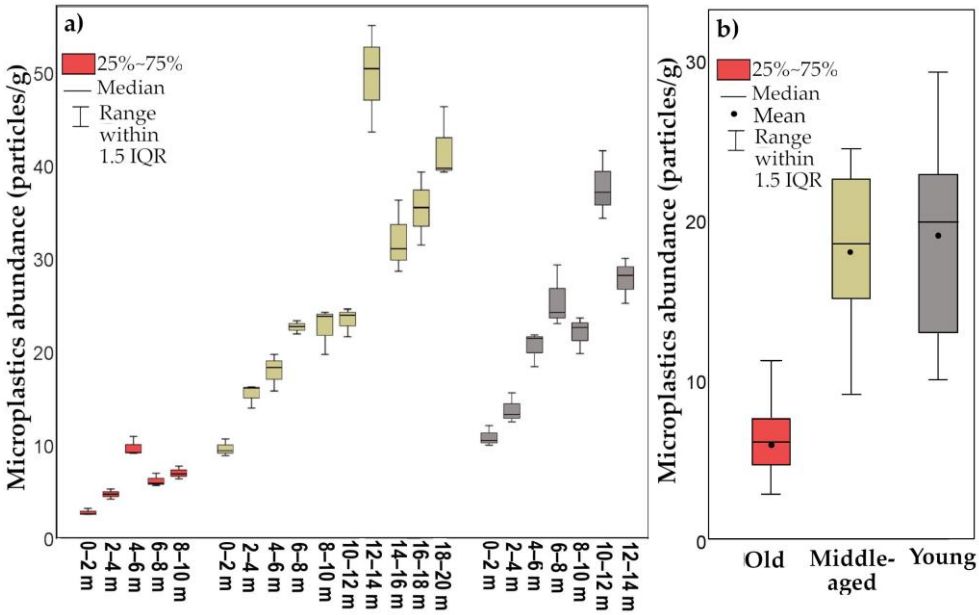

Figure 2. Numerical abundance of microplastics in refuse samples from different landfill depths (**a**) and age sections (0–10 m) (**b**).

The figures show that the abundance of microplastics tends to increase with depth and, accordingly, with the age of the landfilled waste. The abundance in the old section increases from 3 ± 1 particles/g at the point closest to the surface (0–2 m) to 7 ± 2 particles/g at the deepest point; in the middle-aged range from 10 ± 2 particles/g to 42 ± 10 particles/g; and in the young from 11 ± 3 particles/g to 28 ± 6 particles/g. However, a sharp increase in the abundance was noted at about the middle of the drilling depth at each point: 10 ± 3 particles/g at 4–6 m depth in the old section; 50 ± 14 particles/g at 12–14 m in the middle-aged; and 38 ± 9 particles/g at 10–12 m in the young. A correlation analysis between the large plastic content and the microplastics abundance at different depths did not show a statistically significant relationship ($r < 0.2$).

The mass abundance of microplastics is shown in Figure 3. The lowest average mass abundance for depths of 0–10 m was found in the old section (9.1 ± 2.7 g/kg) and the highest in the middle-aged (19.9 ± 3.3 g/kg). However, the difference between young and middle-aged sections is weak and not statistically significant, which is confirmed by the Mann–Whitney test ($p > 0.05$). The mass abundance also increases with depth, but the highest depth-average abundance was recorded at the penultimate depth in all samples: at 6–8 m in the old section (13.2 ± 2.75 g/kg); at 16–18 m in middle-aged (48.9 ± 8.3 g/kg); and at 10–12 m in the young (30.7 ± 4.9 g/kg).

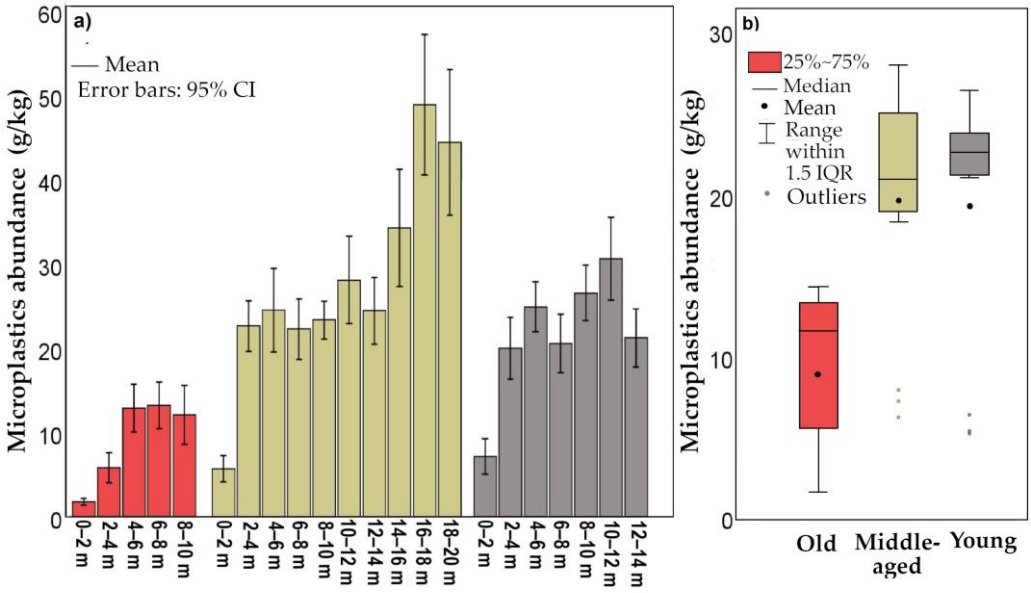

Figure 3. Mass abundance of microplastics in refuse samples from different landfill depths (**a**) and age sections (0–10 m) (**b**).

3.2. Polymer Characterization

The results of the FTIR analysis showed that the polymer types with the highest demand in Europe were the most abundant in the landfill samples. The dominant polymer types were PE (44–53%) and polypropylene (PP) (24–30%) in all sections (Table 1). Polystyrene (PS), fibres (polyamide (PA), polyester) and polyvinyl chloride (PVC) were responsible for 4–6% of all microplastics detected in the samples. Additionally, compared with the old section, the percentage of PE in the young section decreased, while polymer diversity and the content of poly(methyl methacrylate) (PMMA), polycarbonate (PC), nitrile rubber and other plastics increased. It should be noted that the content of nitrile rubber, which is commonly used for medical gloves production, was 2% in the young section compared to 0.5% in the middle-aged and 0% in the old, and the most nitrile rubber particles were found in the upper part of the young section. This was most likely caused by the COVID-19 pandemic. There were no pronounced trends of increase/decrease in the abundance of different polymer types of microplastics with depth.

Table 1. Microplastics polymer type distribution.

Polymer Type	Age of Sections					
	Old		Middle-Aged		Young	
	Particles	%	Particles	%	Particles	%
PE	53	53	88	44	68	49
PP	27	27	60	30	34	24
PS	5	5	10	5	5	4
PET	1	1	1	0.5	2	1
Fibres (PP, PA . . .)	4	4	12	6	5	4
PC	0	0	4	2	4	3
PVC	4	4	7	3.5	5	4
PUR	2	2	5	2.5	3	2
PMMA	1	1	3	1.5	4	3
Nitrile rubber	0	0	1	0.5	3	2
Other	3	3	9	4.5	7	5
Total	100	100	200	100	140	100

The distribution of sizes and shapes of microplastics in different age sections is shown in Figure 4. More detailed results on distributions at different depths are presented in

Tables S2 and S3. With few exceptions, films were the dominant shape of microplastics in all sections at all depths, followed by fragments. The content of film-shaped microplastics increases with age, while the content of fragments decreases. The section average content of films increased from 49.3% (young section) to 50.7% (old section), and fragments decreased from 39% (new section) to 36.7% (old section). However, the opposite trend is observed with the depth distribution (Table S3): the content of fragments mainly increases, while the content of films decreases. In this case, this may not be related to an increase in the age of landfilled waste but to the migration of fragment-shaped microplastics in depth.

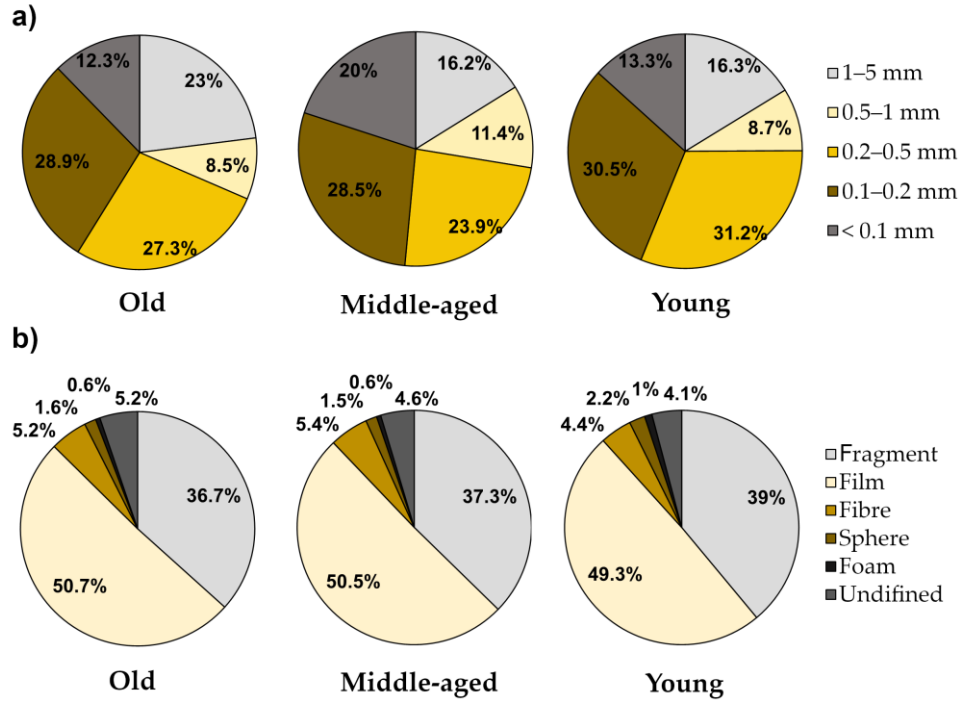

Figure 4. Size (**a**) and shape (**b**) distribution of microplastics by age sections.

The dominant size class was 0.1–0.2 mm in the old (28.9%) and middle-aged (28.5%) landfill sections and 0.2–0.5 mm (31.2%) in the young. Size class 0.5–1 mm was responsible for the lowest percentage of microplastics: 8.5% in old, 11.4% in middle-aged and 8.7% in young sections. Additionally, the percentage of large microplastics was significantly higher in the old section (23%) compared to the middle-aged (16.2%) and young (16.3%) sections. An analysis of the size distribution in samples from different depths (Table S2) did not reveal any clearly pronounced trends.

3.3. Carbonyl Index Calculation

Carbonyl index is presented in Figure 5 as the average value of 3–5 PE microfilms from each depth. It was observed that the carbonyl index of PE microplastics increases with landfill depth and landfill age, which proves their oxidative degradation in the landfill body. However, this increase is not so pronounced in the middle-aged section. The depth average carbonyl index varied from 0.67 ± 0.22 to 0.83 ± 0.25 in the young; from 0.81 ± 0.29 to 0.99 ± 0.21 in the middle-aged; and from 0.89 ± 0.24 to 1.23 ± 0.37 in the old sections. The average carbonyl index for the depth 0–10 m was 0.75 ± 0.05 in the young; 0.92 ± 0.055 in middle; and 1.11 ± 0.08 in the old sections. A Mann–Whitney test confirmed a significant difference ($p < 0.05$) between all sections.

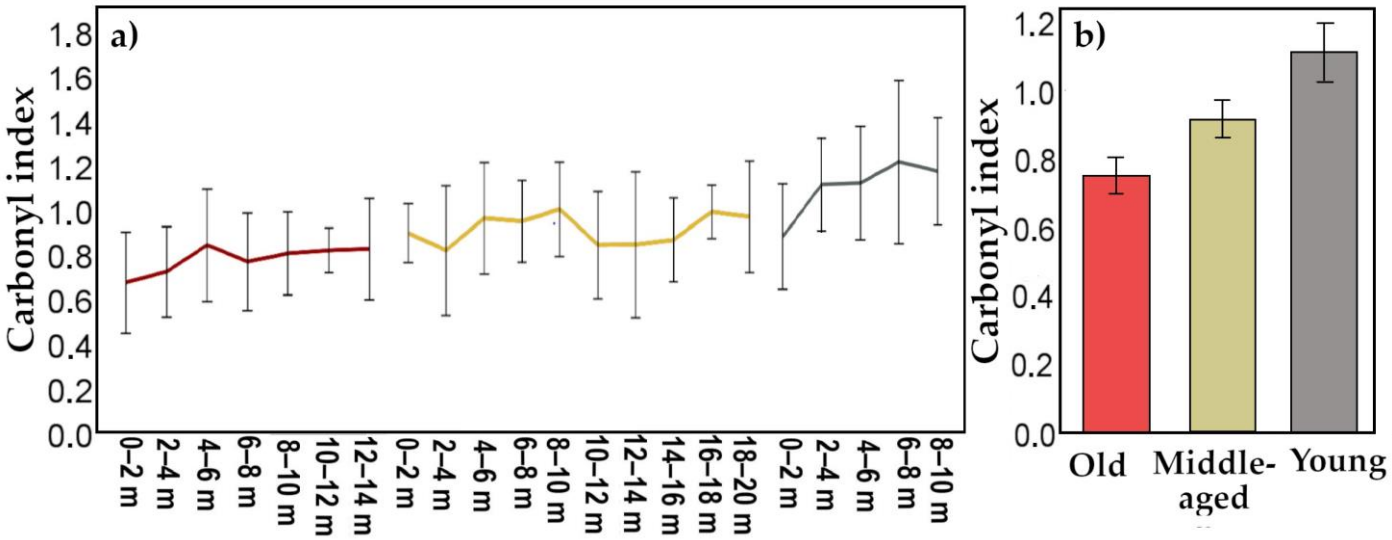

Figure 5. Carbonyl index of excavated polyethene (**a**) from different landfill depths and (**b**) average for the depth 0–10 m. Error bars: 95% CI.

4. Discussion

4.1. Microplastics Abundance and Transportation

In 2021, over 23% of plastic post-consumer waste was still sent to landfills in Europe [32]. In addition to squandering valuable resources and space, the disposal of plastic waste leads to their fragmentation due to physicochemical, mechanical and biological degradation and, consequently, to the accumulation of microplastics in landfill bodies. Extreme environmental conditions, such as the presence of acidic/basic solutions, corrosive organics, hydrogen sulphide and ammonium solution, heavy metals and organic compounds from MSW accelerate the physicochemical degradation of the plastic waste [5,33]. Furthermore, high temperatures up to 130 °C can cause the thermal-oxidative degradation of plastic waste [34]. Mechanical fragmentation can be caused by waste compaction, which is carried out regularly in sanitary landfills to reduce waste volume and increase landfill stabilisation. In addition to the fragmentation and degradation of plastic waste, microplastics can enter landfills as part of landfilled waste. In Europe, all mixed MSW is mechanically-biologically treated before disposal to separate recyclable fractions and stabilise biological waste. However, the SOW output from MBT often contains a significant abundance of microplastics. Brinton [16] found 1.318% or 13.18 g/kg of 1–4 mm microplastics in MSW compost. In the previous article [35], 9–17 particles/g or 3.3–3.9 g/kg were found in the SOW output.

In the current article, the microplastics abundance of up to 55 particles/g or 52.8 g/kg was found. The section's average microplastics abundance was 6–27 particles/g or 9.1–27.9 g/kg, depending on the age. A higher abundance of microplastics in the landfill refuse than in the SOW output from the MBT, which is sent to landfills, confirms the fragmentation of plastic waste and the generation of microplastics in the landfill body. Su [12] and Zhang [22] found significantly higher average microplastics abundance in China landfills with 36–83 particles/g and 38–74 particles/g, respectively. The higher concentration may be explained by the difference in sampling regions and methods for microplastics identification. Su [12], for example, used micro-FTIR, which is far more accurate than the identification using the Nile red dye and a fluorescence microscope; however, the equipment cost and time consumption are also much higher. It should be noted that the mass of small microplastics was calculated theoretically, so it gives only an approximate estimate. Even though the mass of small microplastics is insignificant compared to the large microplastics mass, for more precise calculations, it should be measured using thermal methods such as the thermal extraction desorption gas chromatography mass spectrometry method.

In previous articles, an increase [22] and vice versa decrease [12] in the abundance of microplastics with the age of the landfill were found. In this work, the lowest abundance

was found in the old section, the highest in the middle-aged for mass abundance and in the young section for numerical. The lowest amount of microplastics in the old section can be explained by a lower volume of plastic production and a lower MSW generation rate. A further increase in plastic consumption has led to an increase in the abundance of microplastics in the middle-aged section of the landfill. However, despite the continued increase in plastic production and consumption, the young section was not characterised by a large increase in the microplastics abundance. This is most likely related to the launch of a mechanical-biological treatment plant in 2012 in the Kaunas region for MSW. The plant has reduced the amount of waste disposed of and increased the processing and recovery of plastic waste. Furthermore, in 2016, Lithuania introduced a deposit system for plastic bottles that has significantly reduced the percentage of plastic bottles going to the landfill. The increasing popularity of MBT and the introduction of extended producer responsibility systems are typical not only for Lithuania but for the entire European region. Accordingly, such microplastics distribution in landfill bodies may be similar in many European countries.

In addition to the section's average abundance of microplastics, the article also presents the abundance at depths up to 10–20 m in sections. Results show that the abundance tends to increase with depth. However, this increase reflects not only the fragmentation of microplastics with the age of landfilled waste but also the transport of microplastics in depth and accumulation at the bottom. Microplastics can be transported using hydrological transport as well as passive and active gas flows within MSW bodies [5]. The lack of a scientifically significant correlation between large plastics and microplastics across depths may also reflect microplastic transport. However, to prove microplastics transportation in landfill body, further research is required.

4.2. Polymer Types and Shapes

PE and PP were the dominant types of microplastics. Together, they accounted for an average of 73–80% of all microplastics. Such a large percentage is explained by the wide use of these polymers, especially in bags and packaging production. The dominance of PE in landfill samples was also confirmed by Zhang [22] and Su [12]. PE and PP have always been in demand in Europe. In 2006, for example, they accounted for 29% and 19% of plastics production, respectively [36]; in 2020, 30.3% and 19.7%, respectively [32]. Additionally, an increase in the content of PMMA and PC was noted, which corresponds to an increase in their consumption due to their use in fast-growing industries such as IT hardware, electro/electronic, automotive, medical apparatus, building and construction.

Films were the dominant shape of microplastics in all sections, accounting for 49.3–50.7%. Such shape distribution is consistent with the dominant types of plastic, PE and PP. However, no significant correlation between shapes and polymer types was observed. This may be explained by the fact that some polymer types can be presented in different shapes. For instance, depending on their application, PP products can be sources of microplastics in the shape of film (PP packaging), fragments (PP toys, pipes, automotive parts), fibres (textiles), spheres (personal care products) and foams (expanded polypropylene foam). The shape distribution over depths can be impacted by microplastics transportation. It was observed that the content of fragment-shaped microplastics (Table S3) increases with depth while the abundance of film-shaped ones decreases.

4.3. Carbonyl Index Changes

Carbonyl index is a commonly used technique to monitor the oxidation and chemical change of polymers throughout their lifetime [29]. However, despite its widespread use, there is no universal methodology for calculating carbonyl index. Among the articles, the calculation methodology (by peaks or area under the peaks), the instrument used and the target wavelengths differed. In this paper, the area under the peaks based on the ATR FTIR spectra was used. This approach was chosen for ease of future comparison after a detailed literature review of similar articles. The average for the depth 0–10 m carbonyl

index detected in the current article was 0.75 ± 0.05 in the young; 0.92 ± 0.055 in the middle; and 1.11 ± 0.08 in the old sections. Su [12] found comparable carbonyl index for medium (0.94) and old (1.3) landfill sections. Zhang [22] also confirmed the increase in carbonyl index, with the age of the landfill from 1.5 to 2.16 in the zone with an age of 9–10 years. The result of the current article showed a significant increase in carbonyl index with the age of landfilled waste and landfill depth, confirming the increased oxidation of microplastics. An increase in carbonyl index reflects significant chemical changes on the surfaces of microplastics on account of auto-oxidation or microbial degradation in the landfills [37,38]. Special landfill conditions (oxidants, heat, mechanical stress) cause the formation of hydroperoxide from the methylene group in PE and further chain scission, forming new functional groups (ketones, acids, esters) that contribute to the increase in carbonyl index [34,36].

Canapoli [39], however, who have studied the degradation of excavated polyethene, revealed a trend towards a decrease in carbonyl index from 0.46 for PE < 10 years to 0.41 for PE > 10 years, respectively; however, the difference was not statistically significant. This reduction may be the result of advanced degradation and depletion of the carbonyl group due to chain scission, crosslinking and CO release [39,40].

5. Conclusions

The present study confirms that landfills are large reservoirs for microplastics. The microplastics abundance found in the regional Lapės landfill (Kaunas County, Lithuania) varied from 3 particles/g or 1.7 g/kg to 55 particles/g or 52.8 g/kg. The oldest section was characterized with the lowest numerical abundance of microplastics, while the young section with the highest. The difference between sections is most likely related to changes in plastic consumption, waste generation and plastic waste management system. In addition, the abundance of microplastics increased with the depth of landfill in all sections, which can be caused by the fragmentation of plastic over time and the transport of microplastics in depth. However, to prove the transport of microplastics in depth, future research is needed. The degradation of microplastics was confirmed by an increase in the values of the carbonyl index, both with the age (from 0.75 in the young section to 1.11 in the old) and the depth of the landfill. The FTIR analysis showed that PE and PP were the most common among other polymer types, accounting for 44–53% and 24–30%, respectively. However, polymer diversity was higher in the young section, reflecting the development of the polymer industry and the wider use of plastic. The dominant shape of microplastics was films, followed by fragments.

This article has several limitations that can be addressed in future research, namely a more detailed study of the degradation of microplastics as well as the mechanisms of microplastics transport in the body of the landfill. Furthermore, the numeric concentration of microplastics can be determined by more accurate methods such as micro-FTIR, and the mass of small microplastics can be measured by thermal methods.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15065017/s1, Table S1. Samples description; Figure S1. Main shapes of microplastics: (a) fibers; (b) films; (c) fragments; (d) foams; (e) spheres; (f) undefined; Figure S2. The example of spectra identification by Open Specy; Table S2. The size distribution of microplastic, %; Table S3. The shape distribution of microplastic, %.

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