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The influence of the packing material on the efficiency of BTEX compound removal from air in a biofilter

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Abstract
Biofiltration technology has emerged as the most widely applied and cost-effective method for mitigating odorous and harmful compounds in waste air streams, particularly in municipal waste treatment facilities. This study investigated the influence of different packing materials and the effect of additional microbial inoculation on the removal performance of benzene, toluene, ethylbenzene and xylenes (BTEX) from real post-composting exhaust air in conventional biofilters. The results showed that the highest removal efficiency of these aromatic hydrocarbons (removal efficiency between 0.80 and 0.99) was achieved in biofilters packed with ceramsite when the packing material was additionally inoculated with a commercial bacterial preparation. Under these conditions, the total BTEX elimination capacity reached approximately 11.2 g/(m^3· h). The findings demonstrate promising strategies for the cost-effective enhancement of existing biofiltration systems by selecting appropriate packing materials and inoculation procedures to improve the removal of benzene, toluene, ethylbenzene and xylenes from waste gas streams.

Keywords
waste air, BTEX, biofiltration, packing material, process performance

1. INTRODUCTION

Municipal solid waste management is a fundamental component of a sustainable urban infrastructure, ensuring both environmental protection and public health. Waste treatment is a multi-stage process that includes collection, transport, fraction separation, and subsequent physical and biological processing (Fig. 1). Among the treated fractions, biodegradable waste plays a crucial role and is often subjected to composting. Composting is considered an environmentally friendly technology that supports circular economy principles by transforming organic residues into valuable fertilizer products (compost/soil improver). It simultaneously generates emissions of gaseous contaminants, which significantly complicate its environmental balance (Deng et al., 2023; Lin et al., 2021; Wei et al., 2017).

A major group of odorous gas emissions involves volatile organic compounds (VOCs). While natural sources of VOCs emissions, such as wetlands, forests, and oceans, contribute approximately 1.1×10^6–1.5×10^6 Mg VOCs annually (Guenther et al., 1995), anthropogenic emissions are often more hazardous because they occur in densely populated areas and lead to direct human exposure (Mao et al., 2006). In particular, composting facilities emit VOC concentrations in the range of about 10–150 mg/m^3 (Mustafa et al., 2017; Nair et al., 2019), corresponding to annual loads of 19–280 Mg, assuming a bulk density of 0.7 Mg/m^3 of processed waste. Thus, the technology for biowaste processing and valorization must be adequately controlled to limit the environmental risks.

Among VOCs, aromatic hydrocarbons collectively referred to as BTEX (benzene, toluene, ethylbenzene, and xylenes) are of particular concern. Their emissions intensify during the thermophilic phase of composting (50–70 °C), when microbial activity and temperature accelerate volatilization (Chen et al., 1997; Deus et al., 2017; Zhang et al., 2013). The presence of BTEX is problematic for several reasons. First, these compounds are toxic and may accumulate in human tissues, increasing the risk of cancer and neurological disorders (Masih et al., 2017). Second, they contribute to the formation of secondary pollutants such as tropospheric ozone and secondary organic aerosols, which further deteriorate air quality (Wolkoff et al., 2006). Finally, since exposure occurs not only in occupational settings but also in surrounding communities, composting plants are a potential source of chronic health risks, a significant concern given that, according to the World Health Organization, air pollution accounts for approximately 5.5 million premature deaths globally each year (WHO, 2017; Yue et al., 2021), and VOCs, including BTEX, are key contributors to this burden. Biomonitoring studies provide direct evidence of these risks. Rafiee and co-workers detected unmetabolized BTEX in urine samples of composting plant workers, with mean concentrations of 1.27, 2.12,

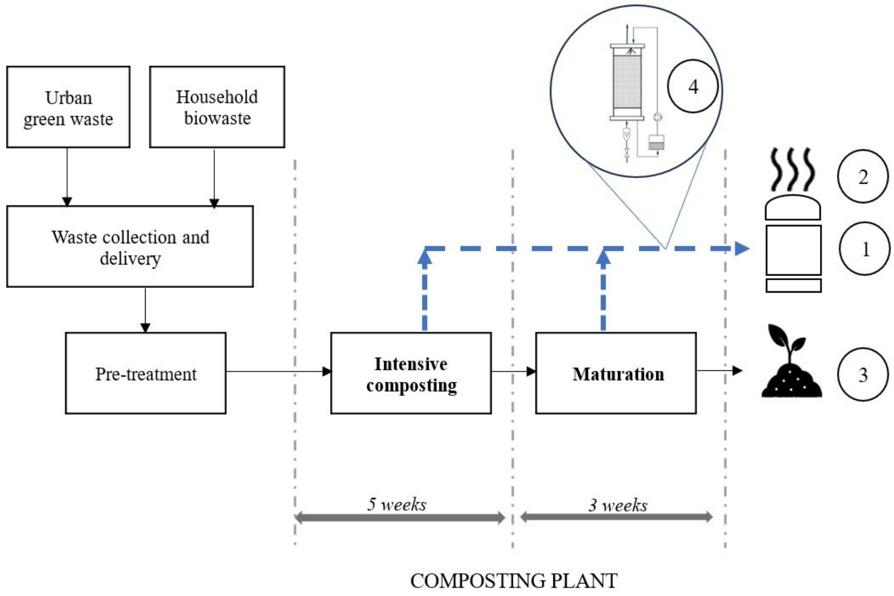


Figure 1. Idea of municipal waste management with a focus of biological waste management: 1 – biofilter treating air from composting plant, 2 – biofilter-treated air, 3 – compost (soil improver), 4 – experimental set-up.

0.54, and 2.73 µg/dm^3, respectively, for benzene, toluene, ethylbenzene, and a mixture of xylenes (Rafiee et al., 2019). These values were 1.4–3.7 times higher than those in control populations ($p < 0.05$). Similar findings were confirmed (Liu et al., 2022), highlighting the occupational and environmental health significance of uncontrolled BTEX emissions. According to the European Commission Implementing Decision 2018/1147, the permissible levels of the total VOC emissions from the biological waste treatment facilities must not exceed 40 mg/m^3.

Due to health hazards, BTEX compounds must be effectively removed from waste gases. Low investment and operating costs, as well as the absence of secondary pollutants, combined with sustainability and high efficiency, make biological methods, particularly biofiltration, a viable option for managing BTEX emissions. Biofiltration relies on the metabolic activity of microorganisms, which oxidize VOCs into less harmful end products such as CO_2, water, and biomass (Wierzbińska and Modzelewski, 2015). Microorganisms develop in the form of a biofilm over the packing material elements. Numerous studies confirm that biofilters can achieve >90% removal efficiency for BTEX and other VOCs in optimized systems, even at elevated inlet concentrations (Devinny and Ramesh, 2005). However, the performance, stability, and long-term costs of biofiltration are strongly dependent on the properties of the packing material as well as microbial diversity (Sun et al., 2002).

Conventional biofilters typically use natural packing materials, such as compost, soil, peat or wood chips. Such materials may show a tendency to compact and undergo degradation over time, which can result from excessive moisture or excessive biomass growth (Maestre et al., 2007). Thus, synthetic media also find application in biofiltration technology. Liu et al. (2020) demonstrated that polyurethane (PU) exhibited the highest maximum elimination capacity (101.88 g/(m^3· h)), outperforming ceramsite (74.57 g/(m^3· h), compost (87.81 g/(m^3· h)), and lava (67.13 g/(m^3· h)) during styrene biofiltration. In another paper (Maliyekkal et al., 2004), when using PVC beads, the maximum xylene elimination capacity (EC) of 8.78–19.1 g/(m^3· h) was reached, corresponding to empty bed residence time (EBRT) ranging from 42 to 72 s. A novel, although rarely studied approach is the use of waste materials as packing for biofiltration. Sáez-Orviz and co-workers investigated the use of plastic elements made of waste plastics as a biotrickling filter packing (Sáez-Orviz et al., 2024), achieving promising process performance and stability. This approach incorporates the ideas of circular economy and waste valorisation for the treatment of waste gas emissions.

The aim of this study was to evaluate the effectiveness of biofiltration in removing BTEX from real composting exhaust air using different packing materials. Five different packing materials were investigated: ceramsite, pine bark, polyurethane foam, commercial packing elements for disrober units, and shredded PET/PE waste plastic materials. The investigations involved evaluating the packing material performance for two systems: five biofilters were operated without additional inoculation, while the other five biofilters were inoculated with a commercial bacterial preparation DBC Plus R5 (BioArcus, Poland). By linking biofiltration performance to the type of packing and the development of microbial populations, the research provides insights into designing robust biofiltration systems that comply with Best Available Techniques (BAT) requirements and mitigate the health and environmental hazards associated with composting facilities. To the best of the authors' knowledge, this study is the first to apply shredded

PET/PE waste as a conventional biofilter packing material for treating waste air from biodegradable waste composting, whereas similar PET-based fillings have been used in wastewater biofilters, enabling efficient removal of organic pollutants and suspended solids (Dorji et al., 2021).

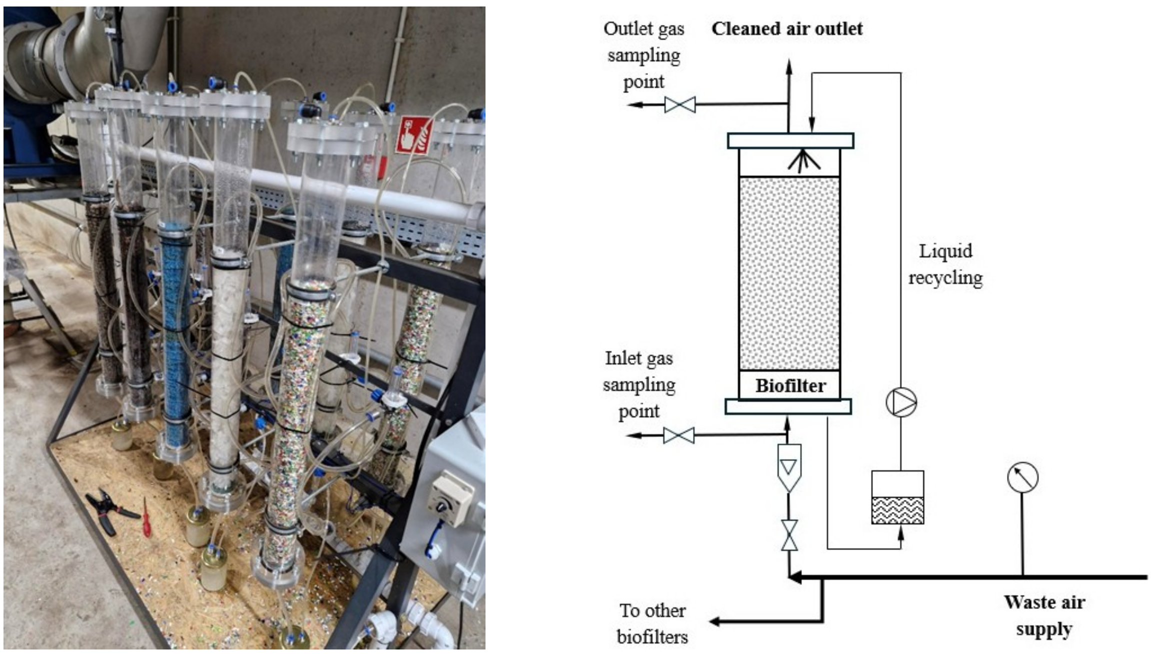
2. MATERIALS AND METHODS

Investigations were conducted in ten similar biofilters, which treated outlet air from a composting plant operated by Waste Rendering Facility Ltd. in Gdańsk, Poland. The composting process proceeds in two phases: the first involves five weeks of intensive aeration through the floor grates, and the second phase, which occurs in the hermetic maturing hall, consists of a three-week stabilization and maturation period in static piles. The ventilation system of the enclosed composting plant operates under negative pressure. Process air is continuously extracted by four centrifugal fans with a total ventilation capacity of approximately 124000 m^3/h. In the process conditions, the post-composting waste air is directed through water and acid scrubbers to a conventional biofilter packed with pine bark. However, the waste air supplied to the experimental biofilter set-up was taken directly from the composting hall, without any gas pre-treatment (Fig. 1).

Each biofilter was made of PVC and was 0.08 m in diameter and 1 m in height. Waste gas was supplied from the bottom of the biofilter, and water was periodically sprayed from the top of the biofilter to maintain the humidity of the packed bed using the peristaltic pumps (S-3Z+WX08, Baoding Signal Fluid Technology, China). The temperature of the waste gas supplied to the biofilter set-up was 35 ± 2 °C. The gas was supplied by a centrifugal fan (GBRKFRRADIR V0.1, Almeco sa, Belgium) using the inverter (Altivar ATV312HU55N4, Schneider Electric, France). The pressure and the gas flow rate were controlled using a manometer (Preciman, MR-025 mbar) and a rotameter (Magnum, ROTAMETR-OXY). The gas flow rate through each biofilter was kept constant at the value of 2.5 dm^3/min, equivalent to an empty bed residence time (EBRT) of 78 s. The scheme of a single biofilter and a photo of the experimental set-up are shown in Fig. 2.

Two series of investigations lasting 60 days were run in parallel and each series was composed of five biofilters. In series 1, there was no additional inoculation of the packing, and the microbiota of the bioreactors was established by autochthonic microorganisms naturally present in the outlet gases from the composting plant (biofilters *a, c, e, g, i*). In series 2, bacterial preparation was inoculated on the packing media (DBC Plus R5, BioArcus, Poland; biofilters *b, d, f, h, j*). The freeze-dried powder of the bacterial preparation was dissolved in distilled water (100 g/dm^3) and circulated through the biofilter packing. During the inoculation period (days 1–14), the liquid circulation lasted for 3 minutes every 25 minutes with a liquid flow rate of 0.001 dm^3/s. After day 14, the circulation liquid was discharged and changed for tap water. In addition, the liquid circulation frequency was reduced to last for 3 minutes every 3 hours.

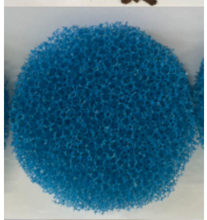
Biofilters were packed with different materials, i.e., ceramsite, pine bark, polyurethane foam discs, desorber packing plastic elements, and shredded recycled waste plastic pieces. The packing volume in each biofilter was 3.25 dm^3. Basic characteristics of the packings are given in Table 1.



(a) (b)

Figure 2. Experimental set-up: overview of the biofilters (a) and scheme of a single biofilter (b).

Table 1. Characteristics of packing materials (Chen et al., 2022; Danila et al., 2022; Moe and Irvine, 2000).

Packing type	Producer	Size, material	Porosity, m^3/m^3	Apparent density, kg/m^3	Specific surface area	Appearance in the biofilters
Ceramsite	Sobex Ltd., Poland	8–20 mm in diameter, calcinated clay (pure)	49	273	1.10 m^2/g	
Pine bark	Sobex Ltd., Poland	Pieces 1–60 mm,	73	130	0.30 m^2/g	
Polyurethane form	Ultramare, Poland	PPI10, used as discs: 80 mm in diameter, 10 mm in height	97	29	600 m^2/m^3	
Desorber packing plastic elements	—	PP (Polypropylene), triangle in shape, base 10 mm, 40 mm in height	87	124	0.35 m^2/g	
Shredded PET/PE waste plastics	Recycled plastic waste, PET:PE=3:1	Rectangular pieces of 5-10 mm length,	72	255	0.11 m^2/g	

Biofiltration process performance was monitored by determining concentration of BTEX compounds in the biofilter inlet and outlet gas streams. Gas samples were collected in Tedlar bags and analyzed using gas chromatography with a flame ionization detector (Varian CP-3800, Varian Analytical Instruments, USA). DB-624 column (60 m × 0.32 mm × 1.80 µm, Agilent Technologies, USA) was applied. Nitrogen was used as a carrier gas. Parameters of the method were set as follows: oven temperature 100 °C (isothermal conditions), detector temperature 200 °C, carrier gas flow rate 3 cm^3/min, split ratio 10.

Upon completion of the biofiltration processes, microbial community analysis was performed. Samples of circulating liquid were taken from all biofilters (30 cm^3) and were filtered through syringe filters (Sterile PES syringe filters, 0.22 µm, Qpore, Germany). After the filtration, the filters were subjected to DNA isolation by external service (A&A Biotechnology, Poland). Real-Time PCR in the direction of 16S and ITS was performed on the DNA eluates. Further, metagenomic analysis of DNA samples was performed via an external service (Genomed, Poland). The analysis involved sequencing of amplicons containing V3-V4 fragment of 16S rRNA gene, using Aviti sequencer with paired-end technology (Aviti, Element Biosences, USA). The bioinformatic analysis of the results was performed using the following software and databases: MiSeq Reporter (MSR) v2.6. (Illumina), Qiime2 (v.2024.5), Silva 138.2, CUtadapt (v. 4.7) and Silva 138.2.

Performance of biofiltration processes was evaluated using the values of removal efficiency, *RE* (Eq. 1), and elimination capacity, *EC* (Eq. 2). Empty bed residence time, *EBRT*, was calculated using Eq. 3:

$$RE = (C_{\text{in}} - C_{\text{out}})/C_{\text{in}} \tag{1}$$

$$EC = Q_G(C_{\text{in}} - C_{\text{out}})/V \tag{2}$$

$$EBRT = V/Q_G \tag{3}$$

where C_{in} and C_{out} are inlet and outlet BTEX concentrations (g/m^3), V is the volume of the packed bed (m^3), and C_G is the volumetric gas flow rate (m^3/s).

3. RESULTS AND DISCUSSION

3.1. BTEX biofiltration performance

Performances of biofilters are presented in Fig. 3. All the dependencies between changes of the removal efficiency with biofiltration time show similar trends, for all BTEX compounds investigated. Thus, the general discussion of the biofiltration performance will be performed on a selected compound, i.e. toluene.

During the initial 3–4 days of biofiltration, the removal efficiency of toluene (Figs. 3c and 3d) is about 0.1–0.2. These are low values of removal efficiency, but can indicate that some fraction of toluene is removed from the gas upon passing through the biofilter bed. This phenomenon may be attributed to the adsorption of the VOC in the biofilter packing. As the packing reaches saturation, the removal performance drops from RE about 0.2 to about 0.1 and lower, until day 6. Similar effects were observed by Colón and co-workers (Colón et al., 2009). Further, the removal efficiency of toluene begins to increase gradually. This may be the result of VOC biodegradation initiation because of the start-up of biofilm formation within the packed bed. The values of toluene removal efficiency steadily increase from day 12 until day 39–40, after which the RE values stabilize, irrespective of the inlet BTEX concentration (Fig. 3c). Stabilization of the removal performance indicates completion of the biofilter start-up period and is typically associated with the development of the biofilm, allowing for further stable biofiltration performance (Rybarczyk et al., 2024). Interestingly, the start-up period is shorter and the maximum toluene removal efficiency is higher in the biofilter with additionally inoculated packing (Fig. 3d) than in the one without additional inoculation (Fig. 3c). These differences may be explained by faster development of the biofilm, allowing for enhanced BTEX removal. Thanks to the packing inoculation with bacterial preparation, the biofilter start-up period is reduced from about 40 to 25/26 days from the biofiltration initiation (see Figs. 3c and 3d). Maximum toluene removal efficiency is increased from about 0.85 (Fig. 3c) to about 0.99 (Fig. 3d). The maximum removal efficiency for both biofilters (Fig. 3c and Fig. 3d) is kept constant even when the initial toluene (and other BTEX compounds) increases from day 53 to 57, indicating stable biofilter performance. Please note that the inlet concentrations throughout the investigations vary which is due to composting conditions, including e.g. periodic mixing and shuffling of the composted biomass. This operation takes place about every two weeks, thus inlet BTEX concentrations vary (see Fig. 1). Similar trend of biofiltration performance as for toluene was observed for benzene, ethylbenzene, and xylene, for all packing materials and biofiltration systems investigated.

However, while the general trends of biofiltration performance are similar for all BTEX compounds, the exact start-up periods and maximum removal efficiencies are not only compound-specific, but also depend on the packing type and the biofiltration system considered (with or without additional inoculation). Irrespective of the packing type, the results show that the highest values of the removal efficiency are observed for toluene, while the lowest for xylene and benzene (Fig. 1). Removal efficiencies are higher by about 10–15% for the biofilters with additional inoculation compared to those without the inoculation. The sequence of the removal performance for the BTEX compounds is as follows (in the order of decreasing removal): toluene > ethylbenzene > xylene > benzene. A similar sequence has been presented by other authors, and the differences in biofiltration performance between the BTEX compounds may be attributed to their physico-chemical properties (Rybarczyk et al., 2024; Wang et al., 2024) (hydrophobicity) and ease of biodegradation (Liao et al., 2018). For example, toluene is regarded as a moderately hydrophobic VOC that undergoes biodegradation much more easily than the other BTEX compounds (Liu et al., 2024). This is why RE values are the highest for toluene (Fig. 1). The maximum total BTEX elimination capacity reached about 11.2 $g/(m^3 \cdot h)$, corresponding to RE of about 85% for a biofilter packed with ceramsite after additional inoculation. These *EC* value corresponds to the following inlet concentrations of BTEX compounds: 48, 99, 42, and 85 mg/m^3 for benzene, toluene, ethylbenzene, and xylene, respectively (equivalent to the total inlet loading of BTEX of about 13.2 $g/(m^3 \cdot h)$. The obtained *EC* value is not high compared to some literature references. For example, total BTEX removal reached up to 120 $g/(m^3 \cdot h)$ for the inlet loading of 120 $g/(m^3 \cdot h)$ (Amin et al., 2017). Elimination capacity of up to 360 $g/(m^3 \cdot h)$ was noted for thermophilic biofiltration for total BTEX inlet loading of 880 $g/(m^3 \cdot h)$ (Mohammad et al., 2017). On the other hand, Liao and co-workers noted the BTEX elimination capacity of about 60$g/(m^3 \cdot h)$, while Raboni and co-workers reached *EC* of only 1.5 $g/(m^3 \cdot h)$ for total BTEX removal (Liao et al., 2018; Raboni et al., 2017). However, the above-reported results consider laboratory studies where a synthetic gas mixture contacting BTEX was treated. The biofiltration processes in this study were also affected by the presence of substances other than BTEX in the treated post-composting waste gas stream. In addition, the elimination capacity depends on the inlet loading. Because the inlet loading of total BTEX was relatively low in our case (up to 13.2 $g/(m^3 \cdot h)$), achieving a total BTEX removal efficiency of about 85% for a ceramsite-packed biofilter with additional inoculation can be regarded as satisfactory.

Depending on the packing type, the biofiltration start-up period as well as removal efficiencies vary between the instigated biofilters. The highest removal efficiencies for all BTEX compounds were noted for ceramsite, while the lowest values were noted for the waste PET/PE pieces used as biofilter packing. However, the difference in removal efficiency between the various packing materials is lower than 10% in all cases. Thus, shredded waste recycled PET/PE plastics can be considered as a suitable packing material for biofilters operating at waste treatment facilities. However, further studies are necessary on the packing stability and performance in long-term experiments.

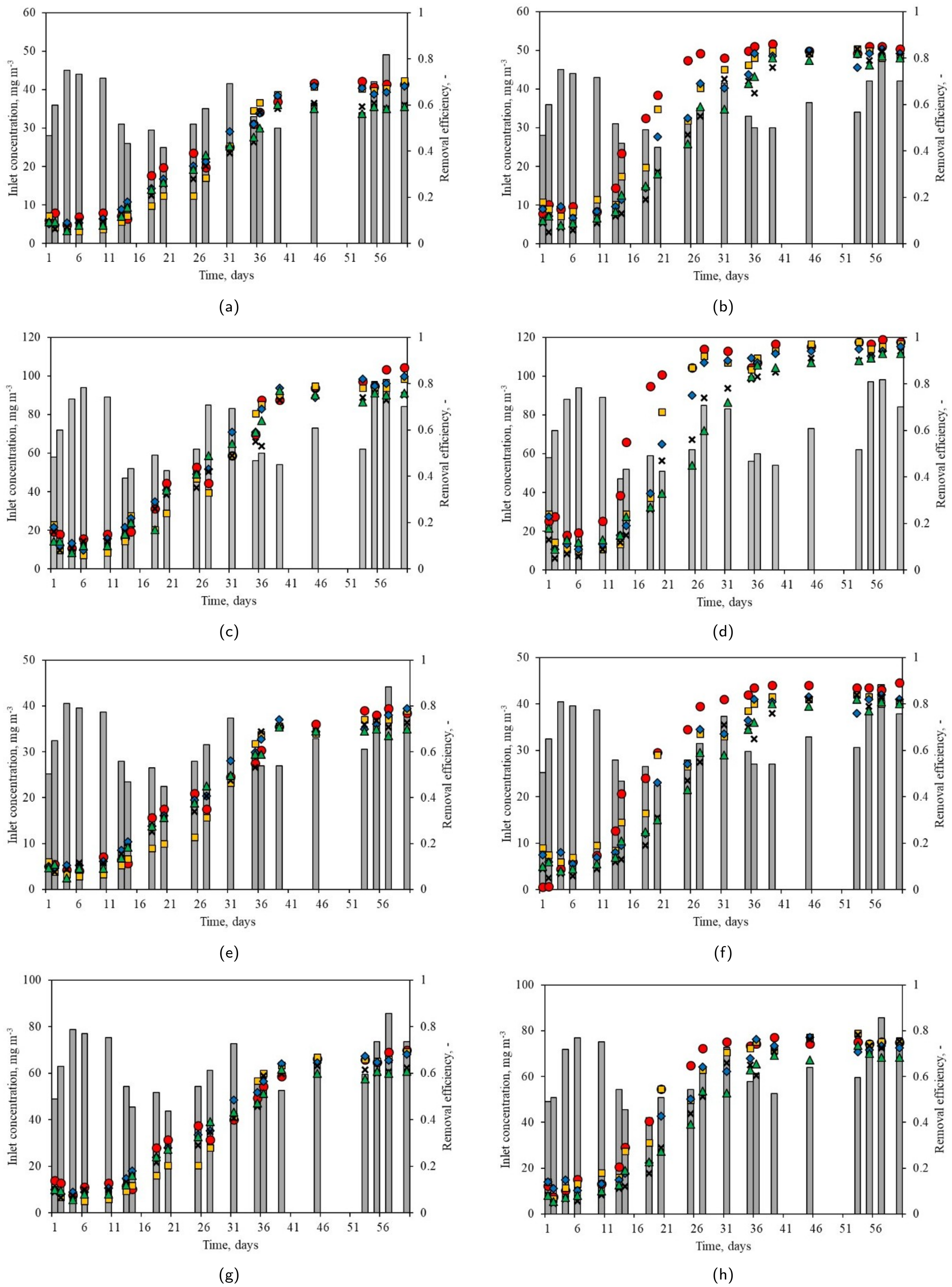


Figure 3. Performance of BTEX biofiltration for various packing materials: a, b – benzene; c, d – toluene; e, f – ethylbenzene; g, h – xylene; a, c, e, g – no additional inoculation; b, d, f, h – inoculation with bacterial preparation.

3.2. Bacterial community analysis

The bacterial community analysis aimed to assess the effect of additional inoculation and the type of media on the structure and diversity of the microbiome developed in the biofilters. The results (Fig. 4) show significant variation in the microbiome composition between individual variants, depending on both the type of packing media and the inoculation with the commercial DBC Plus R5 product. The DBC Plus R5 bacterial preparation used as the inoculum for biofilters B1–B5, contained dried bacterial strains from the genera *Bacillus*, *Arthrobacter, Acinetobacter, Pseudomonas*, and *Enterobacter*, enriched with surfactants, mineral nutrients, and grain substrate. Importantly, in none of the analyzed inoculated samples (B1–B5) was there a dominance of any of the inoculated bacterial genera. This suggests that, despite the stimulating nature of the preparation, the indigenous microflora exhibited higher competitiveness and better adaptation to the prevailing environmental conditions in the biofilters. However, in all inoculated variants, a statistically higher proportion of rare taxa (marked as "others") was observed compared to their non-inoculated counterparts. The average proportion of rare taxa in biofilters B1–B5 was 42.3%, while in the control group (B6–B10), this value was 17.7%. This observation suggests that the use of DBC Plus R5 preparation had a significant, stimulating effect on overall microbial diversity, likely due to the addition of surfactants and nutrients, which increased the bioavailability of organic and mineral substances for diverse bacterial groups.

In the case of ceramsite-packed biofilters (B1 – inoculated; B6 – uninoculated), inoculation resulted in significantly higher diversity of bacteria. In the inoculated variant (B1), a relatively even distribution of taxa was observed, with a noticeable share of *Azohydromonas* (6.26%), *Azospirillum* (7.69%), *Fluviicola* (17.54%), and *Incertae_Sedis* (9.52%), while "others" accounted for as much as 41.45% of the bio-biome. The control sample (B6), on the other hand, was characterized by a strong dominance of *Stenotrophomonas* (54.77%), *Brevundimonas* (16.97%), and *Delftia* (13.24%), with a minimal share of rare taxa (5%). The effect of inoculation was also clearly visible in the case of polyurethane (PU) foam (B3 – inoculated; B8 – uninoculated). In variant B3, no single taxon dominance was observed, with the highest proportions being *Delftia* (12.80%), *Azospira* (8.45%), and *Stenotrophomonas* (8.10%), with a very high proportion of rare taxa (63.45%). In the contrasting uninoculated variant (B8), a near-monospecific dominance of *Azospira* (45.37%) was observed, along with a high proportion of *Delftia* (26.12%) and *Gluconacetobacter* (20.90%), with a very low proportion of rare taxa (4%). These observations suggest that for ceramsite and PU foam, inoculation prevented monodominance and promoted the development of more balanced and diverse bacterial communities. In the remaining cases, the effect of inoculation on the dominance structure was less pronounced, but still noticeable in terms of diversity. For pine bark (B2 – inoculated; B7 – uninoculated), both variants were characterized by high diversity (share of "others" 46.8% and 46.22%, respectively), although inoculation influenced the proportions of dominant taxa. In the inoculated variant (B2), the highest shares were

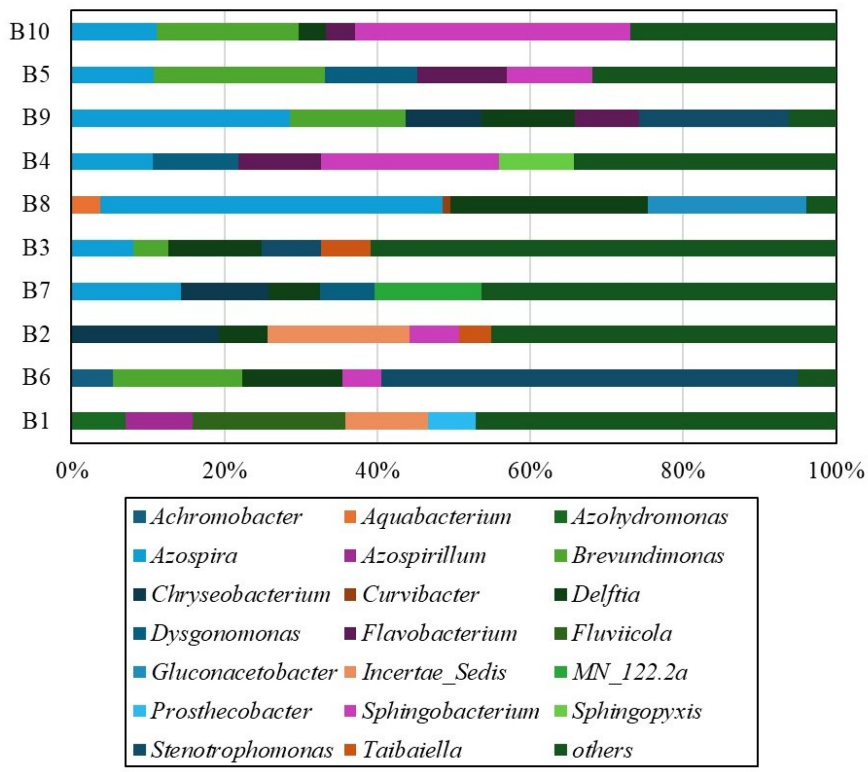


Figure 4. Microbial communities of investigated biofilters.

observed for *Chryseobacterium* (20.04%) and *Incertae_Sedis* (19.23%), while in the uninoculated variant (B7), a clear share of *Azospira* (14.24%) and the non-hierarchical group MN_122.2a (13.95%) were noted. In biofilters with desorber packing elements (B4 – inoculated; B9 – uninoculated), inoculation contributed to an increase in the uniformity of the composition. In variant B4, a relatively balanced share of three bacterial strains was noted: *Azospira* (10.18%), *Dysgonomonas* (10.86%) and *Flavobacterium* (10.32%), while *Sphingobacterium* accounted for 22.35% and "others" for 33.0%. In the control variant (B9), the composition of the biocenosis was more diverse, but with a clearly higher share of *Azospira* (28.52%), *Stenotrophomonas* (19.5%), *Brevundimonas* (15.25%) and *Delftia* (12.2%) had a significant share. In biofilters filled with the shredded PET/PE mixture (B5 – inoculated; B10 – uninoculated), a similar microbiological profile was observed in both variants, with high shares of the genera *Brevundimonas* ($\sim$ 19%) and *Sphingobacterium* (9.52%) in B5 and the uninoculated variant B10. However, a much higher share of *Sphingobacterium* was recorded in biofilter B10 (36.70%), which may indicate a spontaneous succession towards this taxon, driven by natural processes of microbial selection, regardless of the addition of the lyophilized inoculum.

In a study by Zhukov et al. (2024), biofilters inoculated with isolated strains of *Rhodococcus* and *Gordonia* achieved high terpene removal efficiency, exceeding 93% in composting off-gas treatment. Notably, consistent with our findings, the inoculated strains did not dominate the microbiome, representing only 6.5–12.4% of the community, while indigenous microflora remained the primary functional driver. These results suggest that inoculation may enhance microbial diversity and stability, even in the absence of sustained dominance of the introduced taxa.

It was further demonstrated (Su et al., 2023) that the application of synthetic microbial consortia in biotrickling filters significantly improved the removal of ammonia, hydrogen sulfide, and selected VOCs compared to systems relying solely on autochthonous microflora. The enhanced performance was associated with increased microbial diversity and the emergence of rare taxa, which aligns with our observations of an increased proportion of "others" following inoculation.

Similarly, it was reported (Gao et al., 2021) that bioaugmentation of kitchen waste compost enriched microbial communities with functional bacteria (e.g., *Bacillus*), resulting in decreased methane and nitrogen oxide emissions. However, this process was also linked to elevated emissions of ammonia and hydrogen sulfide, indicating that the effects of inoculation are multifaceted and dependent on both the composition of the consortium and operating conditions.

Another review paper (Zainudin et al., 2022) highlighted that microbial inoculation accelerates the degradation of organic matter and improves compost quality, although its contribution to off-gas treatment is more evident in the case of recalcitrant waste. In contrast, for municipal waste rich in readily degradable compounds, indigenous microflora often achieves sufficient performance, with inoculation primarily enhancing community diversity and functional stability.

Finally, the role of packing materials should be emphasized. Our findings demonstrate that the type of packing strongly influences microbial succession and pollutant removal efficiency, which is consistent with previous studies reporting that materials with high porosity and specific surface area promote the establishment of diverse and stable microbial communities (Su et al., 2023; Tahsini et al., 2025; Zhukov et al., 2024).

3.3. Limitations of the study and future research directions

This study presents the performance results of BTEX compound removal in conventional biofilters packed with different materials. The results presented are limited mainly to the removal performance evaluation, joined with the identification of microbial species found in the biofilm samples. More in-depth studies are suggested to reveal the effects of packing materials on the condition of microflora and the long-term performance of the systems. These should include monitoring of carbon dioxide evolution, stability of the packing materials, and comparison of the surface properties and changes of the investigated packings (e.g., evaluation of hydrophobicity and analysis of scanning electron microscopy photographs of the packing elements).

Future research should concentrate on testing various inoculation procedures and microbial preparations. These preparations should contain fungal-based configurations that will be benchmarked against biofilters inoculated with a commercial bacterial preparation, as the reference system. Such an experimental design will allow to identify the effects of bacterial, fungal, and mixed inocula on key biofiltration parameters, including biofilm development dynamics, BTEX biodegradation kinetics in complex VOC mixtures, operational stability under fluctuating inlet loads, and the reduction of odour-active compounds. These studies will also enable detailed evaluation of fungal–bacterial interactions, metabolic complementarity, and potential syntrophic relationships, which may enhance microbial community stability and shorten biofilter start-up periods. Moreover, there is a noticeable gap in research focused on direct comparisons of fungal and bacterial inoculation strategies under industrially relevant conditions, where dynamically changing parameters such as humidity, temperature, inhibitory compounds, and fluctuations in off-gas composition significantly influence biofilter performance.

4. CONCLUSIONS

In this work, the removal of BTEX compounds from real post-composting waste gases in conventional biofilters was investigated. Five different packing materials with or without additional bacterial inoculation were tested. A novel approach of using shredded PET/PE plastic materials was investigated. The results showed that the highest removal efficiency of BTEX compounds (RE between 0.80 and 0.99) was achieved for biofilters packed with ceramsite when the packing was additionally inoculated with a bacterial preparation, corresponding to a total BTEX elimination capacity of about 11.2 $g/(m^3 \cdot h)$.

Such performance allows to obtain concentrations of BTEX well below 40 mg/m^3 in the biofilter outlet gas, thus meeting the EU regulations for biological waste treatment facilities. The microbiological analysis demonstrated that additional inoculation enhanced the overall bacterial diversity in the biofilters, primarily by increasing the share of rare taxa. The application of the bacterial preparation significantly shortened the start-up period, which correlated with the faster establishment of stable and more diverse microbial communities. At the same time, it was found that despite inoculation, the autochthonous microflora from the composting plant played a key role in shaping the biocenosis, being best adapted to the specific environmental conditions prevailing in the biofilters.

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SYMBOLS

C	concentration, g/m^3
EBRT	empty bed residence time, s
EC	elimination capacity, g/(m^3·s)
Q	volumetric flow rate, m^3/s
RE	removal efficiency, –
V	volume of the packing, m^3

Subscripts

G	gas
in	inlet
out	outlet

Abbreviations

BTEX	benzene, toluene, ethylbenzene, xylene
PE	polyethylene
PET	polyethylene terephthalate
PVC	polyvinyl chloride
VOC	volatile organic compounds

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