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Trade-Offs Between Environmental Sustainability and Occupational Safety: Carbon Monoxide Emissions in Enclosed and Open Composting Systems

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Abstract

This study investigates carbon monoxide (CO) emission potential and kinetics in two biowaste composting facilities, one of which implements process hermetization in a closed hall, in accordance with the Best Available Techniques (BAT) for Waste Treatment, representing a more sustainable waste management approach due to the reduction in uncontrolled gaseous emissions to the environment. The flux chamber method was used to measure cumulative CO concentrations before and after compost turning across 10 compost piles located either indoors or outdoors. Maximum cumulative CO concentrations (C_{COmax}) and CO production rate constants (k) were calculated. Results indicate that indoor composting leads to significantly higher net CO emissions, both before and after pile turning. In all indoor piles, cumulative CO concentrations exceeded the United States Environmental Protection Agency (EPA) 1 h and 8 h exposure limits. Post-turning cumulative CO levels reached over 3000 mg CO·m^{-3}, with averages ranging from above 15 to over 70 mg CO·m^{-3}. These levels pose a serious health risk, potentially causing headaches, collapse, or even loss of consciousness in workers after approximately two hours of exposure. Additionally, compost turning in closed systems resulted in slower CO production, prolonging exposure. The study demonstrated that, although BAT-compliant enclosed systems are beneficial for the environment and support sustainable waste management practices, they may create hazardous conditions for workers. Therefore, continuous monitoring of gas concentrations is essential in closed composting facilities to ensure that environmentally sustainable waste treatment technologies are implemented together with adequate occupational safety measures, supporting a more comprehensive and balanced approach to sustainability.

Keywords: sustainable waste management; carbon monoxide (CO) emissions; flux box chamber; sustainable indoor composting; gas production kinetics; United States Environmental Protection Agency (EPA) standards; World Health Organisation (WHO) standards; occupational safety; Best Available Techniques (BAT)

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1. Introduction

The Best Available Techniques (BAT) reference document for waste treatment has been developed to compile the most favorable methods, measures, and technologies that address key environmental issues in the waste management sector. Their introduction to

the waste treatment industry is expected to lead to higher performance levels, including lower emissions and better process monitoring [1].

Moreover, the implementation of BAT is intended to increase the environmental sustainability of biological waste management by minimizing the negative environmental impacts associated with waste treatment processes. In the case of composting, to ensure a less harmful impact of the process on the atmospheric air quality, the Waste Treatment BAT document recommends placing the composted waste in hermetic halls equipped with negative air pressure, air curtains, and fast-acting doors [1]. The intended effect of introducing such solutions is to reduce the release of a wide range of pollutants, including CO_2, CH_4, NH_3, N_2O, VOCs, and odors [2,3]. Since the last version of the BAT report was published in 2018, not all composting plants operating in Europe have implemented the document's recommendations. Nevertheless, over the previous few years, the waste composting sector has seen a gradual shift in its practices, with some facilities now operating in closed, hermetic halls or bioreactors, while others continue to compost in open outdoor yards. Implementing BAT and locating compost piles indoors and/or outdoors indirectly affects the process conditions, including the ambient temperature and process gas emissions.

Carbon monoxide (CO) is a relatively new compound in the context of composting emissions, though its formation has been confirmed across various waste types, including green waste, sewage sludge mixtures, plant and food waste, animal waste, and municipal solid waste [4–9]. CO production results from both biological processes—driven by aerobic and anaerobic microorganisms—and abiotic thermochemical reactions [10]. Due to this dual origin and the variability of aerobic and anaerobic conditions, CO emissions from large compost piles are difficult to measure accurately.

According to recent studies, CO emissions in compost halls can reach much greater levels than the safe thresholds for humans set by the World Health Organisation, putting plant workers at risk [11]. Such data becomes significant when considering the BAT document's recommendations to close waste piles in sealed halls or in-vessel systems, as both of these practices cause an excessive build-up of CO in enclosed areas [12]. What cannot be overlooked is the fact that in the case of CO, the kinetics of the gas's release are just as important as the emission level itself. It provides information not only about the maximum concentration of released CO, but also about the rate of its production. These details are crucial due to the toxic nature of CO and how extensively it affects the human body, displacing oxygen and forming carboxyhemoglobin. According to research, CO poisoning causes not only temporary, reversible health effects, but also significant injuries [13].

Generally, the health risks depend on CO concentration and the length of CO exposure. However, what is particularly noteworthy is the fact that long-term, low CO exposure is reported to be equivalent in health effects to short, intense exposure to high concentrations of CO. Both extended low-level exposure and extreme CO concentrations can result in unconsciousness or even death [14]. Regular exposure to relatively low CO concentrations can lead to dizziness, nausea, mental disorientation, and dyspnea [15]. Long-term effects of chronic CO exposure also include persistent symptoms like fatigue, diarrhea, recurrent infections, insomnia, difficulty concentrating at work, and memory impairments [16].

The United States Environmental Protection Agency (EPA) lists CO as one of the six principal pollutants that can be harmful to public health and the environment [17]. Following the Clean Air Act, the EPA is obliged to set National Ambient Air Quality Standards (NAAQS) for CO, considered to be the 'primary standards', ensuring public health protection and protecting the health of 'sensitive' populations such as asthmatics, children,

and the elderly [18]. The NAAQS for CO includes two averaging times, establishing an 8 h primary standard level of 10 mg·m^{-3} (9 ppm) and 40 mg·m^{-3} (35 ppm) for a 1 h average.

As a result, in enclosed spaces, preventing the adverse health effects of CO exposure requires an assessment of both the maximum concentration levels that may occur and the rate at which CO is released. Therefore, this study aimed to evaluate the potential implications of implementing BAT in composting systems (i.e., indoor versus outdoor composting) on the kinetics of net CO production from compost piles. The flux chamber method was applied to measure cumulative CO concentrations during full-scale composting processes. Maximum cumulative CO concentrations (C_{COmax}) and CO production rate constants (k) were determined for 10 compost piles located in two composting facilities differing in process configuration (closed hall vs. open yard). The obtained cumulative CO concentrations were subsequently compared with the EPA's NAAQS for CO exposure to assess the potential occupational health risk associated with different composting technologies. In this context, the study also aimed to evaluate whether environmentally sustainable waste treatment solutions implemented in accordance with BAT principles simultaneously ensure adequate occupational safety conditions, supporting a more comprehensive and balanced approach to sustainability.

2. Materials and Methods

2.1. Experiment Matrix

Ten piles processed in two full-scale composting plants in Poland were selected for the study (Table 1). Composting piles differed in location in the facilities (indoor vs. outdoor composting) and age of the composted material (from 2 to 8 weeks). Tests in Facility A were carried out on 4 piles made of green waste (grass cuttings, branches, and wood) and sewage sludge (80 and 15% by weight of fresh mass, respectively) placed in a closed hall, in the autumn season (Poland, September–October). In Facility B, analyses were carried out in winter (Poland, February) on 5 piles located outside: 4 piles of green waste and one of the undersized fraction (<80 mm) of municipal solid waste (MSW). In both facilities, passive aeration combined with daily turning between measurements was employed: in Facility A, using a windrow turner Topturn X6000, Komptech, Frohnleiten, Austria, and in Facility B, using a standard hydraulic excavator equipped with a bucket of approximately 0.8–1.0 m^3 capacity. Detailed machine operating parameters were not monitored as experimental variables. The spatial configuration of the composting facilities was illustrated in previous work using top-view imagery sourced from Google Maps, including the delineation of individual windrows in Facilities A and B [11]. In the case of Facility B, the spatial arrangement of the compost piles is additionally presented schematically together with relevant information regarding the prevailing wind directions during the measurement campaign in Figure 1.

Table 1. Matrix of measurements in Facilities A and B; 'measurement series' is defined as measuring gas concentrations from one pile before and after turning the compost.

Facility	Type of Composting	Pile Number	Composting Substrates	Age of the Pile, Weeks	Measurements Series
A	Indoor composting (closed hall)	1	Biowaste mixture: grass cuttings, branches with wood, sewage sludge (80, 5, 15%, by fresh mass, respectively)	2	2
		2		2	
		3		3	3
		4		4	2
B	Outdoor composting (open yard)	1	Green waste (from backyards and parks)	8	1
		2		8	
		3		6	
		4		4	
		5		3	
		6	Undersized fraction of MSW (<80 mm)	3	

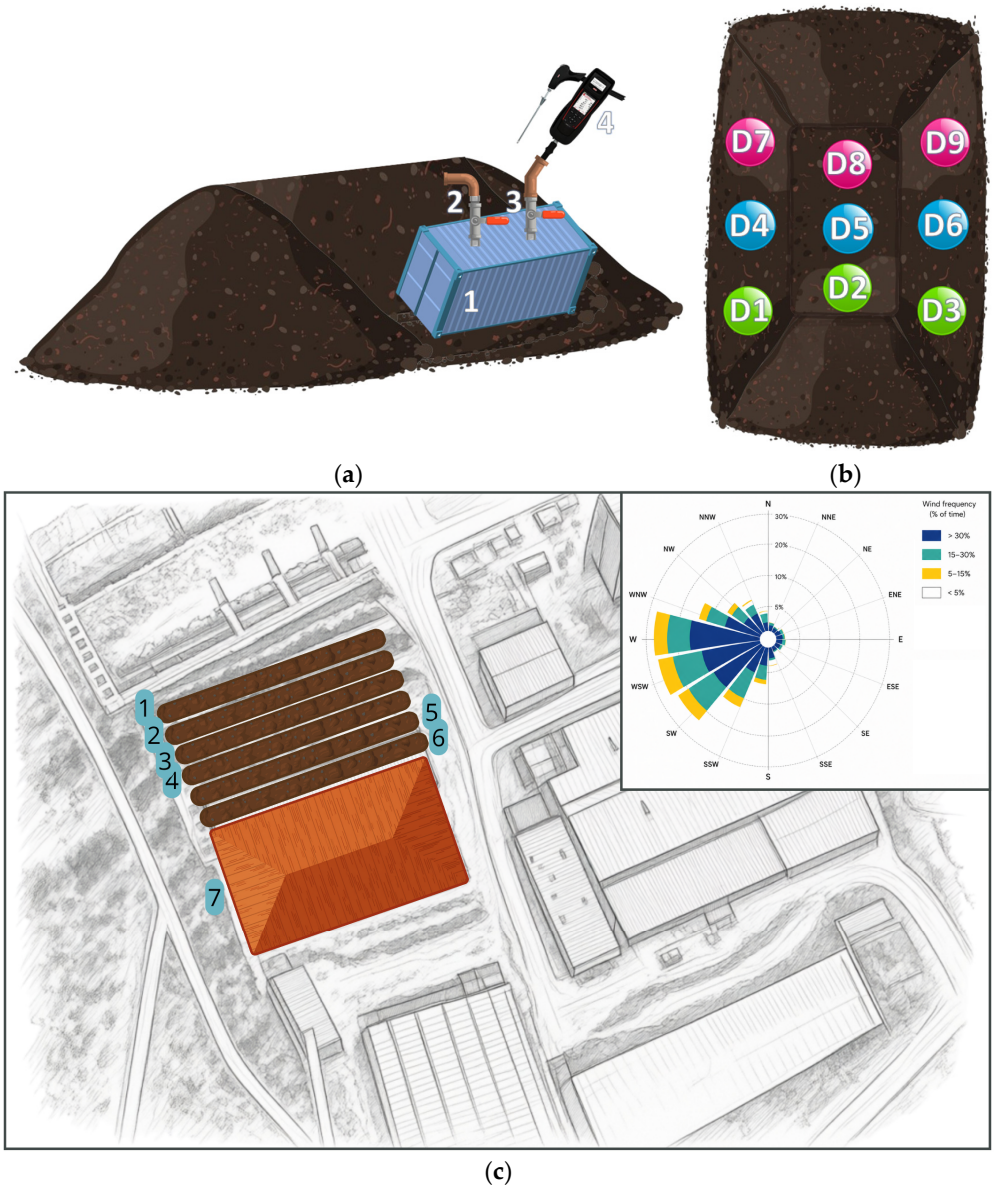


Figure 1. Experimental set-up with the use of the flux chamber method: (**a**) flux chamber placed on a pile; 1–flux chamber, 2–the pressure relief port, 3–valve, 4–gas concentration analyzer and thermocouple, (**b**) the location of the flux chamber during measurement in the top view of the pile. Spots D2, D5, and D8 are pile tops (upper section), D1, D4, and D7–on the left side, and D3, D6, and D9 right side of the pile; the front side of the pile is marked in green, the middle part in blue, and the backside in pink, (**c**) the spatial arrangement of the compost piles in facility B (outdoor composting) together with a wind rose showing the wind directions during the measurement period; 1–6 composting piles, 7–storage building. Selected graphical elements presented in Figure 1c were generated with the assistance of ChatGPT (GPT-5, OpenAI) and subsequently reviewed and edited by the authors.

Compost samples were analysed for dry matter content, organic dry matter content, and respiratory activity (AT4) in accordance with relevant standards [19–21]. The compost characterization was reported in detail in a previous study [11], and the results are additionally presented in the Supplementary Materials.

2.2. Process Gas Concentration Analyses

The concentrations of CO (ppmv) and O_2 (%) were measured using the flux chamber method with an adapted plastic flux box (V = 0.071 m^3) and Kimo KIGAZ 300 gas analyzer

(KIMO Instruments, Montpon-Ménestérol, France), following the procedure commonly used in the assessment of process gas emission on landfills [22] (Figure 1a). The temperature inside the chamber was measured with a thermocouple (±0.1 °C). During each measurement, the flux chamber was placed at 9 measurement points on the pile (Figure 1b). The measurement was carried out for 5 min, and changes in CO concentrations over time were recorded using a camera. The obtained data with intervals of 5 s were entered manually into an Excel sheet. Each measurement series was done once a day before and after pile turning.

2.3. Estimating CO Production Kinetics

CO concentrations (ppmv) at every 5 s of measurement were converted to mass units ($mg \cdot m^{-3}$) at standard temperature (273 K) and pressure (101.3 kPa) [11]:

$$c_m = \frac{c_v \cdot M_{CO}}{V_{CO}} \cdot \frac{273}{T} \quad (1)$$

where:

c_m—CO concentration, $mg \cdot m^{-3}$,
c_v—CO concentration, ppmv,
M_{CO}—molecular weight of CO, $M_{CO} = 0.028\ mg \cdot mol^{-1}$,
V_{CO}—the molecular volume of CO at standard conditions, $V_{CO} = 0.0224\ m^3 \cdot mol^{-1}$,
T—temperature of measurement, K.

The cumulative CO concentration during 5 min of measurement was estimated as follows:

$$c_{m\ total} = \sum_{n=1}^{60} c_m \quad (2)$$

where:

$C_{m\ total}$—cumulative CO concentration after 5 min of measurement, $mg \cdot m^{-3}$,
c_m—CO concentration estimated for every 5 s step, $mg \cdot m^{-3}$,
n—number of 5s steps, n = 60.

Cumulative CO concentration increase kinetics during composting were analyzed using nonlinear least-squares regression and a first-order reaction model:

$$C_{CO} = C_{COmax} \cdot \left(1 - e^{-k \cdot t}\right) \quad (3)$$

where:

C_{CO}—cumulative CO concentration at time t, $mg \cdot m^{-3}$,
C_{COmax}—maximum cumulative CO concentration, $mg \cdot m^{-3}$,
k—CO production constant rate, s^{-1},
t—time, s.

2.4. Visualization

For each pile in Facilities A and B and each measurement series, the obtained data on cumulative CO concentration were visualized based on the created value grids. Color-coded isopleths were generated using Surfer 10 (Golden Software, Cracow, Poland) to illustrate the spatial distribution of cumulative CO concentrations before and after compost turning. The visualizations were created as a top view in the shape of a rectangle, corresponding to the tested piles' real dimensions (6 m × 30 m).

2.5. Statistical Analyses

Statistical analyses were performed using Statistica 13 software (StatSoft Inc., TIBCO Software Inc., Palo Alto, CA, USA). For each analyzed parameter, descriptive statistics were calculated, including mean values and standard deviations. To characterize composted waste, one-way analysis of variance (ANOVA) followed by Tukey's HSD post hoc test was applied to determine significant differences among the analyzed materials at $p < 0.05$.

Statistical analyses were also conducted to evaluate the effect of pile turning on cumulative CO concentrations and kinetic parameters describing CO emissions during composting in Facilities A and B. Because the dataset was characterized by a relatively small number of observations, non-normal distribution, and high variability, non-parametric statistical methods were applied. Differences in cumulative CO concentrations, maximum cumulative CO concentrations (C_{COmax}), and kinetic constants (k) measured before and after pile turning were analyzed using the Wilcoxon signed-rank test for paired observations. Comparisons between Facility A and Facility B were performed using the Mann–Whitney U test. Statistical significance was assumed at $p < 0.05$.

Relationships between cumulative CO concentrations and O_2 concentrations were evaluated using Spearman's rank correlation coefficient. Correlation analyses were performed separately for Facilities A and B, as well as for measurements conducted before and after pile turning.

The kinetics of cumulative CO concentration increase during the 5 min measurement period were evaluated using nonlinear least-squares regression. Experimental data were fitted to a first-order reaction model to estimate the maximum cumulative CO concentration (C_{COmax}) and the CO production rate constant k, as described in Section 2.3. The goodness of fit of the regression models was assessed based on the coefficient of determination (R^2) and visual inspection of the agreement between measured and predicted values.

3. Results

3.1. Cumulative CO Concentration and O_2 Levels

Cumulative CO concentrations varied with the measurement location on the pile and increased markedly after pile turning. Median cumulative concentrations increased from 169.3 to 612.7 mg CO·m^{-3}, while the mean increased from 202.7 to 647.1 mg CO·m^{-3} (Table S1). In both facilities, these values ranged from 0 mg CO·m^{-3}, up to >3000 mg CO·m^{-3} and in the case of Facility A, varied from 6.99 to 3206.35 mg CO·m^{-3} (Table S1).

The Wilcoxon signed-rank test indicated that in Facility A, cumulative CO concentrations after turning were significantly higher than before turning ($W = 55$, $p < 0.001$). On average, CO emissions after turning were approximately 3.7 times higher than before turning. Pile 1 (2 weeks old) at Facility A was analyzed twice during the study. During the 1st trial, and before the material was turned over, the highest cumulative CO concentration was recorded in its front upper section (Figure 2a; point D2 with 159.56 mg CO·m^{-3}, Table S1). The D2 location also actively produced CO after the turning with a cumulative CO concentration of 2446.98 mg CO·m^{-3} (Figure 2a, Table S1). During the 2nd series of measurements, the highest CO production before and after turning was maintained in the composted material's front upper section (Figure 2b; 331.93 and 590.49 mg CO·m^{-3} at D3 before and after turning, respectively, Table S1). For pile 1, the average cumulative CO concentration for the 1st trial increased by over 5× after turning (from 99.80 to 560.60 mg CO·m^{-3}, respectively, Table S1), and in the case of the 2nd trial, by over 3× (from 160.70 to 519.10 mg CO·m^{-3} before and after turning, respectively, Table S1).

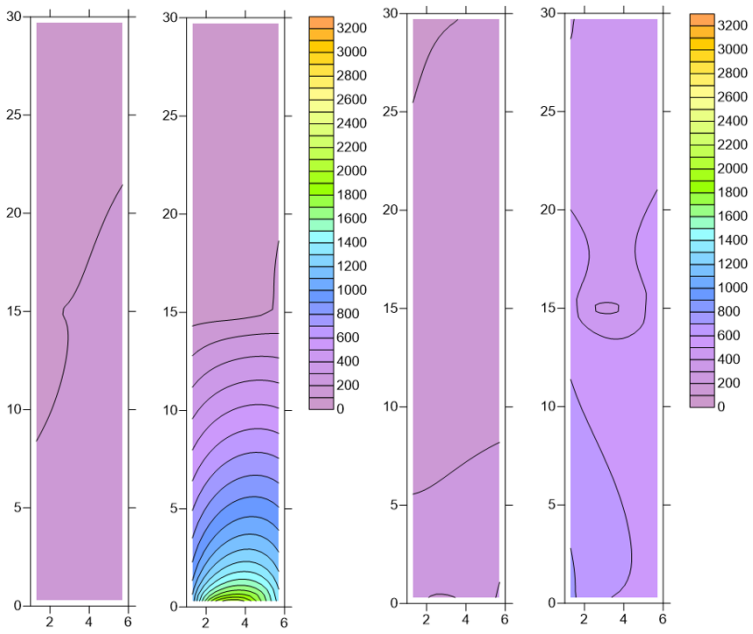


Figure 2. Cumulative CO concentration (mg CO·m^{-3}) before (left) and after turning (right), measured in pile 1 at Facility A (indoor composting): (**a**) 1st measurement series, (**b**) 2nd measurement series.

Cumulative CO concentration in pile 2 (2 weeks old) at Facility A was measured three times. During the 1st series, the highest value before turning was in the middle upper part of the pile (point D5, 354.06 mg CO·m^{-3}, Table S1), at the 2nd series the hot spot moved to the front upper part (458.88 mg CO·m^{-3}, Table S1), and during the 3rd series–again changed to the middle upper point (D5, 494.99 mg CO·m^{-3}, Table S1). After the turning, the cumulative CO concentration increased (Figure 3); the value was higher over 7× after turning for 1st trial of measurements (from 122.40 to 924.10 mg CO·m^{-3}, respectively, Table S1). With subsequent repetitions, the values did not exceed a 2-fold increase (175.20 and 275.00 mg CO·m^{-3} for the 2nd series and 317.10 and 543.40 mg CO·m^{-3} for the 3rd series, before and after turning, respectively, Table S1).

CO production from pile 3 (3 weeks old) at facility A was tested three times and again, an increase in the cumulative CO concentration after turning was observed (Figure 4). The values of the highest cumulative CO levels in each series exceeded 1100 mg·m^{-3} (1312.59 at D2 and 1 107.61, 1385.96 mg CO·m^{-3} at point D8, respectively, for three measurement series, Table S1). The highest increase in the average cumulative CO concentration after turning was observed during the 2nd measurement series; the value increased 4× (from 163.30 to 664.80 mg CO·m^{-3}, Table S1).

For pile 4 (4 weeks old) in Facility A, the highest cumulative CO level before turning was found at the front section, both in the upper and right side of the pile (Figure 5; 391.33 mg CO·m^{-3} and 917.76 mg CO·m^{-3} at D3 and D2 for the 1st and 2nd measurement series, respectively, Table S1). After turning, the cumulative CO production in both series exceeded 1000 mg CO·m^{-3} (D5 and D7, respectively), with the lowest cumulative CO concentrations ~500 mg CO·m^{-3} (Table S1). The increase in average cumulative CO level was ~3× (from 239.10 to 838.60 mg CO·m^{-3} and from 273.80 to 781.80 mg CO·m^{-3}, respectively, Table S1).

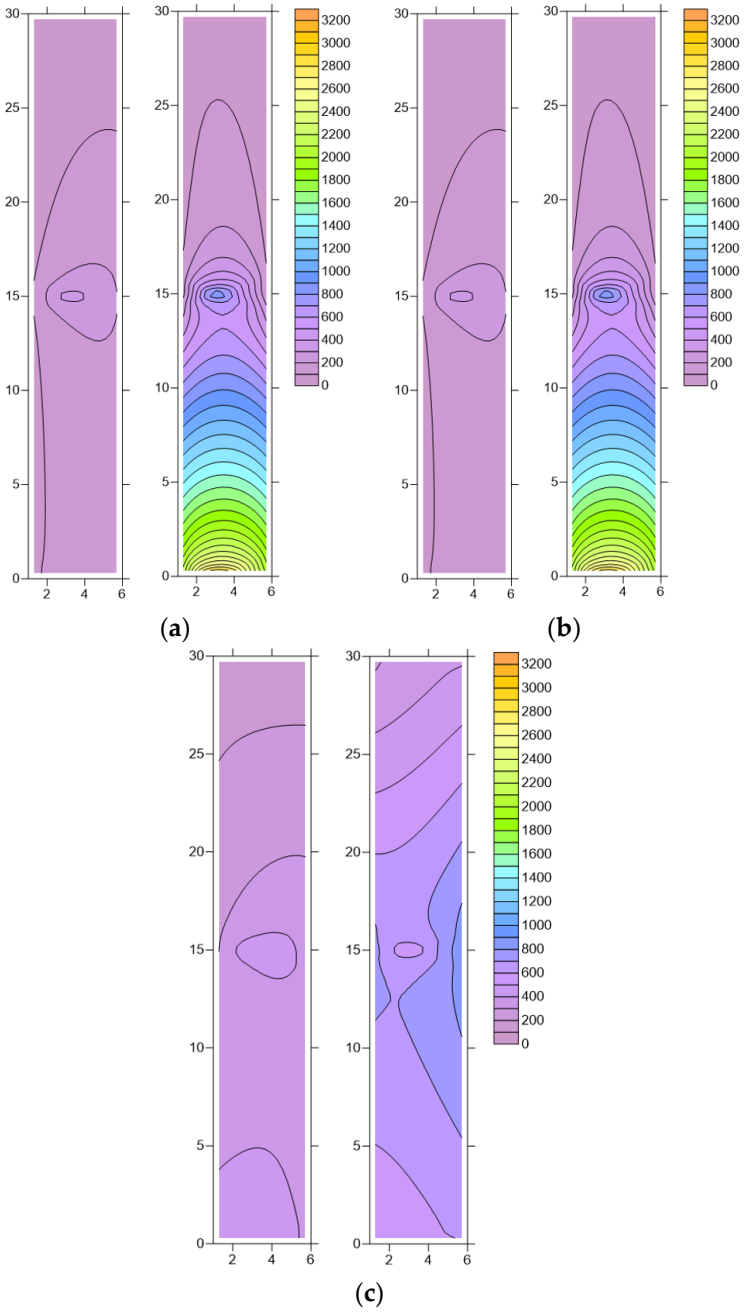


Figure 3. Cumulative CO concentration (mg CO·m^{-3}) before (left) and after turning (right) measured in pile 2 at Facility A (indoor composting): (**a**) 1st measurement series, (**b**) 2nd measurement series, (**c**) 3rd measurement series.

In Facility A (indoor composting), the 8 h average CO standard (NAAQS) was exceeded at all analyzed measurement points (D1–D9) for each pile and in every measurement series, both before and after compost turning. In the case of the 1 h average standard, Facility A was also characterized by exceedances for all average cumulative CO concentration values (each pile, all measurement series, both before and after turning). Considering individual measurement points, 93.3% exhibited excessively high CO levels (168 out of 180 measurement points). Among the points with values below the 1 h average standard, 7 did not exceed the safe level before compost turning (3.9% of all points), while 5 remained below the limit after turning (2.8%).

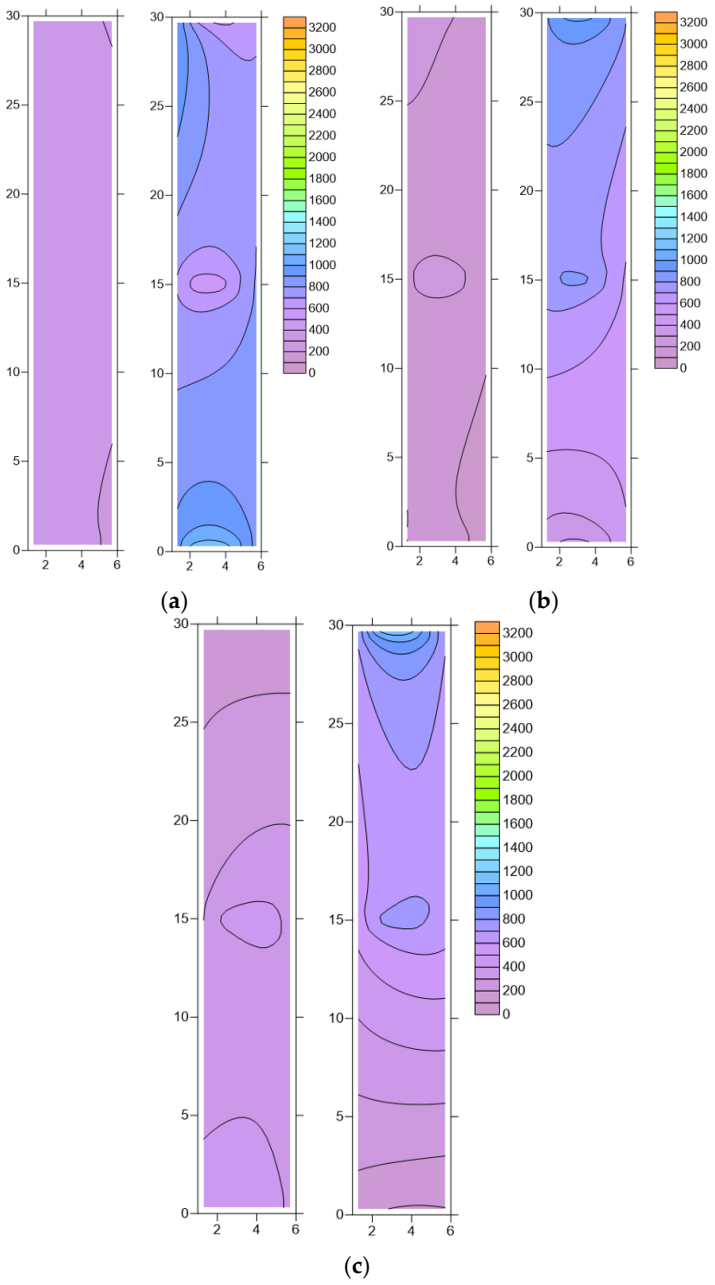


Figure 4. Cumulative CO concentration (mg CO·m^{-3}) before (left) and after turning (right), measured in pile 3 at Facility A (indoor composting): (**a**) 1st measurement series, (**b**) 2nd measurement series, (**c**) 3rd measurement series.

Production of CO from piles in Facility B (outdoor composting) was also analyzed before and after compost turning with one measurement series for each pile (Table 1). Similar to Facility A, the cumulative CO concentrations here increased significantly after pile turning (Wilcoxon signed-rank test, $p < 0.05$). Mean cumulative CO concentrations increased from 0.72 to 20.52 mg CO·m^{-3} after turning.

Piles built from green waste (1–5 with age between 3 and 8 weeks) had zero cumulative CO concentrations before turning, except pile 1, where low CO emission was recorded at the end of the pile at the level of 2.33–6.99 mg CO·m^{-3} (points D9-D7, Table S1, Figure 6). It was only after the turning that the cumulative CO concentrations began to increase and were detectable (Table S2, Figure 6). The highest average cumulative CO levels were measured for pile 3 (27.30 mg CO·m^{-3}); followed by 17.30, 15.10, 10.60 and 10.50 mg CO·m^{-2} (piles 5, 4, 1 and 2, respectively, Table S2). Due to difficult accessibility, pile 6, built from the

undersized fraction of municipal solid waste, was only tested in the front at points D1, D2, and D3, and the visualizations show only these measurement spots. Before turning, the highest cumulative CO concentration was 4.66 mg CO·m^{-3} (left front part, D1), and after turning, it reached ~12× higher value (D1, 57.07 mg CO·m^{-3}, Table S2).

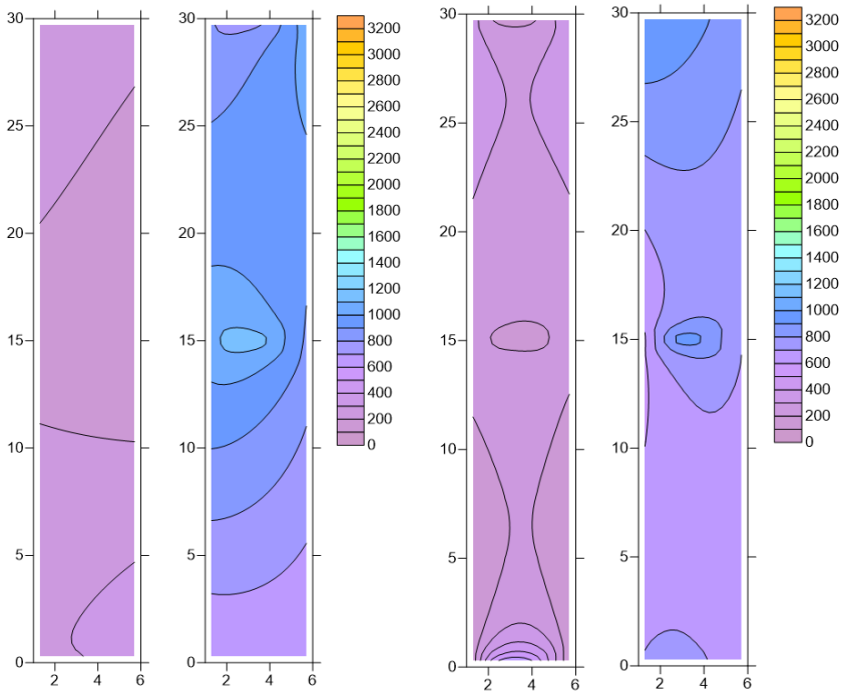


Figure 5. Cumulative CO concentration (mg CO·m^{-3}) before (left) and after turning (right), measured in pile 4 at Facility A (indoor composting): (**a**) 1st measurement series, (**b**) 2nd measurement series.

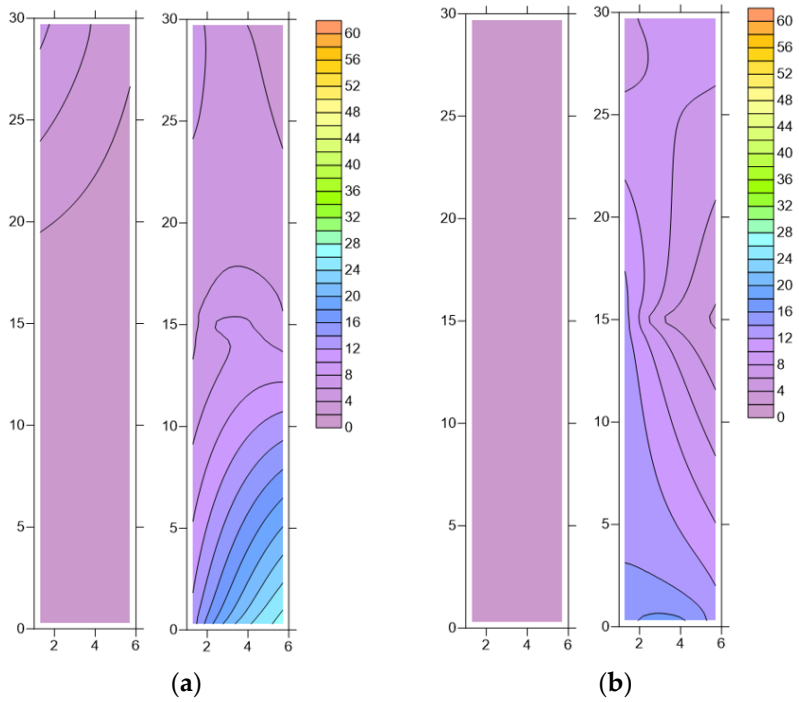


Figure 6. *Cont.*

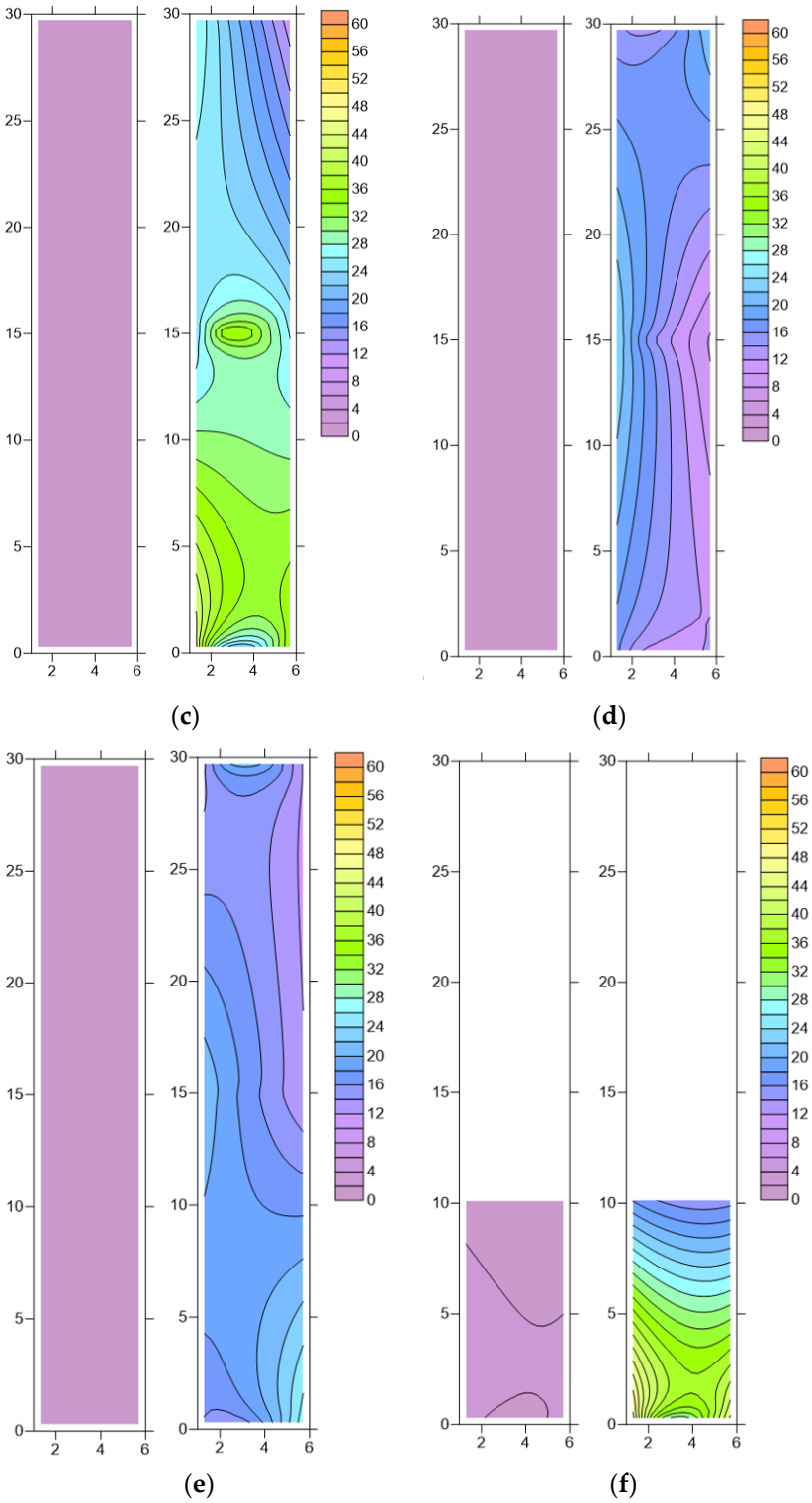


Figure 6. Cumulative CO concentration (mg CO·m^{-3}) before (left) and after turning (right), measured at Facility B (outdoor composting) for piles 1–6 (**a**–**f**).

In Facility B, the 8 h average CO standard was exceeded only after compost turning. However, this exceedance was observed for every analyzed pile in each measurement series. At the level of individual measurement points, exceedances were recorded at more than one-third of the analyzed spots (36.5%). Regarding the 1 h average CO standard, only 3 measurement points exceeded the permissible limit of 40 mg CO·m^{-3} (3.1%), and these exceedances were observed exclusively after compost turning.

It is important to highlight that the EPA standards for CO exposure referenced in this study are based on 1 h and 8 h time-weighted average concentrations, whereas the measurements conducted at both facilities were based on 5 min sampling periods. Therefore, the obtained values should not be interpreted as direct equivalents of the regulatory exposure limits. The short-term measurements were intended to provide a preliminary assessment of CO emission intensity and to identify potential peak exposure situations associated with specific workplace activities.

The compost in both facilities was characterized by high oxygenation (>18% O_2, Tables S3 and S4). The lowest O_2 level in Facility A was ≥18.30%, while the average O_2 concentration for piles 1–4 before and after turning exceeded 19% (Table S3). The piles in Facility B showed even higher concentrations of O_2, with the lowest oxygenation in the pile of an undersized fraction of municipal waste (average 20.30% after turning, Table S4).

No statistically significant correlation between cumulative CO concentrations and O_2 concentrations was observed in either Facility A or Facility B (Spearman correlation, $p > 0.05$). However, differences in the observed tendencies between the two facilities were identified. In Facility A, only a weak negative relationship between CO and O_2 concentrations was observed after pile turning, likely due to the high variability of CO emissions and heterogeneous conditions within the compost piles. In contrast, Facility B exhibited a stronger negative tendency after turning ($\rho = -0.71$), indicating that higher cumulative CO concentrations tended to occur at lower O_2 concentrations. Nevertheless, this relationship also remained statistically non-significant, most likely because of the very narrow range of O_2 concentrations and the limited number of observations. Overall, the results suggest that O_2 concentration alone was not a significant predictor of cumulative CO emissions under the investigated composting conditions.

3.2. Cumulative CO Concentration Increase Kinetics

In each of the analyzed compost piles in both facilities, an increase in the average maximum cumulative CO concentration (C_{COmax}) was observed after turning (Table 2). In the case of Facility A (indoor composting), the highest C_{COmax} before material turning was recorded for the oldest pile 4, processed for 4 weeks (13.74 and 17.63 mg CO·m^{-3} during both measurement series), and for pile 3 during the 1st trial (19.25 mg CO·m^{-3}). After turning, all piles achieved C_{COmax} > 28 mg CO·m^{-3}, with the highest values for piles 2 and 4 (72.39 and 53.11 mg CO·m^{-3} for the 1st measurement series, respectively). In Facility B (outdoor composting), C_{COmax} was much lower; after material turning, the values ranged from 0 to 0.0031 mg CO·m^{-3}. However, this result was exceeded by the pile made of the undersize fraction of municipal waste; for this material, the C_{COmax} increased from 0 to 0.4570 mg CO·m^{-3} after turning.

The CO production constant rate (k) for piles in Facility A reached a similar level before and after the material was turned (~0.0100 s^{-1}), with the highest result for pile 1, processed for 2 weeks (0.0116 s^{-1}). However, in most cases in Facility A, a decrease in the average k after turning was noted (the lowest values were recorded in pile 1, where k was close to 0.008 s^{-1} in each measurement series).

Due to the lack of measurable cumulative CO concentrations in piles built from green waste in Facility B, before turning, the apparent rate constant was 0 in each of the analyzed cases. The exception was pile 1 (k = 0.0408 s^{-1}), and the undersized fraction pile, for which the constant k reached 0.0772 s^{-1}. After the material was turned, the k increased in most of the analyzed piles; the highest values were recorded for the oldest piles (piles 1 and 2 processed for 8 weeks, 0.0899 and 0.0799 s^{-1}, respectively).

Table 2. Cumulative CO concentration net increase kinetics in Facilities A (indoor composting) and B (outdoor composting) (average ± standard deviation).

Pile Number	Measurements Series	Average C_{COmax}, mg CO·m^{-3}		Average k, s^{-1}		R^2
		Before Turning	After Turning	Before Turning	After Turning	
		Facility A				
1	1	10.40 ± 5.26	48.38 ± 75.33	0.0081 ± 0.0020	0.0075 ± 0.0021	0.99 ± 0.02
	2	8.51 ± 9.23	37.80 ± 9.27	0.0116 ± 0.0027	0.0080 ± 0.0027	0.99 ± 0.01
2	1	9.63 ± 9.31	72.39 ± 85.49	0.0093 ± 0.0018	0.0081 ± 0.0018	0.99 ± 0.01
	2	11.28 ± 9.21	15.76 ± 13.85	0.0100 ± 0.0015	0.0100 ± 0.0012	0.99 ± 0.00
	3	15.32 ± 7.81	28.34 ± 20.08	0.0104 ± 0.0008	0.0105 ± 0.0012	0.99 ± 0.00
3	1	19.25 ± 7.96	46.51 ± 15.37	0.0104 ± 0.0023	0.0099 ± 0.0006	0.99 ± 0.01
	2	9.96 ± 4.81	49.93 ± 28.24	0.0096 ± 0.0016	0.0095 ± 0.0015	0.99 ± 0.00
	3	10.28 ± 7.24	35.47 ± 28.19	0.0091 ± 0.0014	0.0104 ± 0.0021	0.99 ± 0.01
4	1	13.74 ± 5.21	53.11 ± 15.28	0.0099 ± 0.0006	0.0095 ± 0.0006	0.99 ± 0.01
	2	17.63 ± 24.62	46.03 ± 19.92	0.0107 ± 0.0019	0.0100 ± 0.0010	0.99 ± 0.01
		Facility B				
1	1	0.0000	0.0001 ± 0.0003	0.0408 ± 0.0705	0.0899 ± 0.0470	0.99 ± 0.03
2	1	0.0000	0.0000	0.0000	0.0799 ± 0.0230	0.99 ± 0.01
3	1	0.0000	0.0031 ± 0.0064	0.0000	0.0354 ± 0.0140	0.99 ± 0.00
4	1	0.0000	0.0010 ± 0.0016	0.0000	0.0403 ± 0.0120	0.99 ± 0.01
5	1	0.0000	0.0013 ± 0.0017	0.0000	0.0360 ± 0.0061	0.99 ± 0.00
6	1	0.0000	0.4570 ± 0.7820	0.0772 ± 0.0688	0.0250 ± 0.0112	0.99 ± 0.00

In both Facility A and Facility B, C_{COmax} values increased significantly after pile turning (Wilcoxon signed-rank test, $p < 0.05$). In contrast, no statistically significant changes in the constant k were observed after turning in either facility ($p > 0.05$). Comparisons between facilities demonstrated significantly higher C_{COmax} values in Facility A than in Facility B after turning (Mann–Whitney U test, $p < 0.001$). Significant differences between facilities were also observed for the kinetic constant k ($p = 0.001$).

4. Discussion

The investigation of CO emissions from both indoor and outdoor composting systems was performed under standard plant operating conditions and during routine technological processes, ensuring that the measured cumulative concentrations reflected realistic exposure levels to this hazardous compound. It should be emphasized that the composting process itself does not involve hazardous waste; however, CO generated during the biodegradation of organic matter may pose a significant occupational hazard. The level of employee exposure may vary depending on the applied composting technology, including systems based on BAT recommendations with enclosed and airtight facilities, as well as open-air composting operations.

According to official data published on the website of the State Fire Service in Poland, the CO levels recorded in Facility A may adversely affect the health of workers present in the enclosed composting hall [23]. The mildest health effect associated with CO concentrations ranging from 60 to 240 mg·m^{-3} during exposure lasting several hours is headache. Average cumulative CO concentrations within this range were recorded before compost turning for three piles in Facility A, with two occurrences for each pile during different measurement series (99.8–175.2 mg·m^{-3}). An even more rapid onset of headache symptoms could have occurred during the five measurement series for piles 2 and 4, in which the average cumulative CO concentration ranged from 239.1 to 342.7 mg·m^{-3}, both before and after compost turning. Furthermore, all analyzed piles exhibited CO levels in at least one measurement series that may result in more severe health effects. During eight measurement series, the average cumulative CO concentration after turning reached levels associated with nausea, vomiting, muscle weakness, and apathy after 1–2 h of exposure (519.1–819.8 mg·m^{-3}). The most hazardous conditions were observed for pile 2 during

the first measurement series. After compost turning, the cumulative CO concentration reached a level potentially leading to collapse and loss of consciousness after approximately 2 h of exposure (924.1 $mg \cdot m^{-3}$). The predominance of measurement points exceeding CO standards during indoor composting is of particular concern, as the EPA's NAAQS specifies that the 8 h and 1 h average standards should not be exceeded more than once per year. The primary CO standards are based on studies demonstrating that even low levels of CO exposure, resulting in COHb concentrations of 2–3%, may be associated with neurobehavioral effects in exposed individuals [17].

The reasons behind the differences between CO levels from indoor and outdoor composting can be sought in the dual nature of CO production during the process. Indeed, the few studies that have addressed the issue of CO formation from aerobic waste treatment so far have indicated that both biotic and abiotic processes can generate CO. The former is associated with CO generation due to microorganisms' metabolism, while the abiotic mechanisms are based on thermochemical reactions [4,10]. Therefore, the explanation of the dependencies in CO generation must consider biological and physicochemical drivers.

The analyzed composting facilities (indoor vs. outdoor composting) were characterized by different CO production potentials, highlighting the importance of pile location. Compost processed indoors exhibited substantially higher CO levels, both before and after turning, which was particularly evident for piles of similar age in both facilities (3 and 4 weeks for piles 3 and 4 in Facility A and piles 4–6 in Facility B). Compost processed in the enclosed hall of Facility A was not directly exposed to ambient air, resulting in lower O_2 availability. Additionally, although the statistical analysis did not demonstrate significant correlations, a negative relationship between CO and O_2 concentrations after pile turning was observed in both facilities, with a stronger tendency identified in Facility B.

The spatial distribution of cumulative CO concentrations observed in Facility B (outdoor composting) may have been influenced not only by the internal physicochemical conditions within the composted material, but also by local ventilation and aerodynamic conditions associated with pile arrangement and wind direction during the measurement campaign. During the outdoor measurements conducted in February 2022, prevailing winds from the west and south–west (W–SW) directions were observed in the study region. Consequently, the location of individual compost piles relative to the dominant airflow direction may have affected the dilution and transport of emitted CO.

In the case of piles located on the western side of the composting area in Facility B (e.g., piles 1–2), the approaching airflow was less obstructed, which likely promoted more efficient dilution of emitted gases and contributed to lower localized CO accumulation above the pile surface. In contrast, piles located further eastward and closer to the facility buildings (particularly pile 6) were more strongly influenced by airflow obstruction caused by nearby infrastructure. The presence of buildings may have reduced natural ventilation efficiency and favored temporary accumulation of emitted CO in the near-pile zone, especially after compost turning operations.

Additionally, in Facility B, the arrangement of the compost piles themselves may have contributed to partial shielding effects. Piles located downwind relative to neighboring piles could have experienced locally disturbed airflow patterns and reduced air exchange intensity, potentially limiting pollutant dispersion. Such aerodynamic interactions may partly explain the spatial differences observed in the contour maps, including the occurrence of elevated CO concentrations in the frontal and upper parts of certain piles after turning.

Results observed in this study highlight the need to further distinguish between abiotic and biotic pathways of CO production. Abiotic CO formation, associated with the thermochemical degradation of organic matter leading to CO release, has previously been reported to be stimulated by elevated O_2 concentrations [10,24]. However, the findings

obtained in this study did not follow this trend, suggesting that an alternative mechanism of CO generation should also be considered.

In this context, a potential contribution of facultative anaerobic microorganisms capable of producing CO during composting may be hypothesized. Although no microbiological analyses were performed in the present study, it can be cautiously assumed that facultative anaerobic microbial communities may have contributed to CO formation under the investigated composting conditions, which requires further verification through microbiome analysis in future studies. This assumption is supported by the observation that cumulative CO concentrations were consistently higher after compost turning, reaching levels several times greater in Facility A and several dozen times greater in Facility B compared with values recorded before turning. It is possible that compost turning redistributed microorganisms from zones with limited substrate availability to regions enriched in readily degradable organic matter, thereby stimulating microbial activity and enhancing CO production. At the same time, the observed negative tendencies between CO and O_2 concentrations may indicate that these microorganisms were not favored by elevated O_2 availability, which could explain the inverse relationship observed between O_2 concentration and CO generation after turning.

Moreover, besides the location of the piles, other factors could affect CO generation during composting. Within one facility, the age of the piles may have influenced the recorded CO production. For closed Facility A, the highest level of cumulative CO concentration was recorded not for the youngest, 2-week-old piles 1 and 2, but for pile 4 composted for 4 weeks. It may be related to the so-called 'lag phase' during which CO-producing microorganisms multiply, gradually increasing their activity after the occurrence of optimal conditions for their development [25]. Since substrate transport primarily determines the rate of bacterial growth [26], the incubation phase also has an impact on the k constant of CO production after compost turning. In most cases, although no statistically significant changes in the kinetic constant k were observed after turning in either facility ($p > 0.05$), lower k values were generally recorded after turning, which may indicate that microbial communities required a period of adaptation to the newly redistributed compost environment before resuming intensive organic matter degradation.

In turn, in Facility B, the age of the piles could be a factor contributing to the low CO production from piles 1 and 2. These piles were processed for the longest (8 weeks) and of all average cumulative CO concentrations after turning, they achieved the lowest values. This is consistent with the observations reported previously in the literature. It has been reported that the CO concentration is the highest in the initial stage of the process. After about 2 weeks, it decreases, and the reduction is often rapid, which was confirmed during laboratory and technical tests [24,27]. Again, it is related to the degradable organic matter content in compost piles, which can be utilized by bacteria and then declines as the composting process progresses. Furthermore, the seasonal composition of organic waste processed in composting facilities may also play an important role in this context. During spring and summer, biowaste is predominantly composed of grass clippings, soil residues, flowers, hedge trimmings, and other garden-derived materials, whereas in autumn and winter, larger proportions of fruit and vegetable waste, branches, and woody biomass are typically observed [28,29]. Owing to differences in biodegradability among these fractions, "winter" compost piles may decompose more slowly, as they contain higher amounts of cellulose, hemicellulose, and lignocellulosic compounds, which are more resistant to microbial bioconversion into humic substances [30].

Seasonal conditions may also have influenced composting dynamics and, consequently, CO formation in both facilities. The higher net CO production rates observed in Facility A could potentially be associated with the more stable and favorable thermal condi-

tions prevailing inside the enclosed composting hall during the autumn period. Although outdoor temperatures during the measurement campaign ranged between approximately 15 and 18 °C, the average temperature inside the facility remained close to 25 °C. In contrast, the lower net CO production rates observed in Facility B, both before and after pile turning, may have been related to lower ambient temperatures during winter conditions in Central Europe, where outdoor temperatures during measurements did not exceed approximately 10 °C and averaged around 6 °C.

Previous studies have demonstrated that low ambient temperatures may suppress CO production from compost piles located in open composting systems [31]. This interpretation is further supported by the findings of Svedberg et al. [32], who reported that outdoor composted materials emit the highest amounts of gases during warmer seasons. According to these authors, CO concentrations are closely associated with temperature, particularly under thermophilic composting conditions. Therefore, it may be hypothesized that the implementation of enclosed or hermetic composting systems recommended in BAT reference documents could indirectly promote higher CO production by maintaining elevated and more stable ambient temperatures around compost piles, irrespective of seasonal fluctuations. Consequently, CO emissions during colder seasons may potentially increase following the implementation of BAT-based enclosed composting strategies.

Analysis of CO production kinetics in Facilities A and B provides important practical implications for occupational safety in composting plants. In Facility A, all analyzed cases showed an increase in cumulative CO concentrations following compost turning. At the same time, the CO production rate decreased in most piles, indicating that although higher cumulative CO concentrations were generated during indoor composting, CO release occurred more gradually and persisted for a longer period after turning. These observations suggest that workers in composting facilities operating in accordance with BAT recommendations, where composting processes are conducted in enclosed or hermetic halls, may be exposed to elevated and prolonged cumulative CO concentrations, particularly after pile turning. Consequently, a longer waiting period before re-entering enclosed composting halls after turning operations may be necessary to reduce potential occupational exposure to CO.

A similar increase in cumulative CO concentrations after turning was also observed in Facility B. However, under outdoor composting conditions, CO production occurred more rapidly while overall cumulative CO concentrations remained substantially lower than those recorded in Facility A. This indicates that open-air composting systems may be associated with a lower risk of prolonged worker exposure to toxic cumulative CO concentrations compared with enclosed indoor composting systems.

The research presented in this paper has several potential limitations. First, as it has already been presented in the discussion, the compared composting facilities differed not only in terms of operational conditions (indoor vs. outdoor systems), but also in feedstock composition and seasonal conditions during the measurement campaigns. Facility A processed green waste mixed with sewage sludge during the autumn season, whereas Facility B processed green waste and the undersized fraction of MSW during winter conditions. While the impact of the season on CO production has been mentioned in the discussion, it is worth noting that these differences may have also influenced microbial activity, composting dynamics, temperature profiles, oxygen availability, and consequently CO generation patterns. Moreover, due to the limited availability of literature addressing the influence of composted waste composition on CO production, the kinetic parameters of CO emissions discussed in this study should be considered representative only for the specific waste fractions investigated.

In addition, the compost turning equipment differed between the investigated facilities. Facility A used a specialized compost turner, whereas Facility B used an excavator for pile-turning operations. Differences in the operating characteristics of these machines, including the intensity and depth of material disturbance, may have affected aeration conditions and the amount and dynamics of CO release during compost agitation. Therefore, the potential influence of turning technology should also be considered as a confounding factor when interpreting the observed differences between the studied composting systems.

Although the study was intentionally conducted under real industrial operating conditions to reflect practical exposure scenarios, the use of separate full-scale facilities made complete standardization of feedstock characteristics and environmental conditions difficult to achieve. Therefore, the observed differences in CO emissions cannot be attributed exclusively to the configuration of the indoor or outdoor composting system. Future studies should aim to minimize these confounding factors by conducting comparative analyses within a single composting facility operating both indoor and outdoor systems under comparable technological conditions and using the same type of waste material. Such an approach would allow for more accurate isolation of the specific effect of composting system configuration on CO generation and occupational exposure.

Additionally, as has already been discussed above, the compost piles analyzed in the selected facilities differed in age. This factor may have influenced the physicochemical properties of the composted material, including waste composition, despite originating from the same waste fractions, ambient and pile temperatures, and the degree of organic matter degradation within the piles. Consequently, these variables may also have affected the observed CO production dynamics. Future studies should therefore be conducted using compost piles of comparable age to minimize the influence of external environmental and operational factors.

An important limitation in the context of assessing occupational exposure of composting plant workers is related to the short-term measurement strategy applied for CO monitoring. Cumulative CO concentrations were measured during 5 min sampling periods associated with active compost handling operations, whereas regulatory exposure limits established by the EPA are based on 1 h and 8 h time-weighted average concentrations. Therefore, the obtained results should not be interpreted as direct indicators of compliance with occupational exposure standards. Instead, the measurements provide screening-level information regarding short-term emission episodes and potential peak exposure situations occurring during specific workplace activities. Future studies should include long-term continuous monitoring to enable more accurate assessment of worker exposure under full-shift operating conditions.

Furthermore, the exceedance of cumulative CO concentrations considered safe for humans according to EPA standards assumes complete air-tightness of the composting hall, as recommended in BAT reference documents. In practice, however, achieving fully hermetic conditions in industrial composting facilities may be difficult because of current technical limitations and operational requirements.

Additionally, no microbiological analyses were performed to confirm the involvement of facultative anaerobic microorganisms or other microbial groups in CO production during composting. Therefore, the hypotheses proposed in this study regarding the potential contribution of microorganisms to CO generation remain speculative and cannot currently be directly verified.

5. Conclusions

The gradual implementation of BAT Reference Document recommendations for composting in recent years has led to the current operation of composting plants that differ in

their CO release potential. The study has demonstrated that the location of compost piles (indoor vs. outdoor composting) affects CO production and release. Generally, closed composting systems (indoor composting in hermetic halls) recommended in the BAT document result in higher net CO production from the process, both before and after compost turning, exceeding safe levels for humans according to EPA standards. This effect is probably driven by higher ambient temperature and lower O_2 availability. Additionally, in a closed system, the compost turning resulted in slower CO production (the CO production constant rate k was lower than before turning), extending workers' exposure to CO inhalation. In addition to the location of the piles, the season and compost age could have an indirect impact on the CO production kinetics.

Although the study demonstrated that indoor composting systems were associated with higher CO levels, such systems may also create more favorable conditions for the future implementation of CO emission monitoring and mitigation strategies. Therefore, it is recommended that BAT guidelines be comprehensively considered, including gaseous pollutant monitoring and process air purification in composting plants. Moreover, the use of appropriate personal protective equipment for workers should be considered, particularly in facilities operating under enclosed composting conditions. Further studies are required to determine the optimal technical and operational solutions for effective CO exposure mitigation in industrial composting systems.

The results presented in the study pertain solely to the specific compost fractions examined, making it essential to broaden the research by investigating CO accumulation in enclosed spaces and the exposure of composting plant workers handling different types of organic waste. Furthermore, the preliminary data obtained through the flux box method should be complemented by testing CO emissions in closed composting halls using more advanced techniques, such as infrared thermography. This approach will enable not only the assessment of the risk level to employees but also the spatial distribution of CO.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su18147203/s1. Supplementary Material S1—Table S1, containing cumulative CO concentration from composted waste in Facility A (indoor composting); Supplementary Material S2—Table S2, containing cumulative CO concentrations from composted waste in Facility B (outdoor composting); Supplementary Material S3—Table S3, containing O_2 concentration from composted waste in Facility A (indoor composting); Supplementary Material S4—Table S4, containing O_2 concentration from composted waste in Facility B (outdoor composting); Supplementary Material S5—Table S5, containing compost characterization in Facility A (indoor composting) and Facility B (outdoor composting); Table S6, containing Tukey HSD test for compost dry matter content (%) in Facility A; Table S7, containing Tukey HSD test for compost organic dry matter content (% d.m.) in Facility A; Table S8, containing Tukey HSD test for compost AT4 activity in Facility A; Table S9, containing Tukey HSD test for compost dry matter content (%) in Facility B; Table S10 containing Tukey HSD test for compost organic dry matter content (% d.m.) in Facility B; Table S11 containing Tukey HSD test for compost AT4 activity in Facility B.

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Abbreviations

The following abbreviations are used in this manuscript:

CO	Carbon monoxide
MSW	Municipal solid waste
BAT	Best Available Techniques
C_{COmax}	Maximum Cumulative CO concentration
k	CO production rate constant
U.S. EPA	United States Environmental Protection Agency
WHO	World Health Organization
NAAQS	National Ambient Air Quality Standards
AT4	Respiratory activity

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