frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 03 September 2025
DOI 10.3389/fenvs.2025.1632196

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RECEIVED 20 May 2025
ACCEPTED 14 August 2025
PUBLISHED 03 September 2025

CITATION
Sobol Ł, Koziel JA and Stegenta-Dąbrowska S (2025) Emissions of carbon monoxide and dioxide from decomposing grass clippings – case study of football turfs. *Front. Environ. Sci.* 13:1632196. doi: 10.3389/fenvs.2025.1632196

Emissions of carbon monoxide and dioxide from decomposing grass clippings – case study of football turfs

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Sports turfs and urban landscapes generate waste biomass in the form of grass clippings. Decomposing grass clippings can recycle nutrients to soil. However, decomposing can have adverse environmental effects such as gaseous emissions. The magnitude of air pollution caused by gaseous emissions from grass clippings is unknown. This research investigated CO, CO_2, and O_2 exchange during the decomposition of grass clippings. Emissions from grass clippings collected at four football fields with different levels of fertilization and agrotechnical treatments were studied. The mowed grass was collected throughout the spring-to-autumn football season. The results showed that grass clippings from sports turfs can generate up to 5 times more CO emissions compared to a mixture of grass and cattle manure. CO_2 production and O_2 consumption were relatively similar for all seasons, except for clippings from the unfertilized pitch. Artificial neural network (ANN) models predicted the CO and CO_2 emissions resulting from the disposal of grass clippings with R^2 for CO > 0.81 and CO_2 > 0.98, respectively. This research contributes to emission inventories and highlights the relatively minor contribution from decomposing biomass.

KEYWORDS

air quality, biomass decomposition, green waste, sports turfs, waste management

1 Introduction

Grass mowing is an indispensable agrotechnical treatment performed on sport turfs to maintain their quality, including increased turf density, improved playability and resistance to wear (Linde, 2015; March et al., 2013). Depending on the purpose and type of sports grass surface, it can be mowed nearly 200 times a year (Tidåker et al., 2017). Due to the high frequency of treatments, significant amounts of grass clippings are generated during mowing, requiring proper disposal. Previous research have shown that it is possible to generate as much as 7.2 $Mg_{DM}•y^{-1}•ha^{-1}$ grass clippings from sports grass surfaces during the season (Grossi et al., 2004). The dry matter (DM) yield from grass sports surfaces is relatively high compared to similar managed landscapes (Table 1).

Despite the suitability of grass clippings for mulching, composting, and biogas production, some sports facilities classify clippings as 'waste' and therefore, leaving

TABLE 1 Comparison of biomass yield from sport surfaces to other grass surfaces.

Source	Potential yield (Mg $_{DM}$·y^{-1}·ha^{-1})	Reference
Sports grass surfaces	7.2	Grossi et al. (2004)
Side road grass	3–4	Brown et al. (2020)
Herbaceous biomass from urban park	4.1–7.8	Zalacáin et al. (2019)
Temperate grassland	6.8	Van Hook and Robert (1971)
Lawn clippings	3.5–4.4	Springer (2012)

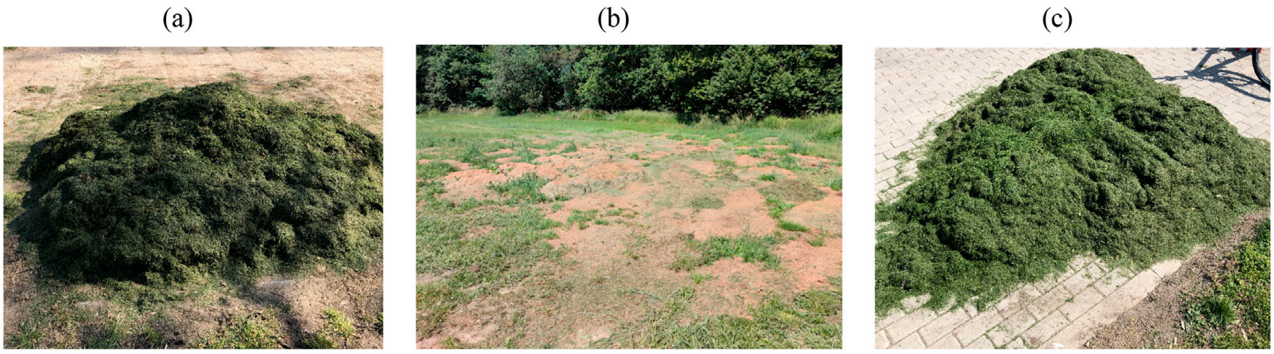

FIGURE 1
Uncontrolled disposal of grass clippings from mowing sports turfs; **(a)** on soil; **(b)** effect of grass clippings from a small football field (0.7 ha) on vegetation, **(c)** on paver stones.

them as-is in random locations to decompose and reduce weight and volume. Thus, there is a concern about the impact of such poorly managed biomass on the environment. Microbiological activity can increase greenhouse gas (GHG) (CO_2, N_2O, and CH_4) emissions and leaching our of toxic substances to soil (Boldrin et al., 2009; Haarstad et al., 2006; Stegenta-Dąbrowska et al., 2020; Figure 1).

To date, research has focused on gaseous emissions related to managed grass surfaces, in particular, GHGs (Bremer, 2006; Follett et al., 2011; Law et al., 2021; Van Delden et al., 2016), carbon sequestration in the soil (Qian and Follett, 2002; Zirkle et al., 2011) or the use of specialized equipment to perform agrotechnical and pratotechnical treatments (Montgomery, 2009). There is a gap in knowledge about gaseous emissions from the *decomposition* or poorly managed *composting* of grass clippings. Specifically, the emission rates of primary air pollutants such as CO are not well known. Due to its odorless, tasteless, colorless nature, and toxicity, CO poses a significant risk to human health and living organisms, including most microorganisms (Stegenta-Dąbrowska et al., 2020; Techtmann et al., 2009; Afzal et al., 2025).

Gaseous emissions from composting green waste can be managed (Sobieraj et al., 2021). The spatial and temporal variability of CO emissions from managed, industrial scale composting operations was reported (Stegenta et al., 2019a; Stegenta et al., 2019b). However, the uncontrolled decomposition of grass clippings makes it challenging to estimate the CO and CO_2 production rate and emission to the atmosphere, as the process is affected by many environmental factors. Therefore, the determination of the kinetic parameters and predicting CO and CO_2 emissions from grass clippings can improve emission source inventories. In addition, estimates of gaseous emissions from clipping associated with similarly managed residential and municipal lawns are needed as both sources are an essential element of landscape architecture (Ignatieva et al., 2020; 2024). Estimating CO emission rates allows determining the risk associated with human short-term and chronic inhalation exposure to toxic gases. This problem can be exacerbated if the clippings are spread near sports stands or in urban stadiums, negatively affecting local air quality, creating public health implications. On the other hand, there is a growing interest in generating bio-renewable CO as a key ingredient to bio-based economy which can find industrial applications (Dang and Chou, 2018; Foresti et al., 2008; Sobieraj et al., 2025). Artificial intelligence (AI) enables the evaluation and optimization of process parameters, particularly in agricultural and environmental fields (Zhong et al., 2021). For example, AI can improve the control of fermentation, composting, and waste management processes (Ye et al., 2020; Rosik et al., 2024; Cheng et al., 2023).

Our working *hypothesis* is that gaseous emissions (CO, CO_2, and process-associated O_2 utilization) from clippings are affected by management practices. Chemical composition of grass clippings depend mainly on the grass variety (Wolski et al., 2021) and the agrotechnical treatments, e.g., the fertilization and irrigation (Noer,

TABLE 2 Summary of football field characteristics.

Field	Fertilization ($kg·ha^{-1}•y^{-1}$)	Pitch type	Irrigation	Mowing frequency during growing season	Mowing height	Field age
A1	504.6 N 230.7 P_2O_5 346.0 K_2O 80.7 SO_3	Match and training pitch	Pop-up sprinklers	2-3x · wk^{-1}	2–2.5 cm	10 years
A2	326.0 N 271.7 P_2O_5 407.5 K_2O 95.1 SO_3	Match and training pitch	Pop-up sprinklers	2-3x · wk^{-1}	2–2.5 cm	9 years
A3	27.9 N 9.3 P_2O_5 27.9 K_2O 3.7 MgO 3.7 CaO	Match pitch	Manual sprinklers	1x · wk^{-1}	3–3.5 cm	12 years
A4	none	Recreation pitch	none	3-4x · y^{-1}	unknown	>30 years

1945). Research show the role of moisture content (MC) on the production of CO (Schade et al., 1999). However, to the best of our knowledge there are no direct reports linking CO emissions with fertilization in the literature. Fertilization is one of the most important elements influencing the visual and functional features of the turf (Wolski et al., 2016) and the chemical composition of grass clippings (Waddington et al., 1964). Therefore, it can be also hypothesized that fertilization may affect CO emissions during the decomposition of grass clippings. Highly fertilized turfs may exceed 600 kg $N•ha^{-1}$ (Salman and Avcioglu, 2010), while the turfs of lower-league clubs are not necessarily fertilized. This research is the first attempt to quantify the magnitude of CO emissions from grass piles generated on sports turfs. These results can significantly contribute to the estimation of the inventory of emissions from sports surfaces, not limited only to football fields, but also to similar types of managed surfaces - golf courses, rugby fields, urban lawns.

This study aimed to address the following gaps in knowledge:

i. CO and CO_2 emissions during the decomposition of grass clippings from sports turf under controlled laboratory conditions,
ii. the kinetics of CO emissions during the decomposition of organic matter in grass clippings,
iii. predicting the CO, CO_2 emissions, and O_2 consumption during the decomposition of grass clippings,
iv. identifying the main mechanisms and parameters responsible for CO emissions during the decomposition of grass clippings from sports turf, in particular the role of fertilization and season.

2 Materials and methods

2.1 Sport turfs

Grass clippings were collected immediately after mowing the turf at four football fields in the Dolnośląskie Voivodeship, Poland. The summary is presented in Table 2:

2.2 Grass clippings properties

Samples were evaluated for their physicochemical properties before and after the decomposition process. MC was determined with the dryer (WAMED, model KBC-65W, Warsaw, Poland) according to PN-ISO 11465:1999 standard. Volatile solids (VS) were determined using a muffle furnace (SNOL, model 8.1/1100, Utena, Lithuania) according to PN-EN 15169:2011 standard. Electroconductivity and pH were evaluated on a 1:10 w/v solid/water suspension (Al-Wabel et al., 2013; Świechowski et al., 2022) using Elmetron CPC-411. CHNS Elemental Analyzer (CE Instruments Ltd., United Kingdom) was used according to PN-ISO 13878:2002 standard for C, H, and N. The respirometry activity (a.k.a. AT_4) was determined according to Binner et al. (2012) with the OxiTop Control system:

$$AT_4 = \Delta p \cdot \frac{M_{O2}}{R \cdot T} \cdot \frac{V_{gas} - V_{abs} - V_{sample}}{m_{sample}}$$

where: AT_4 – respirometry activity ($mg\ O_2•g^{-1}d.m.$),
Δp–pressure difference (hPa),
M_{O2} – molecular mass O_2 (31.998 $mg•mol^{-1}$),
R–ideal gas constant (83.14 $mL•hPa•(K•mol)^{-1}$),
T–temperature (293.15 K),
V_{gas}–total volume (mL),
V_{abs}–sorbent volume (mL),
V_{sample}–sample volume (mL),
m_{sample}–dry sample mass (g d.m.).

The kinetic parameters of the AT_4 process (P_0, k, t) were determined using the same method as for the process gases.

2.3 The experimental design and simulation of decomposition process

The experiment was carried out in bioreactors at a constant temperature of 20 °C (in dark), in triplicate, for grass clippings from the spring, summer, and the autumn seasons, respectively (Figure 2). Each 1 L bioreactor was filled with 15 ± 1 g of clippings. The choice

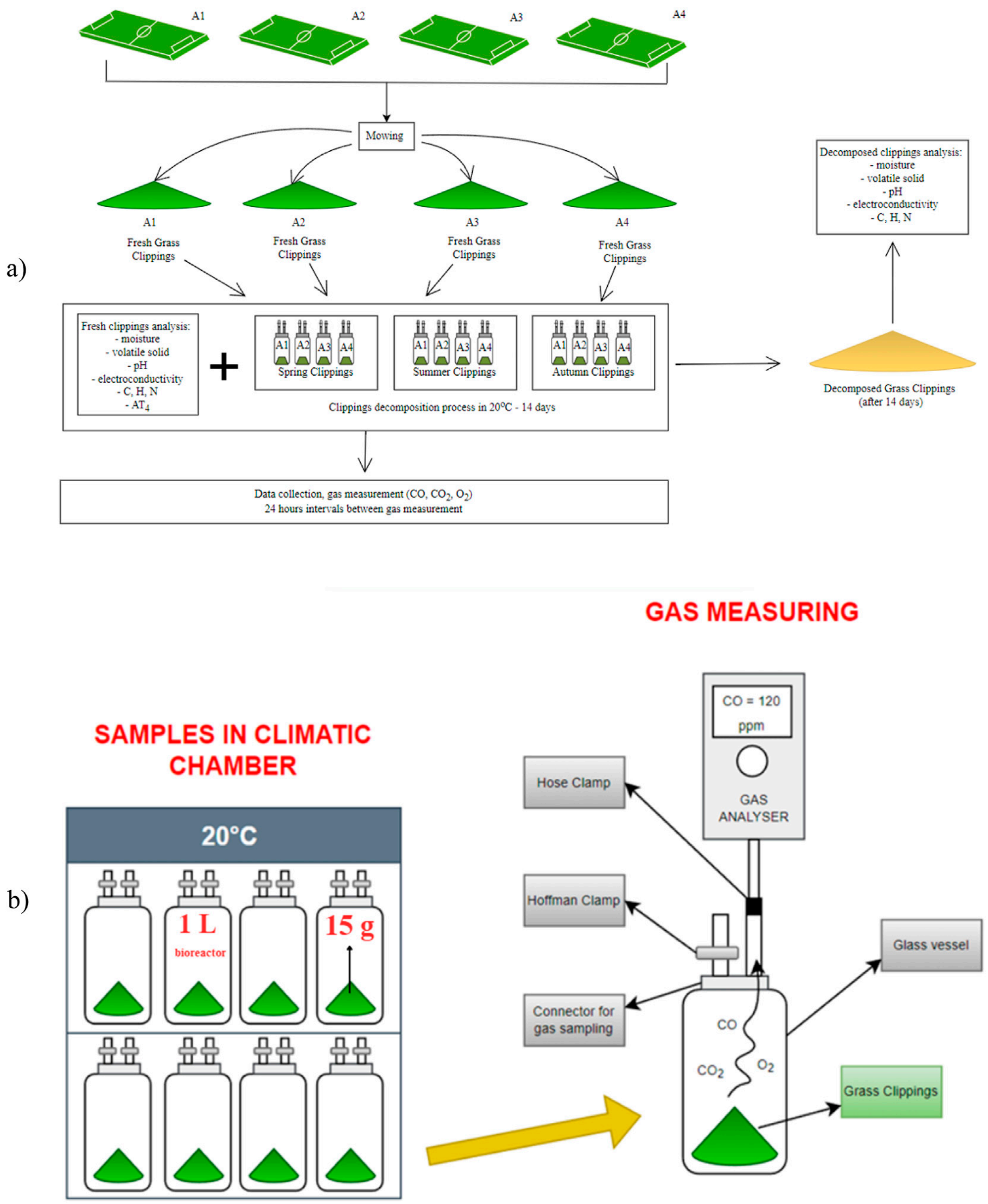

FIGURE 2
Scheme of the experimental set-up **(a)**, measuring process gas production or consumption **(b)**.

of sample mass was due to preliminary trials, where different grass quantities were tested for detectable concentrations.

2.4 Analysis of the gas emissions

Concentrations of CO, CO_2, O_2 were monitored daily for 14 days. The time of 14 days was selected based on the practices of sports surface operators in the region of Lower Silesia, Poland, who decide to remove the grass clipping from the decomposition site after about 2 weeks, when they have reduced their volume. Bioreactors were equipped with sealed caps and two gas measuring ports with short sections of flexible tubing facilitating the connection to a gas analyzer for gas sampling (Figure 2b). Gaseous concentrations were measured using a factory-calibrated KIGAZ 200 gas analyzer (Kimo Instr., Chevry-Cossigny, France). Gas concentrations were measured trice for 30–50 s to stabilize the indicated values. During each measurement, the bioreactors were open to crossflow to ensure oxygen conditions in their headspace. After a few minutes of aeration, the bioreactors were closed and sealed with a Hoffman clamp and returned to the incubation chamber.

2.5 Kinetics of gas emissions

Nonlinear least squares regression was used to determine the kinetic parameters of CO and CO_2 production and O_2 consumption. Cumulative production and consumption curves were determined based on the d.m. of grass clippings. Zero and first-order reaction models were used:

$$P = k \cdot t$$

where:

P—total production/consumption (CO, CO_2, or O_2), (mg·g $^{-1}$ d.m.),

k—production/consumption rate (CO, CO_2, or O_2), (mg·g $^{-1}$ d.m.·h $^{-1}$),

t—time, (h).

$$P = P_0 \cdot \left(1 - e^{-k \cdot t}\right)$$

where:

P_0 — maximum production/consumption (CO, CO_2, or O_2), (mg·g $^{-1}$ d.m.).

The average production or consumption rate (*r*, mg·g $^{-1}$ d.m.·h $^{-1}$) was estimated as:

$$r = k \cdot P_0$$

2.6 Statistical analysis and AI modeling

Statistical analyses were performed with Statistica 13.0 (TIBCO Software Inc., Palo Alto, CA, USA). Firstly, the data distribution was checked for normality using the Shapiro-Wilk test. All variants were characterized by significantly different distributions from the normal distribution, the non-parametric Kruskal-Wallis test was performed at the α = 0.05 significance level to compare differences between variants. The results were also modeled for CO and CO_2 production using ANN. First, principal component analysis (PCA) was performed to exclude parameters irrelevant to CO production. PCA analysis showed that only time, pH, CO_2 production and O_2 consumption are statistically significant (Supplementary Figure S1). The pH was subsequently rejected, since the pH results were measured only at the beginning and at the end of the process, and the dataset was too small to represent the group. Readers should be aware of this limitation, however, due to the fact that pH is a critical parameter in microbial decomposition. Finally, t, CO_2 production and O_2 consumption were used for the ANN analysis for prediction of CO and CO production and O_2 consumption.

The ANN calculations were performed with Statistica 13.3 NEURAL NETWORKS environment. The 540 sets of data were randomly divided into training (75%), validation (15%), and test (15%) subsets. The differ ANN types were considered for the creation of the numerical multi-layer perception (MLP) and radial basis function network (RBF) model, and were trained with back propagation (error) training algorithms. The research covered ANN structures with one single output neuron (representing CO or CO_2 production) and constant (3) inputs representing t, CO or CO_2 production and O_2 consumption) potentially influencing the CO or CO_2 production. The network structure was evaluated by validating the set quality, and simultaneously observing training and testing set qualities (detailed ANN statistic was presented on Figure 7e). The quality parameter was calculated as the standard deviation representing the neural model prediction error divided by the standard deviation for the available original dataset in respect to the mean value of this dataset. Preliminary model verification was also related to the ANN structure, i.e., the smaller number of hidden neurons and the simplest activation function signified a better network The RBF models demonstrated a poor fit; therefore, only the three best MLP models were presented.

3 Results

3.1 Properties of fresh and decomposed grass clippings

Table 3 shows the properties of fresh and decomposed grass clippings. Statistical analysis indicated that fresh and decomposed grass clippings did not statistically differ in MC, VS or pH in terms of season and field type. The statistically higher EC of fresh clippings came from the summer season, while statistically significant differences in EC between the autumn and summer seasons were observed for decomposed clippings.

The MC for fresh clippings was 74.42%, with the arithmetically lowest observed in the spring – 73.58%. Throughout football season, the arithmetically lowest average MC was on the A3 pitch (69.84%) and the arithmetically highest on the A2 pitch – 77.76%. The 14-day decomposition arithmetically increased the average MC to 76.37%. The MC arithmetically increased except for field A3 in the autumn (arithmetically decreased from 63.09% to 55.48%).

The average VS in all fresh samples was 87.76% ± 3.17% and was the arithmetically highest in summer (88.29%) (Table 3). Throughout the football season, fresh clippings from the A3 field had the highest VS (89.61%) followed by those from the A2 field (84.76%). The decomposition arithmetically decreased to the average VS level to 83.86%. The highest VS reduction was observed in the clippings from field A4 (from 88.16% to 82.32%).

Decomposition changed the pH of grass clippings from acid to alkaline. The mean pH increased from 6.48 to 9.05. The pH of fresh grass clippings throughout the football season was relatively stable and ranged from 6.32 to 6.67 (Table 3). The arithmetically highest mean value was observed for clippings obtained from the A1 pitch (6.54) and the arithmetically lowest for clippings from the A2 pitch (6.42). The arithmetically highest pH was observed for clippings from the A4 pitch, characterized by a low level of maintenance (9.23). Regarding the seasons, the decomposed grass clippings from the spring season had the highest average pH (9.15, while the decomposed clippings from the summer and autumn were arithmetically lower (9.00–9.01).

High EC variability was noted (Table 3). The fresh clippings EC ranged from 1.85 to 4.37 mS•cm^{-1} (average of 2.71 mS•cm^{-1}). Decomposition increased EC in all samples (average of 4.83 mS•cm^{-1}). It is worth noting, however, that the change in EC with decomposition varied. For example, the EC in autumn cuttings obtained from the A2 field increased arithmetically by 0.07 mS•cm^{-1} while, in the case of spring cuttings obtained from pitch A4, it increased by 3.57 mS•mS•cm^{-1}. Statistical analysis

TABLE 3 Properties of fresh (FC) and decomposed clippings (DC) depending on the season and type of football pitch. Bold font highlights statistical significance.

Parameter		Season	A1	A2	A3	A4	Mean ± SD
MC, %	FC	Spring	75.48	70.00	74.34	74.49	73.58a ± 2.43
		Summer	75.27	83.90	72.08	70.81	75.52a ± 5.90
		Autumn	75.07	79.39	63.09	79.10	74.16a ± 7.64
		Mean	75.28a ± 0.20	77.76a ± 7.09	69.84a ± 5.95	74.80a ± 4.15	74.42 ± 5.27
	DC	Spring	78.08	76.34	77.20	81.82	78.36a ± 2.41
		Summer	78.14	85.70	72.35	71.46	76.91a ± 6.56
		Autumn	77.26	80.70	55.48	81.95	73.85a ± 12.40
		Mean	77.82a ± 0.49	80.92a ± 4.68	68.34a ± 11.4	78.41a ± 6.02	76.37 ± 7.69
VS, %	FC	Spring	86.55	86.19	90.59	87.51	87.71a ± 1.99
		Summer	90.47	88.76	87.69	86.24	88.29a ± 1.78
		Autumn	88.52	79.34	90.56	90.73	87.28a ± 5.39
		Mean	88.51a ± 1.96	84.76a ± 4.86	89.61a ± 1.66	88.16a ± 2.31	87.76 ± 3.17
	DC	Spring	85.74	83.00	86.06	79.02	83.45a ± 3.26
		Summer	86.31	85.75	85.19	83.27	85.13a ± 1.32
		Autumn	83.43	78.21	85.76	84.68	83.02a ± 3.34
		Mean	85.16a ± 1.52	82.32a ± 3.81	85.67a ± 0.44	82.32a ± 2.94	83.86 ± 2.70
pH, -	FC	Spring	6.60	6.54	6.55	6.46	6.54a ± 0.06
		Summer	6.36	6.37	6.45	6.32	6.38a ± 0.05
		Autumn	6.67	6.36	6.47	6.64	6.54a ± 0.15
		Mean	6.54a ± 0.16	6.42a ± 0.10	6.49a ± 0.05	6.47a ± 0.16	6.48 ± 0.12
	DC	Spring	9.14	9.32	8.90	9.25	9.15a ± 0.18
		Summer	9.09	8.77	8.87	9.30	9.01a ± 0.24
		Autumn	9.07	8.90	8.88	9.14	9.00a ± 0.13
		Mean	9.10a ± 0.04	9.00a ± 0.29	8.88a ± 0.02	9.23a ± 0.08	9.05 ± 0.19
EC, mS•cm^{-1}	FC	Spring	2.89	2.06	2.08	2.68	2.43**a** ± 0.42
		Summer	3.04	3.25	4.37	3.25	3.48**b** ± 0.60
		Autumn	3.02	1.93	2.06	1.85	2.22**a** ± 0.54
		Mean	2.98a ± 0.08	2.41a ± 0.73	2.84a ± 1.33	2.59a ± 0.70	2.71 ± 0.75
	DC	Spring	6.97	4.08	4.49	6.25	5.45**ab** ± 1.38
		Summer	5.42	5.55	6.75	6.05	5.94**a** ± 0.60
		Autumn	5.40	2.00	2.20	2.84	3.11**b** ± 1.57
		Mean	5.93a ± 0.90	3.88a ± 1.78	4.48a ± 2.28	5.05a ± 1.91	4.83 ± 1.72

showed that fresh and decomposed clippings were not statistically different in terms of pitch type, but statistically significant differences occurred in terms of seasonality.

The C, H, and N content was reduced during decomposition (Table 4). The statistical analysis showed significant differences between fresh and decomposed grass clippings from pitch A1 between C, H and N contents. Differences were not detected only for the C:N. No statistically significant differences were detected between any parameters for pitch A2 and A3. In contrast, for unfertilized clippings coming from pitch A4, statistically significant differences between fresh and decomposed clippings were observed only for the C:N parameter.

In general, the average C in fresh clippings ranged from 41% to 46%, the H from 6.2% to 7.4%, and N from 3.1% to 5.2%. The N content in fresh clippings was consistent with the fertilization level. In the case of highly fertilized A1 football turf, the average N was

TABLE 4 Ultimate analysis of fresh and decomposed clippings depending on the season and type of football pitch. Bold font highlights statistical significance.

Field			C, %	H, %	N, %	C:N
A1	Spring	Fresh Clippings	44 ± 9	6.7 ± 1.3	4.9 ± 1.0	10.48
		Decomposed Clippings	39 ± 8	6.2 ± 1.2	4.1 ± 0.8	11.10
	Summer	Fresh Clippings	46 ± 9	7.1 ± 1.4	4.6 ± 0.9	11.67
		Decomposed Clippings	41 ± 8	6.4 ± 1.3	4.1 ± 0.8	11.67
	Autumn	Fresh Clippings	44 ± 9	6.8 ± 1.4	4.8 ± 1.0	10.69
		Decomposed Clippings	42 ± 8	6.5 ± 1.3	3.1 ± 0.6	15.81
	Mean Fresh		44.67**a**	6.87**a**	4.77**a**	10.95a
	Mean Decomposed		40.67**b**	6.37**b**	3.77**b**	12.86a
A2	Spring	Fresh Clippings	42 ± 8	6.4 ± 1.3	3.3 ± 0.7	14.85
		Decomposed Clippings	38 ± 8	5.9 ± 1.2	3.4 ± 0.7	13.04
	Summer	Fresh Clippings	44 ± 9	6.8 ± 1.4	5.2 ± 1.0	9.87
		Decomposed Clippings	42 ± 8	6.5 ± 1.3	3.8 ± 0.8	12.89
	Autumn	Fresh Clippings	41 ± 8	6.2 ± 1.2	3.8 ± 0.8	12.59
		Decomposed Clippings	38 ± 8	5.7 ± 1.1	3.3 ± 0.7	13.43
	Mean Fresh		42.34a	6.47a	4.1a	12.44a
	Mean Decomposed		39.34a	6.04a	3.5a	13.12a
A3	Spring	Fresh Clippings	45 ± 9	7.4 ± 1.5	3.9 ± 0.8	13.46
		Decomposed Clippings	39 ± 8	6.1 ± 1.2	4.6 ± 0.9	9.89
	Summer	Fresh Clippings	44 ± 9	6.7 ± 1.3	3.9 ± 0.8	13.16
		Decomposed Clippings	44 ± 9	6.8 ± 1.4	3.5 ± 0.7	14.67
	Autumn	Fresh Clippings	45 ± 9	6.3 ± 1.3	3.2 ± 0.6	16.41
		Decomposed Clippings	43 ± 9	6.6 ± 1.3	3.2 ± 0.6	15.68
	Mean Fresh		44.67a	6.8a	3.67a	14.34a
	Mean Decomposed		42a	6.5a	3.77a	13.41a
A4	Spring	Fresh Clippings	44 ± 9	6.7 ± 1.3	3.7 ± 0.7	13.87
		Decomposed Clippings	39 ± 8	6.1 ± 1.2	4.3 ± 0.9	10.58
	Summer	Fresh Clippings	43 ± 9	6.5 ± 1.3	3.1 ± 0.7	16.18
		Decomposed Clippings	44 ± 9	6.8 ± 1.4	4.1 ± 0.8	12.52
	Autumn	Fresh Clippings	44 ± 9	6.8 ± 1.4	3.3 ± 0.7	15.56
		Decomposed Clippings	42 ± 8	6.5 ± 1.3	3.7 ± 0.7	13.24
	Mean Fresh		43.67a	6.67a	3.37a	15.20**a**
	Mean Decomposed		41.67a	6.47a	4.03a	12.11**b**

4.76%, followed by A2 (4.10%), A3 (3.66%), and A4 (3.36%). The average C:N in fresh clippings from all football fields was 13.23 and was the highest for clippings obtained in the autumn season (13.81). In general, the average C:N ratio in fresh clippings was 13.23, and 12.88 in decomposed.

3.2 Respirometry activity and kinetics

Respiratory activity and the kinetics of the evaluated grass clippings showed high variability, depending on the season and their origin (Figure 3). Statistical analysis showed that there were

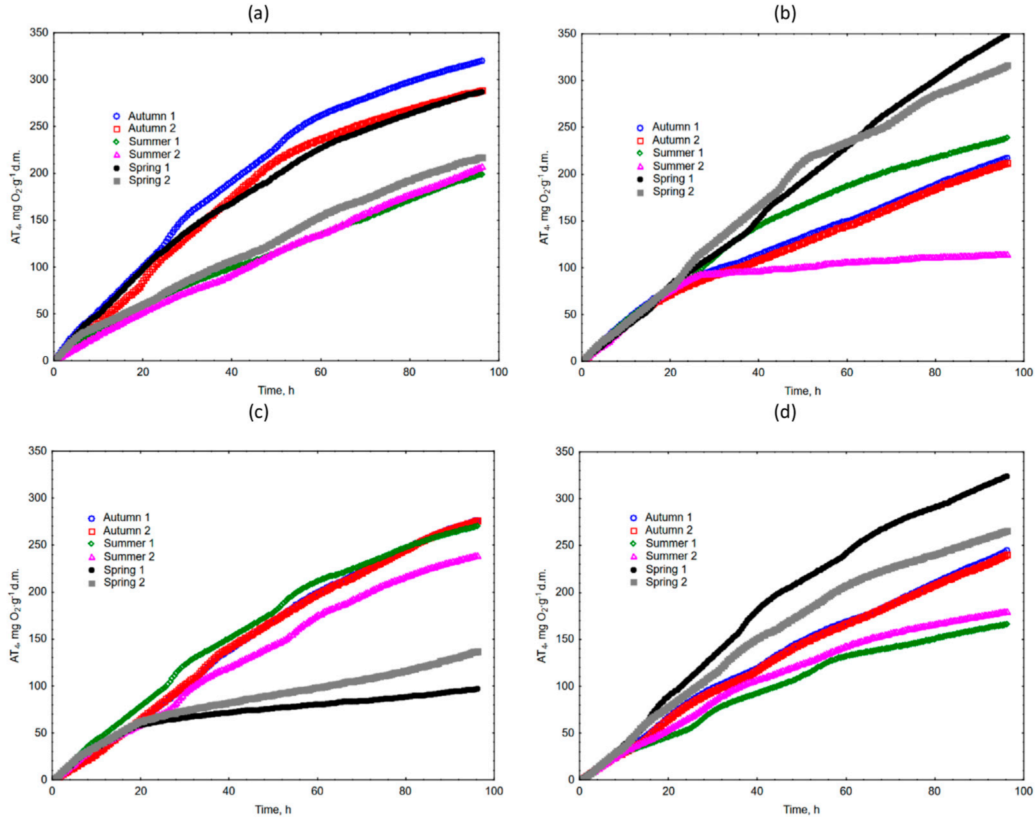

FIGURE 3
The respirometry activity (AT4) of grass clippings for **(a)** A1 turf; **(b)** A2 turf; **(c)** A3 turf; **(d)** A4 turf.

no statistically significant differences between the seasons for cuttings from high-fertilized pitches (A1 and A2). For clippings coming from pitch A3, statistically significant differences were detected between spring and the other seasons. For unfertilized clippings coming from pitch A4, statistically significant differences were detected between the spring and summer seasons. In most cases, the highest AT_4 values were observed in the autumn or spring and the lowest in the summer. In general, the average AT_4 content (from all seasons) was the highest for highly fertilized A1 turf (253.2 mg O_2•g^{-1} d.m.), followed by a turf with an intermediate fertilization level (237.5 mg O_2•g^{-1} d.m.), non-fertilized A4 turf (237.0 mg O_2•g^{-1} d.m.), and A3 turf with low level of N fertilization (216.4 mg O_2•g^{-1} d.m.).

Kinetic constant rate k ranged from 0.00393 h^{-1} to 0.04522 h^{-1}, and r ranged from 2.8831 mg O_2·g^{-1} d.m.·h^{-1} to 6.3342 O_2·g^{-1} d.m.·h^{-1} (R^2 ranged from 0.967 to 0.999, Table 5). The kinetics was the fastest in spring (k = 0.016517 h^{-1}) and slowed as the growing season progressed (summer k = 0.009853 h^{-1}, autumn k = 0.009841 h^{-1}). Regarding fertilization effect, the reaction kinetics was on average the fastest on the A3 turfs (k = 0.016592 h^{-1}), and relatively similar for the other variants (k in the range of 0.009942 h^{-1} – 0.010458 h^{-1}). Statistical analysis showed that there were no statistically significant differences between seasons for the k and r parameters for the cuttings from the A1 and A3 pitches (no statistical analysis was performed for the A2 and A4 pitches due to the inability to determine some of the k and r parameters).

3.3 CO emissions

Cumulative CO emissions are shown in Figure 4. Detailed data are summarized in Supplementary Table S1. The lowest emission was from the summer clippings. The CO emission was <100 μg CO•g^{-1} d.m. at the end of each trial. In the case of highly fertilized A1 turf, the highest CO emission was observed from the clippings from the autumn, where after 14 days, the cumulative emission was 456 μg CO•g^{-1} d.m. Spring clippings from this turf had a cumulative emission of 286 μg CO•g^{-1} d.m. A reverse trend was observed for the remaining three turfs (A2-A4), i.e., higher emissions than autumn characterized clippings from the spring. The most remarkable differences were noted in CO emissions from an average fertilization (A2) and the non-fertilized turfs (A4), where the average spring emissions ranged from 533 to 602 μg CO•g^{-1} d.m., and 270 to 228 μg CO•g^{-1} d.m. in the autumn, respectively. For A3, the difference in spring and autumn emissions was smaller, and ranged from 202 μg CO•g^{-1} d.m. to 181 μg CO•g^{-1} d.m., respectively.

The seasonality of CO emissions for clippings from all types of pitches was characterized by a statistically significant changes, except for A3 pitch in spring and summer. The effect of fertilization was also significant in the CO emission. In spring, statistically significant differences were not observed only between variants A2 and A4, and in autumn - only between variants A3 and A4 (low-fertilized and non-fertilized turf). A slightly different situation was observed in the summer, where statistically significant differences in CO emissions were noted between

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TABLE 5 Kinetics parameter of respiration activity for clippings depending on the season and type of football pitch. Bold font highlights statistical significance.

Field	Season	#.	AT_4		*k*		*r*		R^2
			(mg O_2•g^{-1} d.m.)	Mean ± SD	(h^{-1}) ± SD	Mean ± SD	(mg O_2•g^{-1} d.m.·h^{-1})	Mean ± SD	-
A1	Spring	1	286	252a ± 47.8	0.01498	0.0112a ± 0.00537	5.67	4.43a ± 1.76	0.9996
		2	218		0.00739		3.18		0.9968
	Summer	1	199	203.a ± 5.61	0.00778	0.00586a ± 0.00272	2.88	2.73a ± 0.22	0.9967
		2	207		0.00393		2.57		0.9991
	Autumn	1	320	304a ± 22.4	0.01456	0.01434a ± 0.00032	6.33	6.00a ± 0.48	0.9969
		2	289		0.01411		5.66		0.9925
A2	Spring	1	349	333a ± 23.2	0.00166	0.00531 ± 0.00515	4.00	4.49 ± 0.69	0.9992
		2	316		0.00895		4.98		0.9964
	Summer	1	239	165a ± 104	0.01475	-	4.66	-	0.9984
		2	91.1		-		-		-
	Autumn	1	217	215a ± 3.16	0.01303	0.01218 ± 0.00121	3.78	3.64 ± 0.20	0.9876
		2	213		0.01132		3.49		0.9891
A3	Spring	1	97.2	117**a** ± 28.7	0.04522	0.03557a ± 0.01365	4.06	3.764a ± 0.42	0.9776
		2	138		0.02591		3.46		0.9670
	Summer	1	270	255**b** ± 21.9	0.01141	0.00882a ± 0.00367	4.73	4.074a ± 0.94	0.9982
		2	239		0.00622		3.41		0.9977
	Autumn	1	277	277**b** ± 0.21	0.00510	0.00540a ± 0.00042	3.75	3.79a ± 0.05	0.9967
		2	277		0.00569		3.83		0.9974
A4	Spring	1	324	295**a** ± 41.0	-	-	-	-	-
		2	266		0.01151		4.65		0.9975
	Summer	1	166	173**b** ± 9.85	0.01140	0.01244 ± 0.00147	2.90	3.15 ± 0.36	0.9959
		2	180		0.01348		3.41		0.9978
	Autumn	1	245	243**ab** ± 2.89	0.00761	0.00746 ± 0.00021	3.52	3.49 ± 0.05	0.9988
		2	241		0.00731		3.45		0.9993

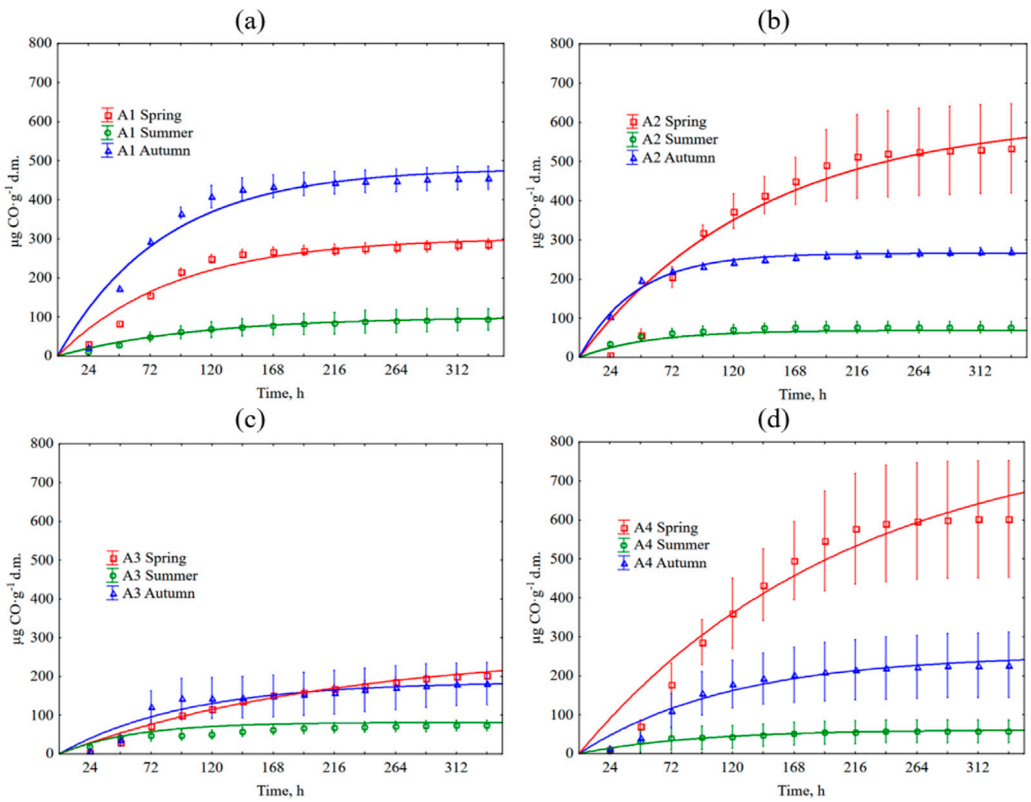


FIGURE 4
Cumulative CO production during grass clipping decomposition depends on the season and type of football pitch. The error bars show +/− standard deviation around the mean. The equations used in the figures are shown in Supplementary Table S2. **(a)** A1 turf; **(b)** A2 turf; **(c)** A3 turf; **(d)** A4 turf.

highly fertilized turfs (A1 and A2) and non-fertilized turf (A4). Tables 6, 7 show detailed statistical analysis.

3.4 CO_2 emissions and O_2 consumption

Cumulative CO_2 emissions are shown in Figure 5. Detailed data is summarized in Supplementary Table S2. In most cases (clippings from A2-A4 turfs), the highest emissions occurred during decomposition of spring clippings. The highly fertilized turf (A1) was an exception, where the CO_2 emissions from the autumn clippings (562 mg CO_2•g^{-1} d.m.) exceeded the spring ones (503 mg CO_2•g^{-1} d.m.). CO_2 emission from A1 clippings in the summer was slightly lower (376 CO_2•g^{-1} d.m.). Generally, for the spring, the higher the level of N fertilization, the lower the CO_2 emission (503, 638, 665, and 745 CO_2•g^{-1} d.m., from A1, A2, A3, A4 turfs, respectively). However, this trend did not occur in the later seasons. For summer, for the clippings from turfs treated with fertilizer (A1-A3), emitted 476, 494, and 558 CO_2•g^{-1} d.m., respectively. The CO_2 emission for clippings from non-fertilized turf was relatively low (283 CO_2•g^{-1} d.m.). The summer clippings had the lowest average CO_2 emissions compared to the spring and autumn seasons (similarly to the CO emissions pattern). In the autumn, the clippings from A4 non-fertilized turf were characterized by the highest CO_2 emissions potential. In contrast, emissions the remaining turfs were very similar and amounted to 562, 557, and 557 CO_2•g^{-1} d.m., for A1 to A3 turfs, respectively. Statistical analyses showed that the level of fertilization has little effect on CO_2 emissions. Statistically significant differences were observed only in summer between the clippings from non-fertilized A4 turf and other pitches. Tables 8, 9 show detailed statistical analysis for CO_2 production.

Cumulative O_2 consumption is shown in Figure 6. Detailed data is summarized in Supplementary Table S3. The process kinetics was similar to that of CO_2 production. The lowest consumption occurred in the summer season (219 O_2•g^{-1} d.m. for A4, and 359, 376, and 426 O_2•g^{-1} d.m., for A1, A2, A3 turfs, respectively). For other seasons, the highest O_2 consumption characterized clippings from non-fertilized A4 turf (spring, 580 O_2•g^{-1} d.m., and 395, 495, and 527 O_2•g^{-1} d.m., for A1, A2, and A3, respectively). As in the case of CO_2 emissions, the lower N fertilization, the greater the O_2 consumption was observed. In autumn, clippings from the non-fertilized A4 turf had O_2 consumption of 463 O_2•g^{-1} d.m., while clippings from the remaining (A1-A3) pitches had a lower O_2 consumption, ranging from 405 to 408 O_2•g^{-1} d.m. The effect of fertilization on O_2 consumption was statistically insignificant in autumn and spring, but statistically significant in summer. The effect of season on O_2 consumption was statistically significant only for the unfertilized football field (A4). Tables 10, 11 contain detailed information on the statistical analysis for O_2 consumption.

3.5 Kinetics of CO, CO_2 emissions, and O_2 consumption

Tables 10, 11 contain detailed information on the statistical analysis for O_2 consumption. Supplementary Tables S2, S4, S6 show

TABLE 6 Results of Kruskal-Wallis tests of the influence of seasonality on CO emission. Results in bold indicate statistically significant differences.

A1	Spring	Summer	Autumn
Spring		0.000010	0.000189
Summer	0.000010		0.000000
Autumn	0.000189	0.000000	
A2	**Spring**	**Summer**	**Autumn**
Spring		**0.000000**	**0.039421**
Summer	**0.000000**		**0.000000**
Autumn	0.039421	0.000000	
A3	**Spring**	**Summer**	**Autumn**
Spring		**0.000000**	1.000000
Summer	**0.000000**		**0.000000**
Autumn	1.000000	**0.000000**	
A4	**Spring**	**Summer**	**Autumn**
Spring		**0.000000**	**0.001356**
Summer	**0.000000**		**0.000011**
Autumn	**0.001356**	**0.000011**	
All clippings	**Spring**	**Summer**	**Autumn**
Spring		**0.00**	0.461539
Summer	**0.000000**		**0.000000**
Autumn	0.461539	**0.00**	

TABLE 7 Results of Kruskal-Wallis tests of the influence of fertilization level on CO emission. Results in bold indicate statistically significant differences.

Spring	A1	A2	A3	A4
A1		0.005361	0.006972	0.001189
A2	0.005361		0.000000	1.000000
A3	0.006972	0.000000		0.000000
A4	0.001189	1.000000	0.000000	
Summer	**A1**	**A2**	**A3**	**A4**
A1		1.000000	0.194158	**0.000744**
A2	1.000000		0.136800	**0.000423**
A3	0.194158	0.136800		0.536997
A4	**0.000744**	**0.000423**	0.536997	
Autumn	**A1**	**A2**	**A3**	**A4**
A1		**0.003254**	**0.000000**	**0.000000**
A2	**0.003254**		**0.000004**	**0.014760**
A3	**0.000000**	**0.000004**		0.318995
A4	**0.000000**	**0.014760**	0.318995	
All clippings	**A1**	**A2**	**A3**	**A4**
A1		1.000000	**0.000000**	0.170034
A2	1.000000		**0.000000**	0.177859
A3	**0.000000**	**0.000000**		**0.005064**
A4	0.170034	0.177859	**0.005064**	

the kinetic parameters of the models used to estimate CO and CO_2 emissions and the consumption of O_2. In all cases, the first-order kinetics model showed higher R^2 than the 0-order model. However, in two instances, i.e., CO_2 emission and O_2 consumption for the A3 spring variant, it was decided to use the 0-order model with a slightly lower coefficient of determination due to the high discrepancy between the samples. Future mathematical modeling should include elements of environmental factors that may affect the decomposition of organic matter, e.g., the ambient temperature. This parameter can fluctuate greatly during the football season, thus affecting the shift in the proportion of a particular type of bacteria (psychrophilic, mesophilic, thermophilic), which can significantly affect CO, CO_2 and O_2 consumption (Stegenta-Dąbrowska et al., 2020). In addition, future mathematical models should include longer organic matter decomposition times (larger datasets) to more effectively estimate emission and consumption kinetics.

3.6 Modeling CO_2 and CO production

In summary, all ANN models effectively predicted CO_2 and CO emissions. The ANN models demonstrate similar dependencies in the raw data (Figures 7a,c). The correlations and high set quality (with values greater than 0.81 for CO and 0.98 for CO_2 as shown in Supplementary Table S4) confirm the effectiveness of these models in predicting CO based on CO_2 and O_2, and CO_2 based on CO and O_2. As all tested models proved to be effective (Figures 7b,d), it was preferable to use the model with the smallest number of hidden neurons, i.e., MLP 3-3-1. Overall, the ANN models displayed reasonable adaptation to the data; however, notable statistical errors were evident in both the assessment of network quality (Supplementary Table S7) and the modeling performed (Figures 7b,d). It was observed that the models performed better at lower CO emissions (up to 350 μg CO•g^{-1} d.m.) where the raw data set was larger (Figure 7a). At higher CO emissions, a significant increase in variability was observed, limiting the ANN's effectiveness to the initial stages of the process. A more comprehensive model is still required for the intensive decomposition phase, where theoretically higher CO emissions could be observed. In the case of CO_2 emission predictions, the ANN model's accuracy was much higher (>0.98) and observed errors were lower, even at high emissions (Figure 7d).

3.7 Key points from the supplementary materials

In Supplementary Tables S1–S6, we included models and parameters for the kinetic models shown in Figures 4–6. The

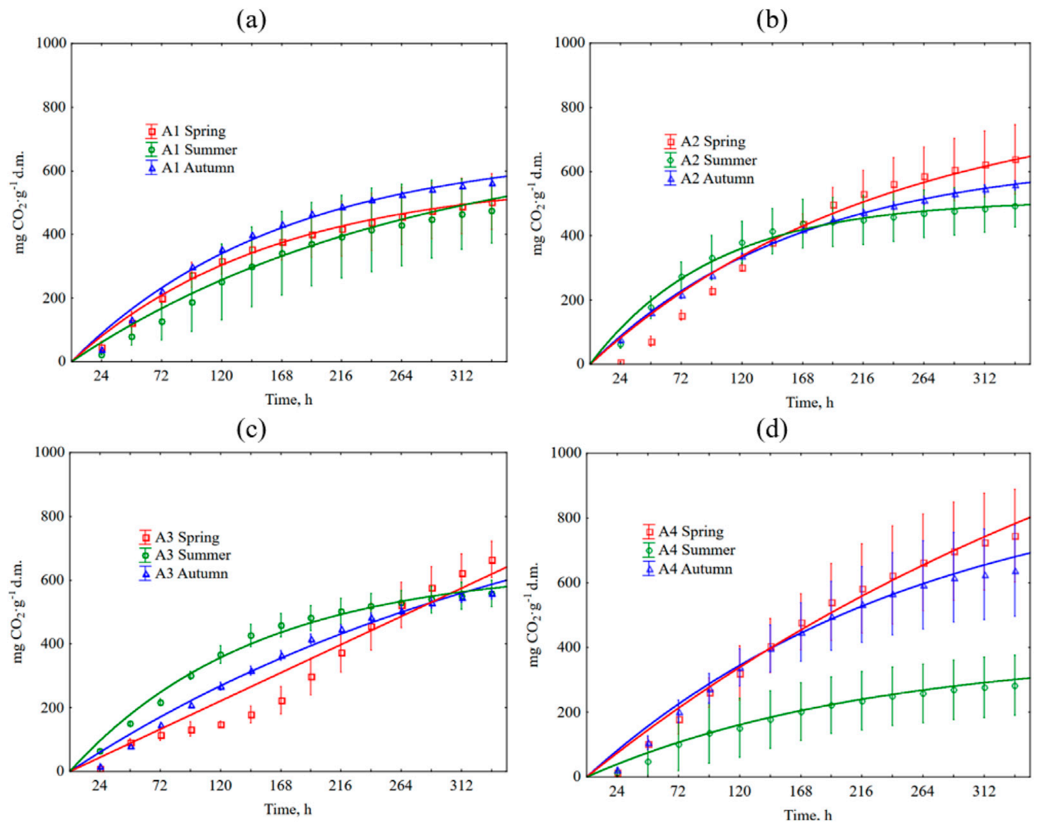


FIGURE 5
Cumulative CO_2 production during grass clipping decomposition depends on the season and type of football pitch. The error bars show +/− standard deviation around the mean. The equations used in the figures are shown in Supplementary Table S4. **(a)** A1 turf; **(b)** A2 turf; **(c)** A3 turf; **(d)** A4 turf.

mathematical models for CO production had an R^2 range of 0.91–0.99, for CO_2: 0.94–0.99, and for O_2 consumption: 0.93–0.99. We have also included in the section ANN configurations for the MLP model and loads scattering plot from PCA analysis.

4 Discussion

4.1 Grass clippings properties

The average MC observed in fresh grass clippings (74.42%) should be considered typical observed on average over the growing season for various species and varieties of turf grasses. This was confirmed by the research of Kauer et al. (2012), who, by evaluating the MC in grass clippings from different periods, which additionally differed significantly in terms of N fertilization, reported MC ranging from 71.3% to 85.7%. Similar MC in grass clippings (73.40%), is a frequent assumption of the average throughout the growing season for various technical and economic analyzes (Sobol et al., 2021; Leible et al., 2015).

The average OM content of 87.76% in grass clippings was consistent with the previous research, i.e., 85.46%–88.34% (Leible et al., 2015; Nitsche et al., 2017), and was similar to the clippings from roadside verges (82.1%–93.11%) (Brown et al., 2020; Obernberger et al., 2006; Piepenschneider et al., 2016). The measured pH and EC did not differ significantly from those found in the literature (Olakanye et al., 2015; Zahrim et al., 2016). The grass clippings had a slight MC increase (~2–3%) with very few exceptions. The process temperature (20 °C) may suggest that water was generated as a result of the progressing OM decomposition (Stegenta-Dąbrowska et al., 2020; Mason, 2006; Sobieraj, 2017; Wetzel et al., 2017).

The decrease in VS content can be explained by the OM loss due to microbiological degradation (Kalamdhad et al., 2012). A slight OM reduction in all cases could be due to the fact that all collected clippings were characterized by a similar initial OM content and MC, hence the decomposition level was also similar (Stegenta-Dąbrowska et al., 2020; De Guardia et al., 2008). In the context of decomposition of grass clippings left on the soil, it has been shown that their decomposition occurs most quickly in high air humidity and temperature up to 10 °C, beyond which the decomposition rate decreases, which may explain a slight decrease in the OM content (Kauer et al., 2012).

However, it is worth adding that this temperature is exceeded in most months of the grass growing season in Polish climate conditions, hence the experiment was carried out at a constant temperature of 20 °C (Talar-Krasa et al., 2021). In addition, because the process provided optimal conditions with regard to the O_2 content, the pH of grass clippings increased due to decomposition, as is the case with composting (Soto-Paz et al., 2019; Wang et al., 2016; Waqas et al., 2018).

TABLE 8 Results of Kruskal-Wallis tests of the influence of seasonality on CO_2 emission. Results in bold indicate statistically significant differences.

A1	Spring	Summer	Autumn
Spring		1.000000	0.227791
Summer	1.000000		0.112696
Autumn	0.227791	0.112696	
A2	**Spring**	**Summer**	**Autumn**
Spring		0.107849	0.107849
Summer	0.107849		1.000000
Autumn	0.107849	1.000000	
A3	**Spring**	**Summer**	**Autumn**
Spring		1.000000	1.000000
Summer	1.000000		1.000000
Autumn	1.000000	1.000000	
A4	**Spring**	**Summer**	**Autumn**
Spring		**0.000001**	1.000000
Summer	**0.000001**		**0.000008**
Autumn	1.000000	**0.000008**	
All clippings	**Spring**	**Summer**	**Autumn**
Spring		**0.000649**	1.000000
Summer	**0.000649**		**0.000976**
Autumn	1.000000	**0.000976**	

TABLE 9 Results of Kruskal-Wallis tests of the influence of fertilization level on CO_2 emission. Results in bold indicate statistically significant differences.

Spring	A1	A2	A3	A4
A1		1.000000	1.000000	0.259645
A2	1.000000		0.401145	1.000000
A3	1.000000	0.401145		0.054168
A4	0.259645	1.000000	0.054168	
Summer	**A1**	**A2**	**A3**	**A4**
A1		1.000000	1.000000	**0.000123**
A2	1.000000		1.000000	**0.000106**
A3	1.000000	1.000000		**0.000007**
A4	**0.000123**	**0.000106**	**0.000007**	
Autmn	**A1**	**A2**	**A3**	**A4**
A1		0.087997	0.606377	1.000000
A2	0.087997		1.000000	0.086371
A3	0.606377	1.000000		0.598025
A4	1.000000	0.086371	0.598025	
All clippings	**A1**	**A2**	**A3**	**A4**
A1		1.000000	1.000000	1.000000
A2	1.000000		1.000000	1.000000
A3	1.000000	1.000000		1.000000
A4	1.000000	1.000000	1.000000	

As expected, a higher N level was observed in grass clippings from sports turf treated with a high dose of N fertilizer. This is consistent with the literature, where increasing the N fertilization rate increases N content in clippings (Grégoire et al., 2022). Our experiment also showed the importance of season. The importance of these two factors is also confirmed by Shaddox and Unruh (2018), who report that many factors may influence turfgrass uptake of N, including turfgrass species, season, N type, N rate, and MC management. On the other hand, the obtained C:N ratio of fresh grass clippings were relatively low; however, they were within the standard range, which is 12–25, according to Singh and Longkumer (2018). The 2-week process of decomposing grass clippings resulted in a percentage decrease in N content in some samples; this phenomenon was especially noticeable in the case of clippings obtained from highly fertilized turfs (A1 and A2). This could be caused by NH_3 volatilization and leaching (Ansari and Rajpersaud, 2012). On the other hand, in the case of turf fertilized with a low N dose (A3) and non-fertilized turf (A4), a negative percentage change was observed, which can probably be explained by microbiological utilization (Ansari and Rajpersaud, 2012).

This experiment showed a reduction in C content, which is often an indicator of enhanced decomposition (Ansari and Rajpersaud, 2012; Agrawal et al., 2011; Rahul, 2011; Sharma et al., 2003; Stoffella and Kahn, 2001). On average, a slightly higher C reduction was obtained for grass clippings obtained from highly fertilized turfs (A1 and A2). This may indicate that the fertilization level affects the rate of clippings decomposition, but on the other hand, the level of C reduction was relatively similar between treatments, hence the need for further research to explain this phenomenon.

AT_4 was higher than those for grass clippings reported in the literature, i.e. (Godley et al., 2004), 119 mg $O_2 \bullet g^{-1}$ d.m (Stegenta-Dąbrowska et al., 2020), 188 mg $O_2 \bullet g^{-1}$ d.m, and (Suchowska-Kisielewicz and Jędrczak, 2019) 162 mg $O_2 \bullet g^{-1}$ d.m. Likely, these differences were due to a wide range of grass species and varieties, habitats and conditions, diverse chemical composition and heterogeneous structure (Waliszewska et al., 2021). These aspects are often overlooked when describing the substrate origin but can have an impact on microorganisms and the decomposition of grass clippings. Based on the results, it can be concluded that the level of N fertilization was not a factor that strongly influences the respiratory activity. Initially, it can be assumed that the season plays a much greater role. However, readers should be aware that between samples it was sometimes possible to observe large fluctuations between results, as exemplified by the A2 grass clippings sample from the summer season. All mathematical models used to describe the AT_4 were first-order and were characterized by a high R^2 (>0.967), which is typical for modeling the kinetics of the respiratory activity process (Stegenta-Dąbrowska et al., 2020). The *r* constant, apart from a few

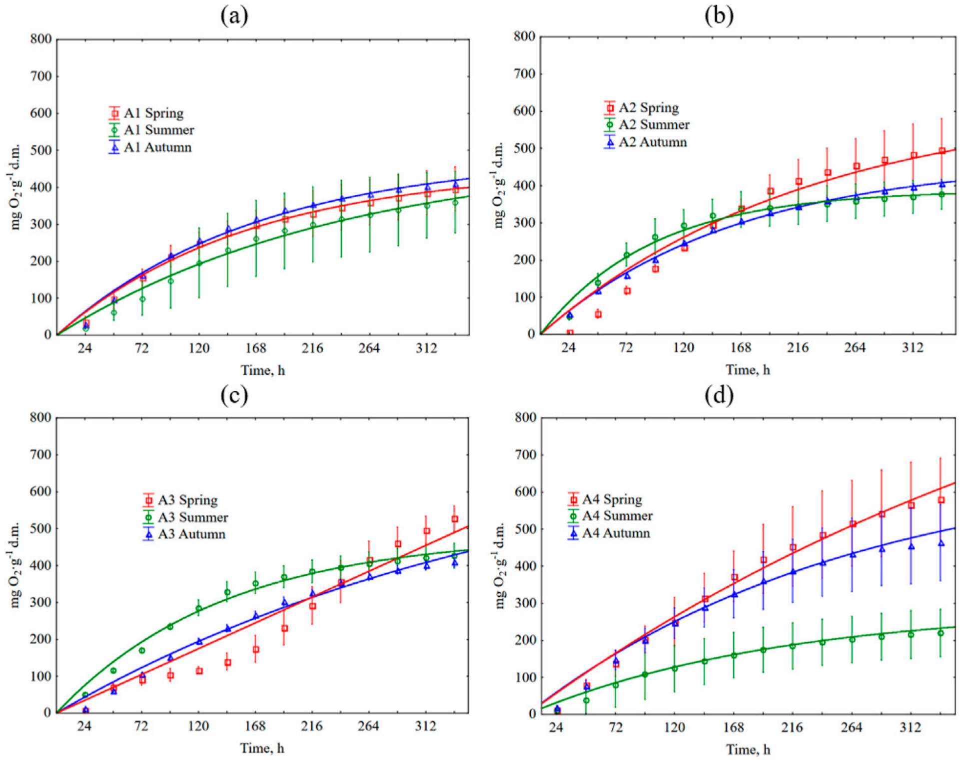


FIGURE 6
Cumulative O_2 consumption during grass clipping decomposition depends on the season and type of football pitch. The error bars show +/− standard deviation around the mean. The equations used in the figures are shown in Supplementary Table S6. **(a)** A1 turf; **(b)** A2 turf; **(c)** A3 turf; **(d)** A4 turf.

outliers, were comparable with the Fernández et al. (2008) studies, with *r* values ranging from 0.0009 to 0.0018 h^{-1}.

4.2 CO, CO_2 production and O_2 consumption during clippings decomposition

To date, managed grass surfaces were considered in the context of CO_2 emissions and in relation to biogenic CO_2 emissions (the effect of mowing grass on soil respiration) and anthropogenic CO_2 emissions (emissions resulting from the use of gasoline for mower engines) (Lerman and Contosta, 2019). In this research, the seasons and fertilizer amount did not have a significant effect for microorganism activity as a production of CO_2 (Figure 5). In turf A4 (no fertilization), the effect of the seasons was clear–the highest activity was observed in spring and the least in summer. This could be explained by C:N ratio, e.g., the A4 C:N ratio was the most optimal for decomposition of biodegradable OM. The ideal range for the C:N ratio varies from 15 to 30, while composting can have a broader range of values. According to Ba et al. (2020), the total C and N contents are the key variables impacting CO_2 emissions because greater C and N contents are more favorable to microorganism respiration. This was clearly visible only on A4 turf. Bai et al. (2020) observed that addition of lignite reduced N losses, but increased CO_2 emissions, i.e., the total GHG emissions from the lignite-amended manure were 2.6 times greater than that of the non-lignite treatment. This means that variants with fertilization (A1, A2 and A3) with low C content, have less CO_2 emissions, which was observed in this research.

Influence of biomass type decomposition on OM has been widely studied by Montejo et al. (2015) who confirmed that materials with optimal range of nutrients effect the quality of compost. Temperature, humidity, pH, aeration and C:N ratio are important in the process of aerobic degradation (Martínez-Valdez et al., 2015), facilitating fast biodegradation and lower impact on environment in terms of gaseous emissions and leaching. In this study we did not observe this, which could possibly be explained by pesticide use, which is known to strongly affect microbiological consortia in soil and grass. Pesticides could remain in the environment, affecting long-term changes in the microbial community. Overall, our results suggest that the pesticide application might affect the soil C cycle and may disrupt the formation of soil OM and structure stabilization (Sim et al., 2022).

All the analyzed variants showed low CO emissions during the summer (Figure 4), regardless of the applied fertilization. High summer temperatures could induce thermochemical production of CO, still on the football fields; hence the CO emissions during incubation at 20 °C were low. As recent research by Sobieraj (2025) has shown, higher temperatures intensified CO production, which is an important finding in the context of our work, because in the summer season, the air temperature can be higher than 20 °C, at which the experiment was conducted. The author also emphasizes the need to conduct research on different moisture content levels in substrates, which may also yield interesting findings regarding the impact of irrigation systems on CO emissions in future studies.

TABLE 10 Results of Kruskal-Wallis tests of the influence of seasonality on O_2 consumption. Results in bold indicate statistically significant differences.

A1	Spring	Summer	Autumn
Spring		0.641648	1.000000
Summer	0.641648		0.193157
Autumn	1.000000	0.193157	
A2	**Spring**	**Summer**	**Autumn**
Spring		0.985651	0.590354
Summer	0.985651		1.000000
Autumn	0.590354	1.000000	
A3	**Spring**	**Summer**	**Autumn**
Spring		0.152076	1.000000
Summer	0.152076		0.158548
Autumn	1.000000	0.158548	
A4	**Spring**	**Summer**	**Autumn**
Spring		0.000000	1.000000
Summer	0.000000		0.000032
Autumn	1.000000	0.000032	
All clippings	**Spring**	**Summer**	**Autumn**
Spring		**0.013978**	1.000000
Summer	0.**013978**		0.080055
Autumn	1.000000	0.080055	

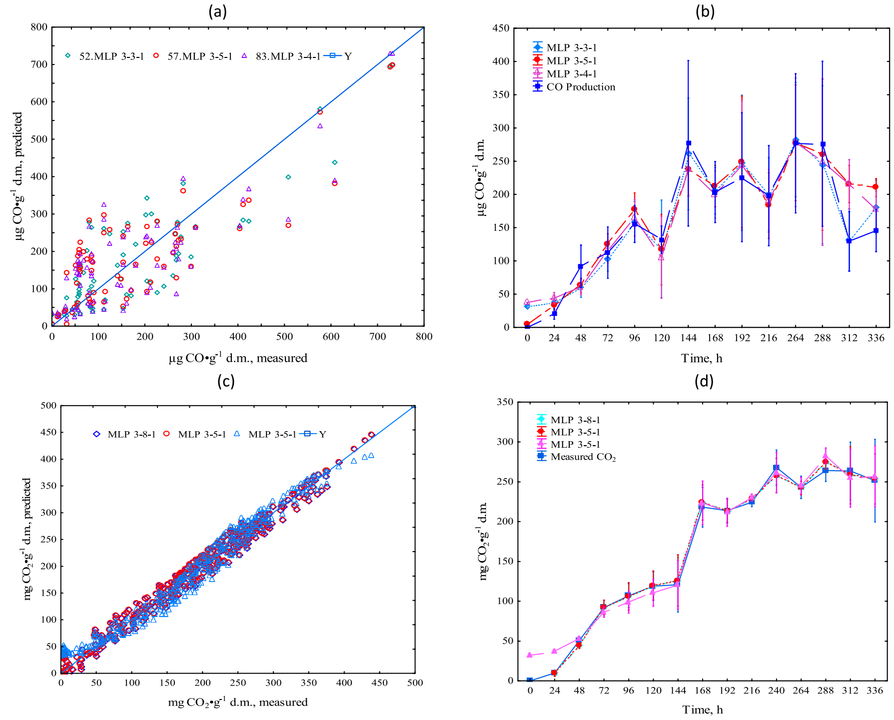
TABLE 11 Results of Kruskal-Wallis tests of the influence of fertilization level on O_2 consumption. Results in bold indicate statistically significant differences.

Spring	A1	A2	A3	A4
A1		1.000000	1.000000	0.294948
A2	1.000000		0.447242	1.000000
A3	1.000000	0.447242		0.055970
A4	0.294948	1.000000	0.055970	
Summer	**A1**	**A2**	**A3**	**A4**
A1		0.272441	**0.033607**	**0.007252**
A2	0.272441		1.000000	**0.000001**
A3	**0.033607**	1.000000		**0.000000**
A4	**0.007252**	**0.000001**	**0.000000**	
Autmn	**A1**	**A2**	**A3**	**A4**
A1		1.000000	1.000000	1.000000
A2	1.000000		1.000000	1.000000
A3	1.000000	1.000000		0.726853
A4	1.000000	1.000000	0.726853	
All clippings	**A1**	**A2**	**A3**	**A4**
A1		0.658198	1.000000	1.000000
A2	0.658198		1.000000	0.277464
A3	1.000000	1.000000		1.000000
A4	1.000000	0.277464	1.000000	

However, in comparison with our previous CO emissions report (Stegenta-Dąbrowska et al., 2020) from mixture of grass and cow manure, total CO emission in this experiment was even 5 times higher. This is also confirmed by the results of biological activity (AT_4 index in Figure 3) which were the lowest in the variants from the summer. These differences are visible, especially in the variant without fertilization. On average, 0.26 mg $CO{\cdot}g^{-1}$ d.m. was emitted from the decomposition process (Table 12) which is higher in relation to grass composting (~0.11 mg $CO{\cdot}g^{-1}$ d.m.), but still a small value compared to CO emissions from open burning of the grasslands (59 mg $CO{\cdot}g^{-1}$ d.m.). Nevertheless, grass decomposition can contribute significantly to global CO emissions.

Differences in CO emissions are not clearly related to the level of fertilization, season, or C and N content. Also, the amount of available N in the form of NO_3^-, or simple indicators such as pH or EC, do not have an apparent effect on the amount of CO. Although Conrad and Seiler (1985) clearly indicated the impact of these parameters on emissions. However, the CO production is a very complex process and the net produced is the result of both the consumption and utilization by microorganisms in various metabolic pathways (Sobieraj et al., 2022; Sobieraj et al., 2023). On the other hand, the fertilized turfs (A1, A2, A3), were also sprayed several times with different herbicides. Herbicides could significantly change the composition of the local microflora (Ruuskanen et al., 2023), also contributing to the observed net CO emissions. The observed highest CO emission (A4 variant) confirms our previous results (Stegenta-Dąbrowska et al., 2019) that the amount of CO is a product of the thermochemical and biological pathways, and the disturbance of one of these processes leads to lower CO emissions, but these emissions are then very difficult to predict if based solely on the compost composition itself.

Another possible explanation of the observed differences in CO emissions is that different fertilization levels may have resulted in different soil microflora (Liu et al., 2022; Ren et al., 2020). The varietal composition of the grass itself might be a factor. Future studies explaining the causes of CO emissions from grass clippings should also include microbiological tests, for developing the microbiome. Recent studies indicate that identifying the specific bacteria responsible for CO release and analyzing their metabolic pathways can help understand CO production in similar biological processes (Sobieraj et al., 2025; Sobieraj et al., 2024). Hence, we propose that this is the next step in researching CO emissions from sports turf. Given that both pesticide/herbicide application and fertilization levels could have significantly affected the dynamics of the microflora and the dynamics of changes in its community (Figure 8), microbiological tests can greatly facilitate the interpretation of CO production variability.



(e)

Type, configuration	Training set quality	Validating set quality	Testing set quality	Training set error	Validating set error	Testing set error	Activation functions (hidden)	Activation functions (output)	Training algorithms
MLP 3-8-1	0.991	0.993	0.992	94.9	66.0	86.4	linear	linear	BFGS 11
MLP 3-5-1	0.991	0.993	0.992	94.9	66.0	86.5	linear	linear	BFGS 13
MLP 3-5-1	0.984	0.987	0.985	180.6	148.4	173.2	linear	logistic	BFGS 13

FIGURE 7
Process simulation with the neural network model–comparison of predicted and measured CO and CO2 production, **(a)** CO production in a time, **(b)** for entire dataset comparison of MLP 3-3-1, MLP 3-4-1, MLP, 3-5-1 for CO predictions, **(c)** CO2 production in a time, **(d)** for entire dataset comparison of MLP 3-3-1, MLP 3-4-1, MLP, 3-5-1 for CO2 predictions, **(e)** ANN statistical characteristics; mean ± standard error.

TABLE 12 Emission factors for processes involving grass.

Process	CO emission factor, $mg \cdot g^{-1}$ d.m.	Reference
Composting	~0.11	Stegenta-Dabrowska et al. (2020)
Decomposition	0.26	This study
Open Burning	59	Wu et al. (2018), Akagi et al. (2011)

4.3 Prediction of CO2 and CO production

Given the substantial amount of CO and CO_2 emissions produced during storing of grass clippings, it is reasonable to predict these emissions in this process. There have been limited studies on the application of AI - machine learning (ML) models - for emissions prediction during the storage or composting of organic waste thus far. Common ML models used in composting are as follows: Random Forest (RF), ANN, Support Vector Regression (SVR), Decision Tree, and Decision Support (DS) (Temel et al., 2023). The majority of studies primarily address CO_2 and NH_3 emissions, with little attention given to predicting CO emissions, which have been found to exceed those produced in conventional composting methods. The utility of ANN in developing accurate emission prediction models was a key factor in its utilization for this study.

The performance of machine learning (ML) models utilized for predicting composting processes exhibited a variance in R-squared (R^2) accuracy ranging from 0.56 to 0.99 (Temel et al., 2023). However, the majority of cases demonstrated a strong fit, with R^2 values exceeding 0.7. In this study, the obtained R-squared value for the ANN exceeded 0.8.

5 Limitations and recommendations for future plot experiments

Because the nature of our work involved grass clippings, harvested from the real football fields, we could not control several parameters -

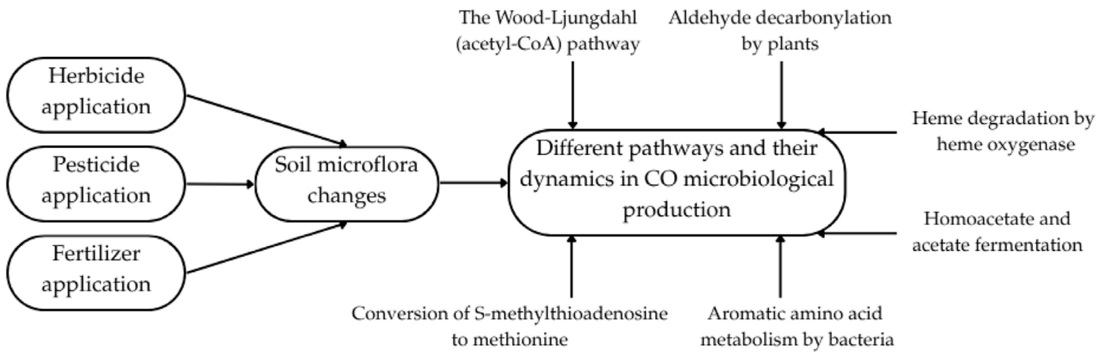


FIGURE 8
Potential change in soil microflora through the application of pesticides/herbicides/fertilizers and its impact on the dynamics of microbiological CO production pathways. Microbiological CO production pathways were used from Sobieraj et al. (2023).

including soil type, irrigation frequency, fertilizer frequency, or the use of a uniform mix of grass species. In addition, some operators admitted to using pesticides, which may have affected the results to some extent. The use of different agronomic treatments at different times also may have distorted the distinction of seasonal effects on the emissions studied. It is also worth mentioning that grass surfaces were mowed with different mowers, so that the shredded levels of grass clippings were also diversified. Moreover, the species composition of grasses on the turf is constantly evolving and changing, so we were not able to monitor their changes throughout the football field. Furthermore, it should be acknowledged that while this article has endeavored to choose a variety of turf surface types with varying management levels, there are likely pitches with entirely different management systems, which may also influence the outcomes on a larger scale. The management practices of the pitches analyzed in the article are characteristic of the Lower Silesia region in Poland. Thus, it is imperative to pursue further research in this domain to optimize the utilization of the findings obtained from this study.

Although we have observed preliminary trends and the effects of some parameters on emissivity (such as pH), in order to distinguish the effect of fertilization on CO and CO_2 emissions from grass clippings decomposition, we propose that future work should focus on experimental plots. Conducting experiments on experimental microplots, along with setting up plots on the same technical parameters - soil type, size and frequency of irrigation, same grass mixture, limiting the use of other chemicals (pesticides/herbicides), using the same agrotechnical equipment - will allow better control of the experiment. Better control of parameters and observation of potential changes in the species composition of grasses will make it possible to better distinguish the direct effect of fertilization and seasonality on emissivity from the decomposition of grass clippings. As we also mentioned in the discussion, microbiological tests seem to be the next critical step that could link the dynamics of microflora and its impact on CO production. The results generated can significantly contribute to emission inventories and CO/CO_2 estimates from other types of sports surfaces and urban lawns. Future work should also evaluate other types of surfaces, such as golf courses and rugby fields, where management is quite different from football fields and the scale of grass generated is larger. Consequently, their GHG budget is different (Kuronuma et al., 2023). To get a better understanding of this phenomenon, it may also be helpful to check the physicochemical characteristics of the turf prisms (pH, humidity, temperature) and adjust the parameters of the decomposition process on this basis.

6 Conclusion

Determination of environmental impacts resulting from the decomposition of grass clippings after mowing sports turfs and grass surfaces is needed to enable the quantification and estimation of gaseous emissions and to ensure the safety of football players, fans, and field operators. This lab-scale experiment showed that the decomposition of grass clippings can generate significant CO emissions, i.e., up to 5 times more than in previous experiments for a mixture of grass and cow manure. However, a high diversification of results was noted, from which the effect of fertilization, seasonality, C and N content on CO emission was not clearly distinguished. A similar lack of apparent relationships was observed in the context of CO_2 emissions and O_2 consumption. Initial models ANN have successfully predicted the CO and CO_2 emissions resulting from the disposal of grass clippings. The models demonstrate satisfactory outcomes with R^2 accuracy: CO > 0.81 and CO_2 > 0.98. More research is needed to account for CO emissions from decomposing biomass such as common grass clippings and improvement of emission inventories of primary pollutants such as CO. More scaled up work is needed (pilot and then full-scale), to elucidate the effects of season, turf type, and management technology on CO/CO_2 emissions to provide best practice recommendations for municipal turf managers and waste handlers.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

ŁS: Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft. JK: Validation, Writing – review and editing. SS-D:

Conceptualization, Data curation, Formal Analysis, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing – original draft, Writing – review and editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was supported by the Wrocław University of Environmental and Life Sciences (Poland) as part of the research program "Young Minds", N010/0001/21".

Acknowledgments

The authors would like to thank the following football clubs that made the research possible - Pogoń Oleśnica, KP Śliwice, Dąb Dobroszyce. The authors would like to thank Zenon Olewiński and Jarosław Sobol for special administrative assistance and making grass clippings available.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1632196/full#supplementary-material

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