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Intra-seasonal variation of particulate matter and volatile organic compound emissions during electrically driven lawn mowing

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ABSTRACT

Lawn mowing is a widespread urban management practice that can generate significant biogenic emissions, even when electric equipment is used. This study investigates the intra-seasonal variability of particulate matter (PM_1, $PM_{2.5}$, PM_{10}) and volatile organic compounds (VOCs) emissions during electrically driven lawn mowing over a full growing season (March–September) in a sub-urban area of central Italy. Measurements were conducted every four weeks on a 100 m^2 turfgrass plot using high-frequency monitoring (0.6 Hz, about 250 data points per session, 80 data points per experiment), allowing detailed characterization of emission dynamics before, during, and after mowing. Results show that mowing itself is the dominant driver of particulate emissions, with very large effects for PM_{10} and $PM_{2.5}$ ($F = 177$ and 123, respectively; $p < 0.001$). Strong intra-seasonal variability was also observed, with coefficients of variation exceeding 130% for all particulate fractions and approximately 69% for VOCs. Normalization by the mass of grass removed did not attenuate seasonal patterns, indicating that emissions appear to be influenced by seasonal changes in plant physiological status, environmental conditions, and vegetation structure rather than biomass yield alone. Particulate matter emissions exhibited a pronounced mid-season peak, whereas VOC emissions were highest in early spring and declined thereafter. Correlation analysis confirmed a strong coupling among particulate fractions ($r = 0.97$–0.996) but weak associations between particulate matter and VOCs, highlighting distinct emission mechanisms. These findings demonstrate that particulate matter and VOC emissions from lawn mowing are highly dynamic and season-dependent, with implications for urban air quality and operator exposure, even under low-combustion management practices.

1. Introduction

Human activities have drastically altered the Earth's atmosphere, leading to a significant increase in emissions of greenhouse gases and other pollutants. These emissions come mainly from the burning of fossil fuels for energy, industrial processes, deforestation and agricultural practices. As societies have industrialized and populations have grown, the demand for energy and resources has increased, leading to higher levels of potentially hazardous emissions. The consequences of these emissions are broad and profound. In particular, emissions from human activities contribute to air pollution, which poses significant health risks, including respiratory and cardiovascular diseases, and can degrade ecosystems and biodiversity. Addressing human-caused emissions requires a multifaceted, multi-scale approach. It involves switching to renewable energy sources, improving energy efficiency, adopting sustainable agricultural practices and food systems, advancing environmental management habits and practices, and implementing policies and appropriate regulations. Attention has to be posed also on human activities which might seem of secondary importance.

Urban green management encompasses a range of practices designed to maintain and improve vegetation within cities, from residential gardens to large public parks. Effective management of urban and peri-urban greenery is critical to mitigating emissions and improving the quality of urban environments. At various scales, from individual households to citywide initiatives, the management of urban green spaces can have a significant impact on emissions and local air quality.

By integrating green spaces into urban planning and encouraging sustainable practices, cities can mitigate the impacts of climate change, improve the resilience of urban environments, and promote the well-being of their residents. Nevertheless, green spaces management

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implies the operation of lawn mowing, a common practice in urban green management, necessary to maintain the appearance and functionality of these spaces. Although switching to electric lawn mowers reduces the environmental load compared to gasoline models, the operation still has significant environmental and health implications. In particular, mowing operations can generate particulate matter and volatile organic compounds (VOCs) even when electrically driven equipment is used. The mechanical action of cutting vegetation can produce airborne particles across different size fractions, while tissue disruption induces the release of volatile compounds commonly referred to as green leaf volatiles. These emissions may affect both local air quality and operator exposure, despite the absence of combustion-related exhausts.

Particulate matter (PM) in the atmosphere consists of a heterogeneous mixture of particles originating from multiple sources, including mineral dust, anthropogenic emissions, and biological material. The biological fraction of PM—often referred to as bioaerosols or bio-particles—includes pollen, fungal spores, bacteria, viruses, and fragments of plant or animal tissues (Šantl-Temkiv et al., 2019; Huffman et al., 2020; Pan, 2015). During mowing operations, mechanical disruption of vegetation can generate airborne particles that may include plant-derived fragments, although resuspension of pre-existing dust and soil particles can also occur. In the present study, total PM (PM_1, $PM_{2.5}$, PM_{10}) was measured using an optical particle counter without discrimination of particle origin; therefore, the particulate fractions reported represent overall airborne particulate matter generated during mowing rather than exclusively biological particles. These particulates play a significant role in air quality and can have considerable effects on human health, particularly for individuals with respiratory conditions such as asthma or allergies. Even with electric mowers, which produce less direct pollution thanks to the absence of the combustion engine, the mechanical action of mowing is sufficient to generate and disperse bioparticles or more in general particulate matter. The health impacts of inhaling these particles range from mild respiratory complaints to more severe allergic responses and infections. So, these emissions contribute to air pollution and have potential health impacts, underscoring the need for sustainable lawn care practices. The same occurrence involves the emission of volatile organic compounds (VOCs), often called green leaf volatiles. In fact, it is well known that plant tissues damaging led to a strong emission of several different organic compounds characterized by a marked volatility. The typical smell of cut grass is generally ascribed to the variable concentration of E−2-hexenal. However, specific literature about the topic of lawn mowing and emissions, particulate matter or VOC, is relatively scarce. Kernerman et al. (1992) directly relate the increased occurrence of allergen such as grass pollen in atmosphere to the lawn mowing operation. Three years later, Comtois et al. (1995) found that mowing operation performed in urban parks gives a significant increase of aeroallergens due to aerosolization of grass fragments. This was true at different scale, from next to the operator level to local level, whereas at regional level the effect was masked. The aerosol characterization in that case mainly found spores belonging to the ubiquitous Cladosporium. From that time, we must drop to the paper of Junker et al. (2000), where the airborne particulates measured during a lawn mowing episode which was dropped into a broader series of reliefs, reach the absolute value of about 75 μg/m3, with a shift in the mass particles distribution toward coarser particles, when compared to the background particulate matter concentration. Particulates in that case were not characterized. Drewnick et al., (2008) found that the mowing operation gives two type of aerosol particles, an ultrafine fraction ascribed to lubricating oil nebulization, and a coarser fraction consisting of swirled-up plant fragments from the actual cutting process. This occurrence especially confirm the trouble of a reliable particulate quantification from the actual mowing work, without interference of exhaust fumes from the engines driving the mowers. To the best of our knowledge, literature information about particulates and lawn mowing stops here.

Regarding the emission of VOCs associated with the grass-cutting operation, the first work dates back to 1999, when de Gouw et al. (1999) observed the emission of (Z)-3-hexenal, (Z)-3-hexenol and hexenyl acetate on a laboratory scale in response to wounding of plant tissues. Similar results were found by de Gouw et al. (1999). This latter study also underlines a secondary emission of some other VOCs several hours after the cutting event, at the starting of dry out of the tissues. Nevertheless, both the studies were not a real observation of the lawn mowing practice. On 2001 Karl et al. (2001) report about some environmental measurement of VOCs performed during two lawn mowing events. They observed the typical pattern of C6 wound compounds ((Z)-3-hexenal, (E)-2-hexenal, hexenol plus hexanal, and acetaldehyde) right after the mowing, as well as an increased level of the same compounds for some hours after. Again, machines driven by combustion engines were used for the operation. On 2004, Kirstine and Galbally (2004) propose a simple model aimed to estimate the VOC emissions from either grass or grass cutting that lets these activities to be incorporated in urban/regional emissions inventories. The model was developed on the base of literature data and two important conclusions arise from the study. First, the VOCs emitted during lawn mowing were comparable to that emitted from the engines driving the mowers; second, the need of taking into account these emissions also because of their concentration over a specific period of about 5 months, corresponding to the spring-summer seasons, being the week-end the hot moments of operation.

Harvey et al. (2014) investigated the emission and subsequent oxidation of VOCs by ozonolysis to give secondary organic aerosol formation as consequence of lawn mowing events. These authors arrive to estimate a potential of about 50 μg of secondary organic aerosol per square meter of mowed lawn. They also underline that the interface between urban and suburban areas could be of meaningful importance because the former represent a potential source of anthropogenic oxidants, and the latter represent a potential source of huge amounts of VOCs induced by mowing.

This review of the literature on emissions generated during lawn mowing, including particulate matter and volatile organic compounds (VOCs), highlights several critical points that require further investigation or improved methodological control.

Specifically:

- None of the pertinent trials were purposely designed to study the bio-emissions during a lawn mowing operation, but rather they consists of indirect measurement or side measurement
- In all the case the mowing device were driven by combustion engines, so that discrimination or contamination of the occurring emissions can't be fully disclosed
- There is no trace of the possible variation of the emissions during the growth season of the lawn.

The present work aims to fill these gaps.

2. Materials and methods

2.1. Study site and experimental design

In this study, particulate matter (PM_1, $PM_{2.5}$, and PM_{10}) and total volatile compounds (VOCs) were measured during a common lawn mowing operation, along with some other parameters specified later in the text. The study was conducted in a sub-urban residential area near Pistoia, Italy (43°49′19.6″N 10°51′50.6″E), on a 18.00 m × 5.55 m rectangular plot of approximately 100 m^2. This area was chosen because it represents a typical sub-urban green space where routine lawn mowing operations are performed. The presence of well-maintained turf, coupled with an environment influenced by surrounding residential activities, made it an ideal setting to assess the intra-seasonal variation of bio-emissions generated during mowing events.

The experimental period spanned seven months, from March to September, covering a full growing season. Measurements were taken every four weeks, ensuring that seasonal variations in grass growth, environmental conditions, and emission patterns could be captured comprehensively. This timeframe was also selected based on the typical lawn maintenance frequency in urban settings of the local area and to provide sufficient data points for intra-seasonal analysis.

The turfgrass composition of the study area consisted of a standard mix of cool-season grasses, commonly found in urban lawns across temperate regions. The species included *Lolium perenne* (perennial ryegrass), *Poa pratensis* (Kentucky bluegrass), and *Festuca arundinacea* (tall fescue). These species were selected because of their widespread use in public and private lawns and their ability to withstand frequent mowing. A key factor influencing turfgrass growth and emission dynamics is water availability, which affects plant metabolism, biomass production, and physiological stress responses. To ensure consistent and healthy turf development throughout the study period, well water irrigation was supplied daily during nighttime using a sprinkler system. Nighttime irrigation was chosen to reduce water loss from evaporation, which is particularly relevant in the warm climate of central Italy, and to ensure that the lawn remained adequately hydrated before mowing operations. All of this reflects the standard management practice applied in the studied residential area and was representative of the standard management practice of the region in urban and sub-urban areas. The irrigation system consisted of six fixed-position sprinkler heads, strategically located along the edges of the rectangular plot to achieve uniform water distribution. The total water dose applied per day was determined based on a reference dose applied in the studied context, which was based on a dedicated survey performed by a door-by-door interview over a sub-urban residential area of about 30 km^2 surrounding the experimental field. Results of this survey indicated an average water supply of 5 mm per day from March to May, and 7 mm per day from June to July. These irrigation rates were applied to the experimental plot. As aforementioned, the water source was a well, ensuring a consistent supply without reliance on municipal water networks. Well water characteristics were not analyzed in this study, but its use reflects common irrigation practices in peri-urban and residential green areas of Tuscany. The efficiency of the sprinkler layout was periodically checked to verify even coverage and prevent localized over- or under-watering, which could affect biomass distribution and, consequently, bio-emission patterns. To ensure consistency across all trials, a single electrically driven, walking-type lawn mower was used throughout the study. The mower operated at 220V, had a 40 cm wide cutting deck, and was equipped with a rotary blade system. Main technical features of the machine are listed in Table 1. The cutting height was set at 4 cm, a typical setting for urban turf maintenance, allowing for controlled measurement of emissions associated with mechanical damage to the grass. The forward speed of the mower was maintained at 0.6 m/s, a pace that ensured uniform cutting without excessive disturbance to the lawn or soil.

During each mowing event, measurements were taken in the operator's breathing zone, at approximately 1.60 m above ground level, in order to reflect realistic exposure conditions. The positioning of the measuring instruments was intended to capture airborne emissions in the breathing zone of the person performing the mowing operation. Given that lawn mowing is a widespread and routine activity, understanding the direct exposure to emissions is critical for assessing potential health impacts.

The grass height before and after mowing was measured to assess variations in biomass removal across different time points in the growing season. Additionally, the total mass of cut grass was collected and weighed after each mowing event to evaluate its relationship with emission levels.

To capture real-time variations, all emission measurements were recorded at a frequency of approximately 0.6 Hz, corresponding to one data point per meter travelled. This high-resolution data acquisition enabled precise tracking of emission patterns along the mowing path and provided detailed insights into fluctuations in airborne contaminants.

Table 1
Main technical features of the lawnmowing machine.

Technical Features	value
model	AL138E, type EL380, ALPINA GGP ITALY SPA
power supply (volt/frequency)	230-240/50Hz
power (W)	1600
cutting speed (rpm)	3300
mass (kg)	13
noise (db LWA)	94
cutting width (m)	0.40
operation (type)	manually operated-walking behind

The experimental area was divided into three adjacent sub-plots of equal size, which were treated as independent replicates. During each sampling date, sub-plots were mowed sequentially using the same mower and operator under the same protocol. For each replicate, background measurements were recorded immediately before mowing along the same path later followed during the mowing operation, and short-term post-mowing measurements were collected immediately afterwards.

2.2. Meteorological conditions

Environmental factors potentially affect bio-emission rates and dispersion patterns. Therefore, atmospheric temperature, relative humidity, and wind speed were monitored alongside VOC and PM measurements. These data helped contextualize emission fluctuations observed across different measurement sessions. Beside, main climatic data (minimum and maximum temperature, rainfall) were derived on daily basis from the nearest weather station (43°49′28.5″N, 10°49′59.4″E – Stazione meteorologica di Larciano Castelmartini). Data were transformed on monthly basis and presented in Fig. 1.

3. Measurements

Particulate matter was measured by an Optical Particle Counters model OPC-N3, Alphasense Ltd (UK). The instrument also has onboard temperature and humidity sensors. The instrument measures total particulate matter (PM_1, $PM_{2.5}$ and PM_{10} as μg m^{-3}) based on optical light-scattering principles and does not discriminate between biological and non-biological particles.

Volatile Organic Compounds (VOCs) were measured by a portable handheld VOCs monitor model RAE Systems ppbRAE 3000+, JJS Technical Services (IL-USA). The instrument provides digital outputs as mg m^{-3}. This photoionization detector provides an integrated measurement of total volatile organic compounds but does not allow chemical speciation of individual compounds. In fact, photoionization detectors quantify the bulk concentration of ionizable volatile organic compounds but do not allow compound-specific identification, and the instrument response may vary among different chemical species depending on their ionization potentials.

Wind speed was measured by an Extech AN100 anemometer, Industrial Electronics Inc (TN-USA).

Each mowing event was conducted following a standardized protocol to maintain consistency across all measurement sessions. To build a pre-mowing baseline measurements, background levels of VOCs and PM were recorded before mowing at the same rate of the mowing event, following the same path taken by the lawn mower on the experimental field during the subsequent mowing event. Atmospheric temperature, humidity and wind speed were simultaneously monitored. As aforementioned, during the mowing event the operator mowed at 0.6 m/s, maintaining a consistent pace. All the parameters were continuously

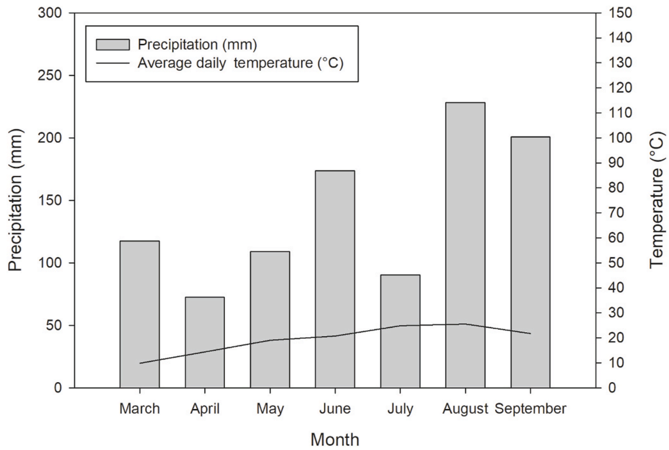

Fig. 1. Climogram of data derived from the weather station (43°49′28.5″N, 10°49′59.4″E – Stazione meteorologica di Larciano Castelmartini) nearest to the experimental area.

recorded at 0.6 Hz.

3.1. Data analysis

The experimental field was divided into three treatment sub-plots measuring 6.00 × 5.55 m (approximately 33 m^2 each), corresponding to three independent replicates. For each plot, the collected data (about 80 observations per parameter) were averaged, and the resulting mean values were used for subsequent statistical analyses. The statistical analysis included the following conventional techniques: (1) basic descriptive statistics; (2) two-way analysis of variance using a standard General Linear Model with two factors—seasonal period (seven levels, from March to September, corresponding to the mowing sessions performed every four weeks) and mowing treatment (three levels: before, during, and after mowing); and (3) correlation analysis based on a conventional Pearson correlation coefficient matrix.

4. Results and discussion

4.1. Results

4.1.1. Meteorological conditions during the mowing trials

To contextualize the observed emission patterns, basic meteorological data were retrieved from a regional weather station located approximately 1.5 km from the experimental site. The parameters available for the duration of the study included minimum, maximum and mean daily air temperature and total monthly precipitation. While limited in scope, these data provide useful environmental context which contribute to the interpretation of the seasonal variation in emissions observed during mowing operations. Data from March to September (Fig. 1) showed a typical seasonal progression, with a few notable anomalies in early and late summer. March was cool and variable, with several precipitation events and minimum temperatures occasionally falling to 0 °C or slightly below. Daytime maxima generally remained under 15 °C, and total rainfall reached approximately 118 mm, resulting in persistently moist early-season conditions. April and May marked a shift toward more stable spring weather. Rainfall became less frequent, with monthly totals of about 72 mm in April and 109 mm in May, although a few moderate events still occurred. Temperatures increased steadily across both months, with daily averages rising from 13 to 15 °C in early April to nearly 20 °C by late May. Maximum temperatures often exceeded 25 °C, promoting vigorous grass growth and biomass accumulation. June represented the wettest month of the monitoring period, with a total of roughly 174 mm of precipitation. Several high-intensity events (e.g., 39 mm on 4 June and ~35 mm on 14 June) produced repeated canopy wetting and likely sustained higher grass water content despite rising temperatures. During this time, mean daily temperatures ranged between 22 and 25 °C, creating a combination of warmth and moisture favorable for active plant metabolism. July remained warm but was not as dry as initially assumed: monthly rainfall reached about 90 mm, including a few intense storms. Temperatures frequently exceeded 30 °C, contributing to high evaporative demand between rainfall pulses. August appeared wet when considering total monthly rainfall, but nearly all precipitation was concentrated in the final 2–3 days of the month (roughly 60% of the monthly total), while the preceding three weeks were largely dry. Temperatures remained seasonally high (23–25 °C daily averages), meaning that grass experienced an extended dry phase followed by an abrupt late-month rehydration. September marked the onset of early autumn, with moderate temperatures (18–20 °C daily averages) and intermittent rainfall.

4.1.2. Emission patterns during a representative mowing session

Fig. 2 shows an example of emissions recorded during a mowing session in early March, corresponding to the first measurement date, and illustrates the evolution of total total particulate matter (sum of PM_1, $PM_{2.5}$ and PM_{10}) and VOC concentrations along the spatial path of the mower. The comparison between measurements taken before, during, and after mowing reveals clear and consistent differences in the emission dynamics of both VOCs and PM fractions. For VOCs, the "during-mowing" curve displays the expected high-frequency fluctuations at relatively elevated concentrations, reflecting strong and diffuse volatilization triggered by mechanical cutting. Conversely, the "before" and "after" curves exhibit lower-amplitude and smoother trends, indicating that background VOC levels are present but that mowing-induced volatilization is tightly coupled to real-time plant damage. The particulate matter signal behaves differently. The "during-mowing" curve is characterized by distinct, impulsive peaks corresponding to localized particle-release events, likely caused by mechanical impacts with denser vegetation patches or accumulated biomass. The "after-mowing" curve lies consistently above the "before" curve, indicating that particulate matter remained suspended in the air rather than settling rapidly. This persistence suggests slow deposition and prolonged suspension of airborne particles in the sampling area. Taken together, these patterns demonstrate that mowing induces a strong and immediate VOC increase with diffuse spatial behavior, while Particulate matter emissions are dominated by short, high-intensity bursts. After mowing, both signals gradually relax toward background levels but do not fully return to baseline within the short-term observation period of approximately 1 h. The post-mowing monitoring window was limited to approximately 1 h because was intended to characterize immediate short-term exposure conditions in the operator's breathing zone. Longer-term secondary emissions occurring several hours after cutting were outside the scope of the present study.

4.1.3. Summary statistics of emission parameters

Table 2 reports the descriptive statistics for all monitored parameters— particulate matter fractions (PM_1, $PM_{2.5}$, PM_{10}) (PM_1, $PM_{2.5}$, PM_{10}), total volatile organic compounds (VOCs), and the environmental variables temperature and relative humidity. For each mowing session, values were averaged at the plot scale, and descriptive metrics were computed across the entire March–September dataset without stratification by date or replicate grouping. The statistics reveal the inherently heterogeneous nature of mowing-induced bio-emissions. All particulate fractions exhibit extremely wide ranges and very high coefficients of variation (CV = 130–144%), indicating that concentrations can fluctuate by more than an order of magnitude across the monitoring season. VOCs show slightly lower but still substantial variability (CV ≈ 69%), in line with their stronger dependence on physiological and environmental constraints. By contrast, temperature and humidity display moderate dispersion (CV = 14% and 22%, respectively), reflecting primarily seasonal progression rather than the abrupt, event-driven dynamics

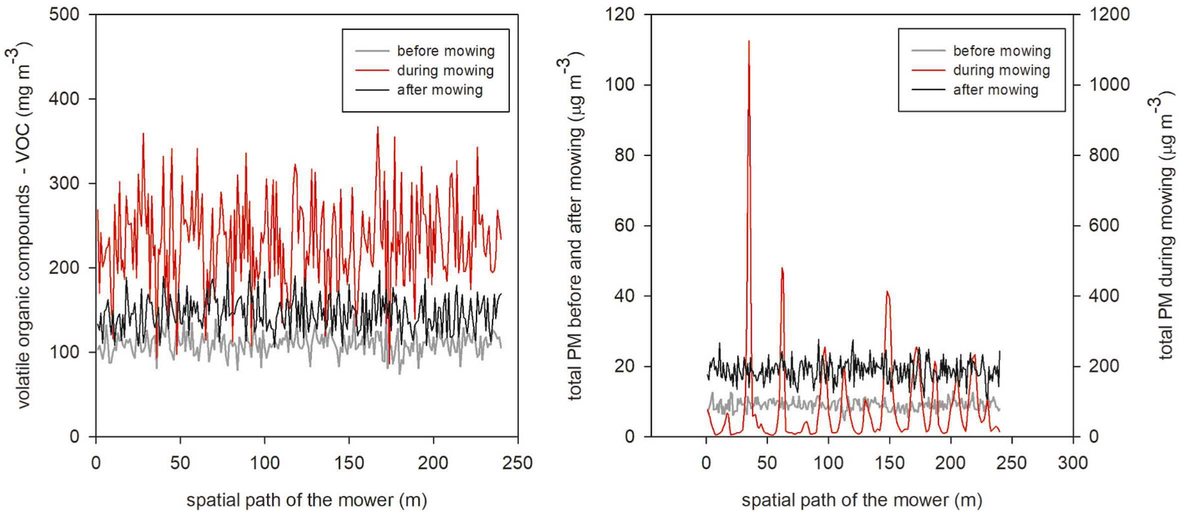

Fig. 2. Emission trends during a mowing session (March 1st): total PM and total VOC vs. path distance (total PM represents the sum of PM_1, $PM_{2.5}$, and PM_{10}; VOC stay for volatile organic compounds).

Table 2
Descriptive statistics of monitored parameters.

Statistics[a]	$PM_{2.5}$	PM_{10}	PM_1	VOC	temperature	humidity
N of Cases	63	63	63	63	63	63
Minimum	1.6	1.3	0.6	29.2	21.0	24.3
Maximum	244.0	315.2	103.6	238.2	37.0	55.1
Range	242.4	313.9	103.0	209.0	16.0	30.8
Arithmetic Mean	35.3	46.6	19.7	75.0	27.9	37.0
Standard Error of Arithmetic Mean	6.2	8.5	3.2	6.5	0.5	1.0
95.0% Lower Confidence Limit	22.9	29.7	13.3	62.0	26.9	35.0
95.0% Upper Confidence Limit	47.7	63.5	26.2	87.9	28.9	39.1
Standard Deviation	49.3	67.2	25.6	51.4	3.9	8.1
Coefficient of Variation	140%	144%	130%	69%	14%	22%

[a] PM ($PM_{2.5}$, PM_{10}, and PM_1) are expressed as μg m^3, when pertinent with the statistical parameter; VOC are expressed as mg m^3, when pertinent with the statistical parameter; Temperature is expressed as °C, when pertinent with the statistical parameter; humidity is relative humidity expressed as %.

typical of mowing emissions. This strong variability is consistent with the mechanisms described in previous literature. Regarding biological part of the particulate matter emissions, early studies (Kernerman et al., 1992; Comtois et al., 1995; Junker et al., 2000; Drewnick et al., 2008) showed that mowing can aerosolize highly variable quantities of biological and plant-derived fragments, depending on grass hydration, canopy structure, and the mechanical intensity of cutting. Our dataset mirrors this behavior: high SD values reflect the stochastic nature of tissue fragmentation and the sensitivity of particle release to subtle changes in grass brittleness, regrowth stage, or mower loading. Similarly, the variability observed in VOC emissions aligns with studies showing that green-leaf volatiles respond strongly to tissue wounding (de Gouw et al., 1999; de Gouw et al., 1999; Karl et al., 2001). The broad concentration range in our measurements reflects the joint influence of instantaneous mechanical damage, metabolic status, and environmental drivers—particularly temperature, which modulates volatilization and has been highlighted as an important determinant of emission magnitude (Kirstine and Galbally, 2004).

4.1.4. ANOVA on emission parameters over time and as response to the mowing operation

The two-way ANOVA (Table 3) showed that both the mowing operation itself and the seasonal period had highly significant effects on all measured emission parameters (PM_1, $PM_{2.5}$, PM_{10}, and VOCs), with $p < 0.001$ in all cases. The factor MOWING—representing the contrast between pre-mowing background, emissions during mowing, and post-mowing conditions—accounted for the largest share of variability in particulate concentrations. For PM_{10} and $PM_{2.5}$, the MOWING factor generated exceptionally large F-ratios (177.0 and 123.3, respectively), indicating that the act of cutting grass is by far the dominant driver of particle release. PM_1 followed the same pattern, although with a slightly lower magnitude, consistent with the mechanical origin of these fine fragments. The PERIOD factor, representing the sampling dates from March to September, also exerted a strong influence on emissions, with F-values ranging from 12.5 (PM_1) to 52.2 (VOCs). This confirms the presence of marked intra-seasonal variability and supports the hypothesis that plant metabolic status, moisture content, and meteorological context jointly modulate the amount of biogenic material released during mowing. VOCs were particularly sensitive to seasonal changes, showing the highest F-value for the PERIOD factor, which aligns with temperature-driven volatility and the seasonal dynamics of plant secondary metabolism. The interaction term (MOWING × PERIOD) was significant for all parameters, though with lower F-ratios than the main effects. This indicates that the magnitude of mowing-induced emissions did not increase or decrease uniformly across the season; instead, the seasonal trajectory modified the relative contrast between pre-, during-, and post-mowing concentrations. For example, periods characterized by higher biomass production or higher leaf water content likely amplified the emission peak during cutting, while drier late-summer conditions may have reduced it.

4.1.5. Effect of normalizing by grass mass removed

To evaluate whether emission variability was merely driven by the amount of grass removed, all emission values were normalized by the corresponding fresh mass of grass cut (g), measured gravimetrically after each session. Fig. 3 shows normalized trends for particulate

Table 3
Output of the Two-way ANOVA of the emission parameters recorded during the experiment.

		Without-normalization				With-normalization			
$PM_{2.5}$-effect	df	Type III SS	Mean Squares	F-ratio	p-value	Type III SS	Mean Squares	F-ratio	p-value
MOWING	2	75827.87	37913.94	123.30	0.000	50.703	25.35	126.153	0.00
PERIOD	6	26126.21	4354.37	14.16	0.000	16.476	2.75	13.665	0.00
MOWING*PERIOD	12	35539.23	2961.60	9.63	0.000	23.465	1.96	9.730	0.00
Error	42	12914.85	307.50			8.440	0.20		
PM_{10}-effect	df	Type III SS	Mean Squares	F-ratio	p-value	Type III SS	Mean Squares	F-ratio	p-value
MOWING	2	138736.75	69368.37	177.04	0.000	92.968	46.48	184.325	0.00
PERIOD	6	52013.88	8668.98	22.12	0.000	33.476	5.58	22.124	0.00
MOWING*PERIOD	12	72362.68	6030.22	15.39	0.000	48.246	4.02	15.943	0.00
Error	42	16456.97	391.83			10.592	0.25		
PM_1-effect	df	Type III SS	Mean Squares	F-ratio	p-value	Type III SS	Mean Squares	F-ratio	p-value
MOWING	2	23058.11	11529.05	136.90	0.000	15.372	7.69	142.298	0.00
PERIOD	6	6297.31	1049.55	12.46	0.000	3.734	0.62	11.522	0.00
MOWING*PERIOD	12	7626.42	635.54	7.55	0.000	4.832	0.40	7.455	0.00
Error	42	3537.05	84.22			2.269	0.05		
VOC-effect	df	Type III SS	Mean Squares	F-ratio	p-value	Type III SS	Mean Squares	F-ratio	p-value
MOWING	2	36950.56	18475.28	59.91	0.000	25.384	12.69	55.776	0.00
PERIOD	6	96533.77	16088.96	52.17	0.000	103.591	17.27	75.873	0.00
MOWING*PERIOD	12	17092.63	1424.39	4.62	0.000	13.376	1.12	4.898	0.00
Error	42	12952.91	308.40			9.557	0.23		

emissions and VOCs over time. The ANOVA (Table 3) performed on emission values normalized by the mass of grass removed confirms the patterns observed in the raw data, highlighting that intra-seasonal dynamics remain a dominant source of variability even after accounting for differences in biomass yield. For all particulate fractions ($PM_{2.5}$, PM_{10}, PM_1), the mowing factor continues to explain the largest share of variance, with very high F-ratios (126 for $PM_{2.5}$, 184 for PM_{10}, 142 for PM_1; $p < 0.001$). This indicates that the act of mowing—i.e., the mechanical disturbance of the canopy—remains the primary driver of particle release regardless of the amount of vegetation removed. Importantly, the PERIOD factor retains a strong and statistically significant effect across all particulate metrics, with F-ratios ranging from 11.5 to 22.1 ($p < 0.001$). This confirms that the seasonally evolving physiological and structural properties of the lawn—such as moisture, leaf brittleness, resin content, and microbial activity—modulate emissions independently of mowing intensity or biomass availability. The persistence of this effect after normalization reinforces that the seasonal signal is not merely a reflection of variable grass mass but instead reflects intrinsic shifts in emission propensity. Interaction terms (MOWING × PERIOD) remain significant for all PM metrics, though their relative contribution is reduced compared to the raw-data ANOVA. This suggests that seasonal conditions not only alter baseline emission levels but also influence how strongly emissions respond to mowing. In other words, the mechanical trigger is modulated by the seasonal state of the vegetation, leading to different emission “sensitivities” across the year. For VOCs, normalization substantially clarifies patterns: PERIOD becomes the dominant factor, with an F-ratio of 75.9—higher than that of mowing (55.8). This contrasts with the raw data, where mowing explained a proportionally larger share of variation. The normalized analysis indicates that VOC emissions are even more tightly linked to plant physiological status than particulate emissions, with seasonal shifts in metabolic activity and volatile biosynthesis rates driving most of the variability. The significant interaction term ($p < 0.001$) further shows that the VOC response to mowing is strongly influenced by the seasonal metabolic state.

5. Correlation analysis

Pearson correlation coefficients were calculated among key parameters (Table 4), including emissions and environmental variables. The resulting correlation matrix provides additional insight into the relationships among particulate matter fractions, VOCs, and environmental drivers across the full March–September dataset. As expected, the three particulate fractions (PM_1, $PM_{2.5}$, PM_{10}) exhibit extremely

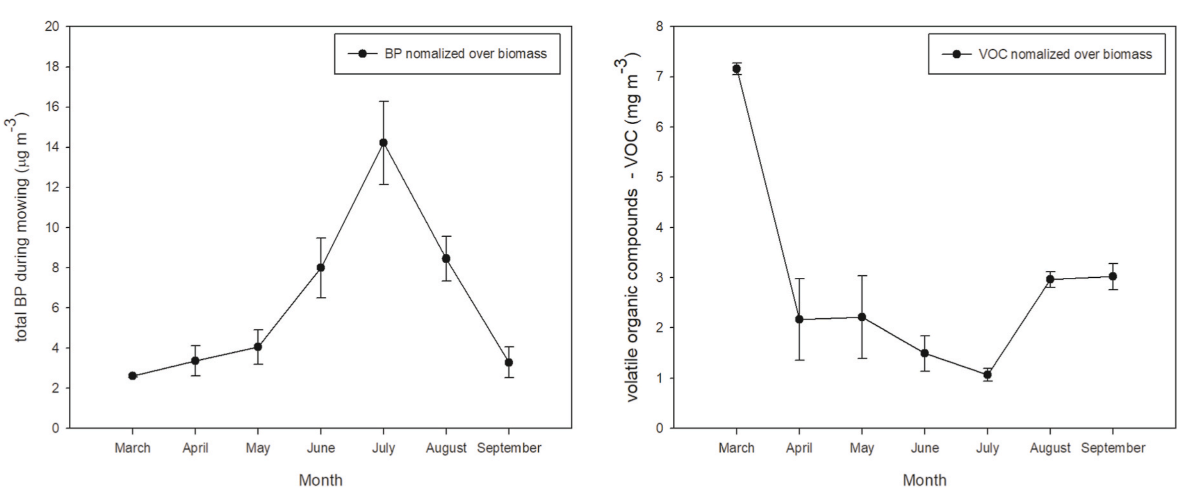

Fig. 3. Emissions during mowing normalized by grass mass removed (per gram of fresh weight); total PM represents the sum of PM_1, $PM_{2.5}$, and PM_{10}; VOC stay for volatile organic compounds; data are means of three independent replicated; error bars are standard errors (n = 3).

strong positive correlations with one another (r = 0.97–0.996), indicating that they respond coherently to the mowing operation and likely originate from the same mechanical fragmentation processes. This tight coupling is consistent with previous observations of mowing-induced aerosols, where co-generation of fine and coarse biological debris is attributed to tissue disruption and canopy disturbance (Drewnick et al., 2008; Comtois et al., 1995). In contrast, VOC concentrations show no meaningful correlation with particulate emissions (r ≈ 0.05–0.11), reinforcing the interpretation that VOCs and PM fractions arise from largely independent physiological and mechanical processes. While particulates are mainly a product of physical shredding of plant tissues, VOCs reflect biochemical wound responses and volatilization pathways (Karl et al., 2001; de Gouw et al., 1999). The lack of linear association across the full dataset suggests that changes in grass water status, tissue age, or environmental stress may uncouple mechanical fragmentation from chemical emissions, in line with prior findings that VOC release is highly sensitive to metabolic state and temperature rather than to mechanical load alone.

Environmental variables display moderate correlations with particulate levels: temperature correlates positively with all PM fractions (r ≈ 0.43–0.46), whereas relative humidity correlates positively but slightly more weakly (r ≈ 0.35–0.38). These trends likely reflect seasonal co-variation rather than direct causality, as warmer periods are associated with both higher mowing-day activity and lower moisture content of tissues, which may enhance brittleness and particle release. Conversely, VOC concentrations correlate negatively with both temperature (r = −0.12) and, more strongly, humidity (r = −0.45). The negative association with humidity is consistent with reduced volatilization under moist atmospheric conditions and with delayed diffusion from wet surfaces, as noted in previous studies on green leaf volatiles (Kirstine and Galbally, 2004).

6. Discussion

Seasonal meteorological dynamics played a central role in shaping the temporal patterns of both particulate matter and volatile organic compound (VOC) emissions observed in this study. The transition from early spring warming to the extremely wet conditions of June, followed by a warm but moderately rainy July, a prolonged dry period in mid-August, and the subsequent late-summer rainfall pulse, directly affected grass hydration status, tissue fragility, and metabolic activity. These environmental fluctuations are well known to modulate both mechanical particle detachment and biochemical volatile release, providing essential context for interpreting the measured emission variability across the season. At the within-event scale, VOC and particulate matter signals exhibited profoundly different temporal structures, reflecting their distinct physical origins. VOC concentrations formed a continuous and highly variable trace along the mower's trajectory, characterized by low-amplitude, rapid oscillations that never approached zero. This diffuse pattern suggests a combination of ongoing metabolic volatile release and environmental modulation by airflow, canopy architecture, and sensor movement. In contrast, particulate matter concentrations were dominated by a low near-background signal punctuated by a limited number of sharp, reproducible peaks occurring at specific points on the path. These impulsive peaks likely correspond to localized mechanical interactions between the blades and patches of denser or more desiccated biomass or to the disturbance of accumulations of cut material. The fundamentally different shapes of the two signals—diffuse and noisy for VOCs, intermittent and peak-driven for total PM —demonstrate that mowing-related emissions arise from distinct mechanistic pathways influenced by different spatial and operational drivers. The magnitude and dispersion of the observations are consistent with previous reports showing that emissions from managed grasslands vary widely at fine spatial and temporal scales (Fares et al., 2010; Klüpfel et al., 2022). The descriptive patterns observed here therefore provide an essential baseline for interpreting the broader seasonal trends, highlighting that any intra-seasonal signal must be evaluated against the backdrop of high short-term variability intrinsic to biogenic emissions.

The seasonal analyses further corroborate earlier findings indicating that emissions from grasses are strongly linked to environmental and physiological drivers, including temperature, radiation, and growth stage (Feng et al., 2018; Klüpfel et al., 2022). The marked variations observed in both PM and VOC emissions over the season strengthen the hypothesis that grass physiological status and weather-driven metabolic processes may modulate mowing-related emissions. Although direct physiological measurements (e.g., leaf area index, chlorophyll content, or plant water status) were not performed in this study, the observed seasonal patterns are consistent with variations in vegetation growth stage and environmental conditions across the mowing season. Importantly, normalization by the mass of mowed biomass—often used to reduce structural noise in emission data—did not diminish the seasonal signal.

This is well evidenced in Fig. 3, where the normalized data of total PM and VOC recorded during the mowing events have been plotted against the seasonal period. Total particulate matter emissions follow a pronounced mid-season peak, with a sharp maximum at the end of July followed by a rapid decline, indicating strong dependence on plant physiological conditions. VOC emissions, in contrast, start very high at early march and then drop markedly, stabilizing at lower values through mid-season before slightly increasing again toward late summer. Again, the divergent shapes of the two curves highlight that particulate and gaseous emissions respond to different biological and environmental drivers, thus confirming that intra-seasonal variability is a dominant factor governing mowing-related bio-emissions.

Finally, the correlation structure between VOC and particulate matter emissions provides further evidence for their mechanistic divergence. Weak or inconsistent correlations across the season indicate that particulate detachment and volatile release respond to different sets of drivers. This reinforces the rationale for treating the two emission classes separately and supports the central premise of the study: bio-emissions during lawn mowing fluctuate markedly across the growing season, and their temporal trajectories diverge across particle-based and volatile-based pathways.

A relevant methodological limitation of this study concerns the interpretation of particulate measurements. The optical particle counter used here quantifies total particulate matter on the basis of light-scattering principles and does not discriminate between biological and non-biological particles. Therefore, the PM fractions reported in this study represent total airborne particles generated during mowing and

Table 4
Pearson Correlation Matrix between experimental variables (n = 63).

	$PM_{2.5}$	PM_{10}	PM_1	VOC	TEMPERATURE	HUMIDITY
$PM_{2.5}$	1.00					
PM_{10}	0.99**	1.00				
PM_1	0.98**	0.97**	1.00			
VOC	0.07ns	0.05ns	0.11ns	1.00		
TEMPERATURE	0.45**	0.46**	0.43**	−0.12ns	1.00	
HUMIDITY	0.37*	0.38*	0.35*	−0.45**	0.66**	1.00

(*$p < 0.05$, **$p < 0.01$).

may include plant-derived fragments as well as resuspended dust or soil particles. Given the dense turf cover and regular irrigation regime of the study area, a substantial contribution from vegetation-derived material is plausible, but this was not directly verified through chemical, microscopic, or fluorescence-based characterization. In addition, VOC measurements were obtained using a photoionization detector (PID), which provides an integrated estimate of total volatile organic compounds based on ionization of organic molecules but does not allow compound-specific identification. Consequently, the discussion of the underlying emission mechanisms should be interpreted as indicative rather than chemically resolved. In addition, VOC measurements were obtained using a photoionization detector (PID), which provides an integrated estimate of total volatile organic compounds based on the ionization of organic molecules but does not allow compound-specific identification. Moreover, the response factors of PID sensors can vary substantially among different organic compounds depending on their ionization potentials. Consequently, the VOC concentrations reported here represent bulk volatile loads rather than the concentration of specific compounds, and the discussion of emission mechanisms should be interpreted as indicative rather than chemically resolved.

7. Conclusions

This study demonstrates that particulate matter and volatile organic compound emissions generated during electric lawn mowing exhibit strong and recurring intra-seasonal variability. These fluctuations persist even after normalizing emissions to the mass of grass removed, underscoring that the primary drivers are plant physiological stage, environmental conditions, and tissue mechanical properties, rather than mowing intensity alone. From an atmospheric perspective, the observed seasonal peaks—particularly in late spring and early summer—are relevant given the role of grass-derived VOCs, including green leaf volatiles and isoprenoids, in the formation of ozone and secondary organic aerosols. Periods of elevated mowing activity may therefore contribute to localized increases in reactive trace gases and aerosol precursors. Anticipated climate-change–induced shifts in temperature and precipitation regimes are likely to alter emission patterns further, highlighting the importance of incorporating biogenic emission dynamics into urban and peri-urban air-quality assessments. The results also have notable implications for worker exposure and occupational health. Both particulate matter and VOCs were consistently emitted at measurable levels during mowing, producing highly dynamic exposure conditions even in the absence of combustion-related pollutants. Particulate matter generated during mowing—potentially including plant fragments and other airborne particles, spores, and shredded leaf tissues—may trigger respiratory irritation or allergic reactions, particularly during periods of high physiological activity in grasses. Similarly, repeated short-range exposure to VOC plumes may induce sensory irritation or discomfort under warm, stagnant conditions. A key finding is that emission intensity is not directly proportional to the amount of biomass removed. As a consequence, operators may experience high exposure even during brief or relatively light mowing operations, depending on the seasonal status of vegetation. This challenges conventional exposure models, which often assume linear relationships between workload and pollutant generation. These insights motivate the development of evidence-based mitigation strategies, including:

- scheduling mowing during low-emission periods when operationally feasible;
- promoting the use of appropriate respiratory PPE;
- improving operator awareness of seasonal emission dynamics;
- exploring engineering solutions such as partial enclosures, suction-assisted cutting decks, or active interception technologies (e.g., ionizing rods) to reduce near-field exposure.

In conclusion, although electric mowers eliminate combustion emissions, they do not eliminate the particulate and chemical emission pulses associated with grass cutting. A more integrated approach—combining environmental monitoring, exposure management, and technological innovation—is needed to minimize both atmospheric impacts and operator health risks in settings where lawn maintenance is frequent and intensive.

CRediT authorship contribution statement

Piernicola Masella: Writing – original draft, Visualization, Supervision, Methodology, Conceptualization. **Ferdinando Corti:** Software, Formal analysis. **Agnese Spadi:** Software, Formal analysis, Data curation. **Alessandro Parenti:** Supervision, Methodology, Conceptualization. **Alessio Cappelli:** Software, Formal analysis, Data curation. **Giulia Angeloni:** Writing – review & editing, Validation, Software, Data curation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, AI-assisted language tools were used exclusively for English language editing and text polishing (ChatGPT version 5.3, OpenAI; accessed between December 2025 and March 2026). The authors reviewed and edited the output and take full responsibility for the content of this publication.

In addition, the graphical abstract was developed with the assistance of an AI-based image generation tool (Gemini 3 Flash, Google), which was used to support the visual representation of the study findings and propose the graphical layout. The conceptual structure, selection of results, and scientific interpretation were fully defined and verified by the authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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