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Original Paper

Nitrous Oxide Removal from Cattle Manure Emissions Using Inorganic and Carbon-Based Adsorbents: A Statistical and Machine Learning Approach

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Abstract

Nitrous oxide (N_2O) emissions from agriculture and livestock significantly contribute to climate change. Consequently, reducing emissions from livestock waste is crucial. This study aimed to assess the removal of N_2O emitted from cattle manure using various adsorbent materials. Nine adsorbents—bentonite, vermiculite, zeolite, pumice, perlite, colemanite, activated carbon, graphite, and boron nitride—were evaluated over 24 days in a total of 10 laboratory-scale reactors, including a control reactor. Each reactor was loaded with 1,000 g of cattle manure; gas samples were measured daily, and the data were analyzed using the Shapiro-Wilk, Levene, Kruskal-Wallis, discriminant analysis, time-series clustering, and random forest methods. The Kruskal-Wallis test indicated no significant difference between the reactors and the control (p=0.416). Time-series clustering identified temporal differences only for pumice and graphite. The random forest analysis predicted a decreasing trend for activated carbon and increasing trends for pumice and perlite. The findings suggest that, over a 24-day monitoring period, the adsorbent types did not exhibit a statistically significant advantage in N_2O removal, highlighting the need for longer-term and multiparameter monitoring.

Keywords

Climate Change, Greenhouse Gases, Nitrous Oxide, adsorbent, Cattle Manure

1. Introduction

It is predicted that in the near term, every region in the world will face a further increase in hazards caused by climate change following global warming, which will increase many risks to ecosystems and people (IPCC, 2023). Climate change is extremely affected by human activities and the atmospheric emissions triggered by these activities (Boggiaa et al., 2019).

Agriculture, forestry, and other land use (AFOLU) are estimated to have contributed 22% of total greenhouse gas emissions between 2010 and 2019. Emissions of agricultural methane (CH_4) and nitrous oxide (N_2O) are estimated at 4.2 GtCO2-eq yr-1 and 1.8 GtCO2-eq yr-1, respectively. Nitrous oxide accounts for 69% of the total net anthropogenic emissions from AFOLU.

Today, agricultural practices are based on intensive livestock production in closed facilities and the application of stored waste to land as organic fertilizer (Broucek, 2017). The main source of (N_2O) is agricultural soil management and waste management from livestock farming. Also, inorganic nitrogen fertilizers cause increased emissions of N_2O (Zhong et al., 2022). Livestock, which meets the increasing food demand, contributes to global warming by significant amounts of N_2O (Schils et al., 2013). N_2O emissions from agriculture mainly caused by storage of urine and dung on pasture and rangelands and manure application (Van der Weerden et al., 2021).

CH_4 and N_2O are produced as a result of the anaerobic digestion of organic matter in the rumen of ruminant animals. Moreover, N_2O is formed by the nitrification and denitrification of organic substance in manure stored under aerobic and anaerobic conditions (Broucek, 2018). Nitrification is a essential prerequisite for the formation of N_2O emissions in fertilizer stores where ammonia nitrogen oxidizes to nitrate and nitrogen in aerobic condition. Unlike, denitrification occurs under anaerobic conditions and nitrites and nitrates are turn into N_2O and dinitrogen (N_2). The amount of N_2O emission depends on carbon and nitrogen constituent, the system type and continuance of manure management (Jose et al., 2016).

N_2O is the most contributor gas to greenhouse effect after CO_2 and CH_4 (Utami et al., 2012). It is extremely stable, and its residence time in the atmosphere is 100-150 years (Utami et al., 2012). On a 100-year time scale, the global warming potential of N_2O is approximately 300 times higher than CO_2 (Fukumoto et al., 2006). Due to its long lifetime in the atmosphere, causes global warming by absorbing infrared radiation (Schils et al., 2013; Skiba & Rees, 2014) and contribute to the depletion of stratospheric ozon layer by acting similarly to chlorofluorocarbons (CFCs) (Ballesteros-Plata et al., 2022). Interest in N_2O sources has stirred up in recent years as it became clear that it has a significant impact on the earth (He et al., 2001). Although N_2O is a natural trace gas in the earth's atmosphere (Schils et al., 2013), since 1750 its increase has been 23% in 2019 and its concentration reached 332 ppb (IPCC, 2023).

The IPCC (2023) report states that some non-CO_2 emissions from agriculture, such as CH_4 and N_2O, cannot be completely eliminated using current and projected technical measures. However, it is crucial importance to reduce N_2O emissions from livestock manure using an effective and low-cost method (IPCC, 2023). An alternative mitigation method of N_2O is the adsorption of these gases on to porous materials with small pores and narrow pore size distribution. Such porous materials act as a molecular sieve through solid-gas interaction during adsorption process. It has been demonstrated that economically accessible porous materials are effective and easy to use in gas adsorption (Ballesteros-Plata et al., 2022). The use of filters through mechanical ventilation will be an economical method of mitigation of N_2O emission from livestock facilities and manure storage units.

Most of the studies in the literature have focused on capturing of CO_2 and precursor greenhouse gas (GHG) emissions via adsorption. Even though there are several studies used raw and modified clay, activated carbon, natural and modified zeolite alternative adsorbent on volatile organic compounds (VOC_s) adsorption (Su-Jin et al., 2008; Jarraya et al., 2010; Manjare & Ghoshal 2006; Valdés et al., 2020). However, considering the harmful effects of N_2O, adsorption studies of N_2O on different filter media have been almost scarcely reported. Cornelissen et al. (2013) has shown that on C-based sorbents have stronger N_2O sorption than inorganic sorbents and metal oxides and also activated carbon have slightly strong sorption than biochar. Hernández Huesca et al. (2016) was studied adsorption kinetic of pure N_2O adsorbent on different zeolite type, *mordenite, clinoptilolite* at from 0°C to 100°C temperature. It was determined that the adsorption capacity zeolite greeter than clinoptilolite at 20°C. However, Clinoptilolite adsorption capacity reached the highest level with the increasing temperature (100 °C). Kloutse et al. (2020) was investigated N_2O, CO_2, CH_4 and N_2 single-component and quaternary mixture adsorption on Copper (II) Benzene-1, 3, 5- tricarboxylate Cu3(BTC)2, CuBTC. Single component adsorption decreased in the order N_2O, CO_2, CH_4 and N_2. In the mixed adsorbed phase, the results shown that the adsorption amount of each component in the equimolar quaternary mixture is much lower than the single component (Kloutse et al., 2020). In another study, the adsorption of N_2O and CO_2 on silica gel was investigated and compared with activated carbon. It was determined that adsorption mechanisms of N_2O and CO_2 on silica gel differented from activated carbon. Moreover, macropore diffusion contributed to the adsorption rate and provided a decrease in particle size by using silica gel (Park et al., 2020). The study for N_2O adsorption with modified graphene oxide (GO) surface (Mg-, Cu-, and Ag-) revealed that Cu-GO can used as strong adsorbent (Liu et al., 2019). studied three different commercial activated carbons at different temperatures to model adsorption-based processes for condensing tail-gas streams containing diluted N_2O or for recovering high concentration N_2O in exhausts from chemical plants by Peng et al. (2009).

While numerous studies have investigated the monitoring and treatment of N_2O across various environmental contexts, research specifically addressing the treatment of N_2O emissions from animal waste using biofilters remains scarce. Table 1 presents a summary of the limited research available in this area.

Utilizing the VOSviewer software tool, a bibliometric network has been established for keywords associated with the removal of N_2O using biofilters (Fig.1). As of December 2025, the Web of Science (WOS) database contains 109 publications, while the Scopus database includes 396 publications. The primary keywords identified in the bibliometric network are 'N_2O', 'gas', 'livestock', 'biofilter', and 'removal'. In the WOS graph, the red clusters emphasize the mechanisms of N_2O emission formation, concentrating on nitrification/denitrification and experimental N_2O processes. Conversely, the green clusters in the Scopus graph pertain to biofilters, N_2O, and removal. However, due to their low frequency, specific biofilter types do not appear in the main clusters. The green clusters predominantly illustrate more effective clusters concerning the effects of biofilter N_2O removal.

Table 1. Literature Review on the Removal of N_2Os from Livestock Using Adsorbent Materials

Source	Biofilter	Time (days)	Emission Flux		References
			Control Group	Biofiltre Group	
Pig manure	Bentonite	43	365.72 mg/kg	258.12 mg/kg	Wu et al. 2023
Compost	Pumice	81	0.3 g/m^3.day	0.2 g/m^3.day	Tung et al. 2021
Pig manure	Wood chips Compost	120	550 ppb/day	686 ppb/day	Janni et al. 2014
Poultry litter manure*	Bentonite Biocar Compost	300	0.84 kg	9.74 kg 7.48 kg 15.65 kg	Westermann et al. 2021
Cattle manure*	Grass-Clover	77	0.78 kg	1.20 kg	Meng et al. 2023
Cattle manure	Various	24	2559 ppb	1956-2593 ppb	This study

*: Units are per hectare

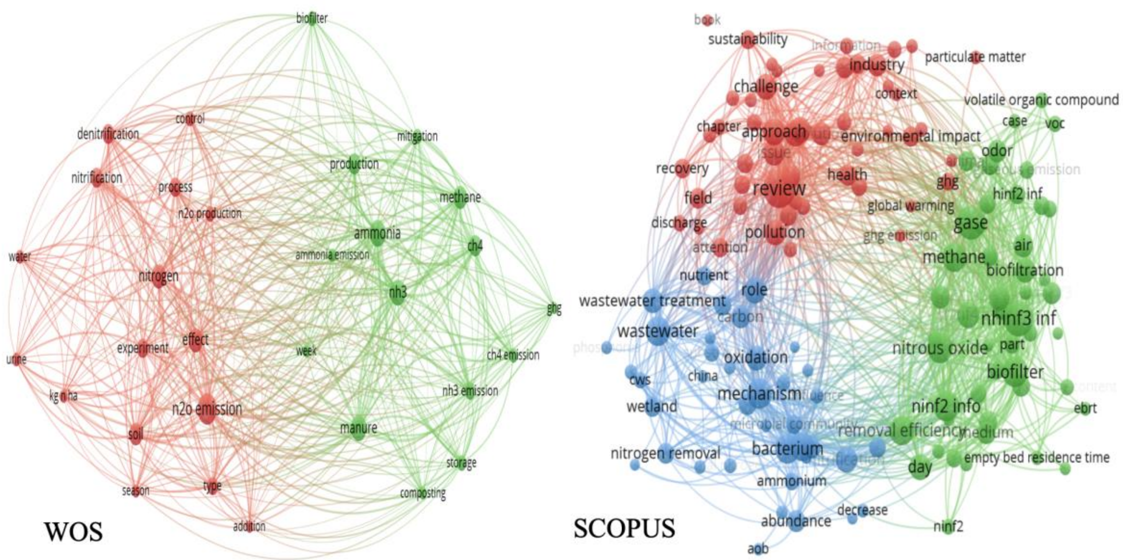


Figure 1. Analysis and Visualization of Keyword Networks Related to N_2O, Gas, Livestock, Biofilter, and Removal, Utilizing Data from Web of Science (WOS) and Scopus

In this study, it is investigated that N_2O gas emission from cattle manure is caught on a filter media which perform as a molecular sieve. The objective of the present study is to compare the gas concentrations obtained from the upper surface of packed columns created with different filter materials (bentonite, vermiculite, zeolite, pumice, perlite, colemanite, activated carbon, powder carbon, and Boron Nitride).

2. Materials and Methods

2.1 Experimental Setup Preparation and Sampling

The present study was conducted utilizing laboratory-scale reactors constructed from polypropylene PP8 plastic material. These reactor cabinets are uniform in size and possess a trapezoidal cross-section, with a volume of 1.45 m³. Cattle manure, sourced from the cattle farm facility at the Faculty of Agricultural, Ondokuz Mayis University, Samsun, Turkey, was sorted prior to the addition of approximately 1 kg to each reactor. The gas generated within the reactors was expelled through a 2.0 cm diameter aperture located at the top of the reactor, and measurements were conducted via this opening. The reactors were continuously supplied with air using a pump with a flow rate of 72 L/hour. The experimental procedure spanned 24 days, with daily measurements being recorded. Each reactor received an addition of 1000 grams of cattle manure, resulting in a manure height of 80 cm. Initial temperature measurements were conducted within the reactors, revealing an average initial temperature of 20.82 °C across the 10 reactors.

2.2 Properties of Porous Materials

The adsorbent materials were procured from various commercial suppliers. Table 2 presents the general characteristics of these adsorbent materials.

Table 2. Measured and Typical Values of Biofilters Used in Experiments

Properties	Bentonite	Vermiculite	Zeolite	Pumice	Perlite	Colemanite	Activated Carbon	Graphite	Boron Nitride
SiO_2 (%)	61.0	41.3	71.0	73.4	72.9	30.5	-	-	0.1
Limit Oxygen Index LOI	6.0	5.0	6.9	3.7	1.0	2-4	-	-	1.0
Surface Area (m^2/g)	30-70	5-15	30-50	1-5	1-3	<1	800-1200	5-20	10-40
Pore Volume (cm^3/g)	0.05-0.15	0.1-0.2	0.15-0.25	~ 2	10-16	< 0.05	0.6-0.9	~ 0	~ 0
Bulk Density (g/cm^3)	0.85-1.10	0.08-0.16	0.7-0.9	2.3-2.5	1.0-1.2	2.4-2.45	0.25-0.4	0.2-0.4	0.3-0.6
Cation Exchange Capacity (meq/100 g)	60-90	100-130	180-220	200-500	1.5-3.0	~ 0	~ 0	~ 0	~ 0
Diameter (µm)	<40	100-300	-	0-63	30-150	1-5	1500	<50	30-50

Carbon Basis (%)	<1	< %0.1 - %0.5	~ 0	~ 0	~ 0	12-13	90.0 ≥	99.9 ≥	~ 0
Supply	Edirne, Türkiye	Sivas, Türkiye	Manisa, Türkiye	İzmir, Türkiye	İzmir, Türkiye	İzmir, Türkiye	Milipore Germany /102514	Superco USA /104206	Balıkesir Tükiye

2.3 Sampling and Analysis Method

The experiments were conducted using reactors with a trapezoidal cross-section. Each reactor was supplied with air at a flow rate of 72 L/min using an aquarium pump from the bottom. Equal quantities of cattle manure were incorporated into the reactors, with the waste reaching a height of 80 cm. A 2 cm wide, leak-proof, filled column was positioned at the top of each reactor. This column, measuring 20 cm in height, contained 1 cm of glass fiber, 18 cm of adsorbent material, and an additional 1 cm of glass fiber, arranged sequentially from bottom to top. Gas discharge through the column was facilitated by a silicone hose, and the accumulated gas was collected in a Tedlar bag. At the conclusion of each day, the N_2O content in the gas collected in the Tedlar bag was quantified using the MIRAN SapphIRE-XL analyzer. This procedure was conducted across nine distinct biofilter reactors. Furthermore, as a control, N_2O measurements were directly performed in a reactor filled solely with cattle manure, omitting the use of a biofilter in the column. A graphical abstract of the experimental setup is shown in Figure 2.

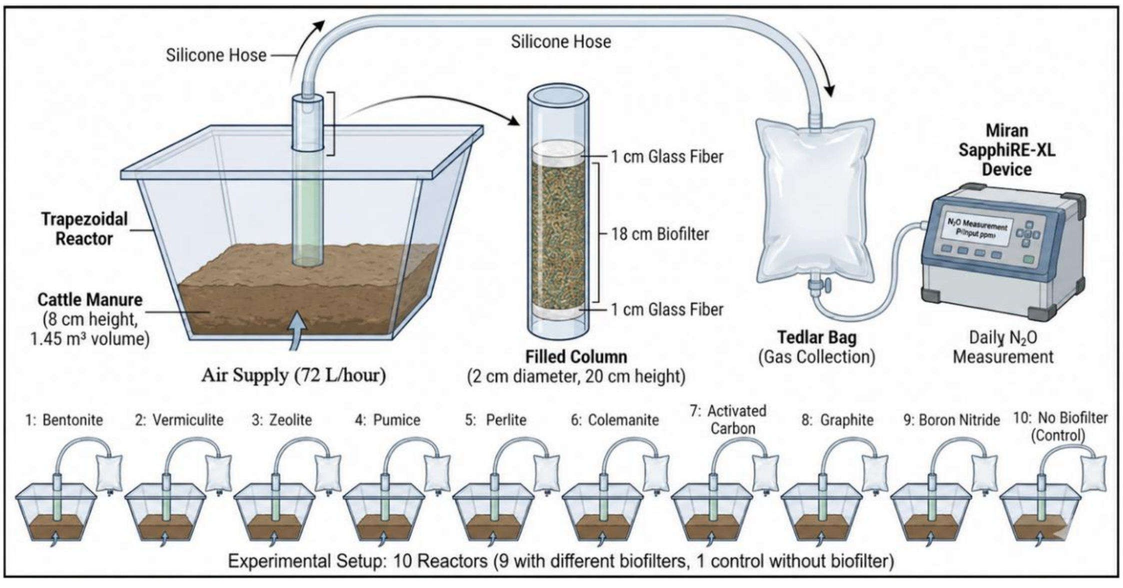


Figure 2. Schematic Design of Experimental Setup

The MIRAN SapphIRE-XL Ambient Air Analyzer, a portable infrared spectrophotometer manufactured by Thermo Electron Corporation, was employed to detect N_2O using the EPA-TO-16 method (EPA, 1999). The analyzer operates with a 60-second sampling interval, and the single gas analysis screen is updated every half-second. The operation is contingent upon the application in multigas mode or the activation of compensations. The concentration of N_2O is recorded by the Miran SapphIRE detector every 90 seconds, with a sample cell volume of 2.23 liters. Prior to commencing the experiments, the instrument was calibrated using standard gas. The instrument automatically initiates the zeroing process via the Installation Chemical Filter at the start of each analysis. Measurements of N_2O were conducted at a wavelength of 4500 nm. The device's maximum measurement limit (HRL) is 100 ppm, the detection limit (DL) is 0.04 ppm, and the measurement accuracy is ±10% per reading. Device calibrations were performed using the Cylinder to N_2O and SF6 Mixture in Air (PN: CR014LN) calibration kit every five days of measurement. Pre-experiment calibrations of the analyzer were performed using a calibration tube containing 80 ppm NH_3 and 5 ppm N_2O with an error range of ±1%.

2.4 Data Analysis

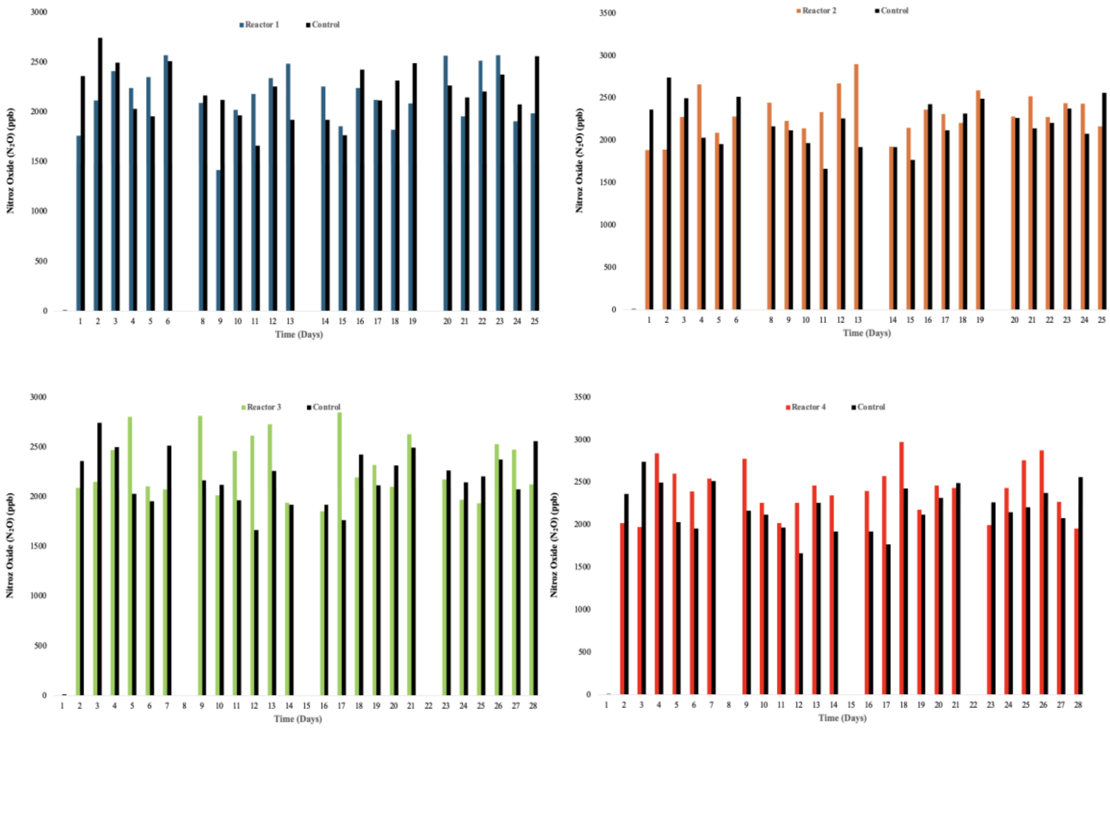
The Shapiro-Wilk test was employed to assess the normality of the data distribution. The Levene test was utilized to evaluate the homogeneity of variances among the reactor groups. The Kruskal-Wallis test was conducted to determine whether statistically significant differences existed between the reactors. Discriminant analysis was executed to identify which reactors were most distinctly separated from one another. Time series clustering, specifically k-means clustering, a data mining technique, was applied to categorise reactors exhibiting similar movement patterns. The random forest method, a machine learning approach, was employed to predict reactor data, addressing regression problems through ensemble learning. This technique involves training multiple decision trees using a random method and deriving the final decision by averaging their outputs. Statistical analyses were performed using IBM SPSS v31.0 and the MATLAB R2025b Regression Learner Toolbar.

3. Results and Discussion

The daily variations in N_2O levels within each biofilter were recorded over a 24-day period. These measurements were compared to the N_2O levels observed in the control group, which consisted of a reactor devoid of a biofilter. Basic statistical analyses, time series predictions, and random forest methods were employed for these comparisons. Figure 3 illustrates the comparison of each reactor's values with those of the control group. Assuming that the control group values represent the initial concentration (C_o) and the values measured at the conclusion of each day in each reactor represent the final concentration (C), the purification efficiency performances were as follows: bentonite, boron nitride, perlite, colomanite, vermiculite, zeolite, activated carbon, graphite, and pumice, respectively.

The temporal variation in N_2O (N_2O) formation in cow manure is influenced by several factors, including the manure's age, temperature, humidity, pH, oxygen levels, climatic conditions, pile height, acetylene presence, and microbial activity. In this investigation, fresh cow manure was introduced into the reactor. Initially, nitrogen compounds such as ammonium are anticipated to facilitate the rapid formation of N_2O. However, over time, N_2O formation exhibits fluctuations due to processes such as mineralization, denitrification, nitrification, and oxygen availability. Previous research has indicated that N_2O formation stabilizes within approximately 60-80 days for animal waste, with sudden increases observed post the

80th day (Yang et al., 2013). Consequently, in our study, a sudden increase in N_2O is not anticipated within the selected 24-day time series across all reactors. Temperature emerges as the most critical factor influencing N_2O formation. Microbial activity, which plays a role in nitrification and denitrification, leads to an increase in N_2O levels up to a certain threshold with rising temperatures (Zhang et al., 2017). In this study, the average temperature within the reactors was recorded at 20.82 °C. Given the absence of temperature fluctuations due to continuous air supply, the temperature effect was not considered. Soil moisture significantly impacts N_2O formation through nitrification and denitrification processes (Zhou et al., 2020). However, due to the continuous air supply provided to all reactors for gas transport, moisture content remained stable and was thus not considered. The pH level, effective in N_2O formation in biofilters, generally remains neutral (6-8) (Yang et al., 2013). As the pH in the reactors ranged between 6 and 8, its relationship with N_2O was not examined. Acetylene, which facilitates the reduction of N_2O to N_2, decreases N_2O levels in biofilters, particularly due to air supply and the creation of an oxygenated environment (Maia et al., 2012). It is posited that the continuous air supply in the reactors induces acetylene-related nitrification (incomplete nitrification) and a reduction in N_2O levels.



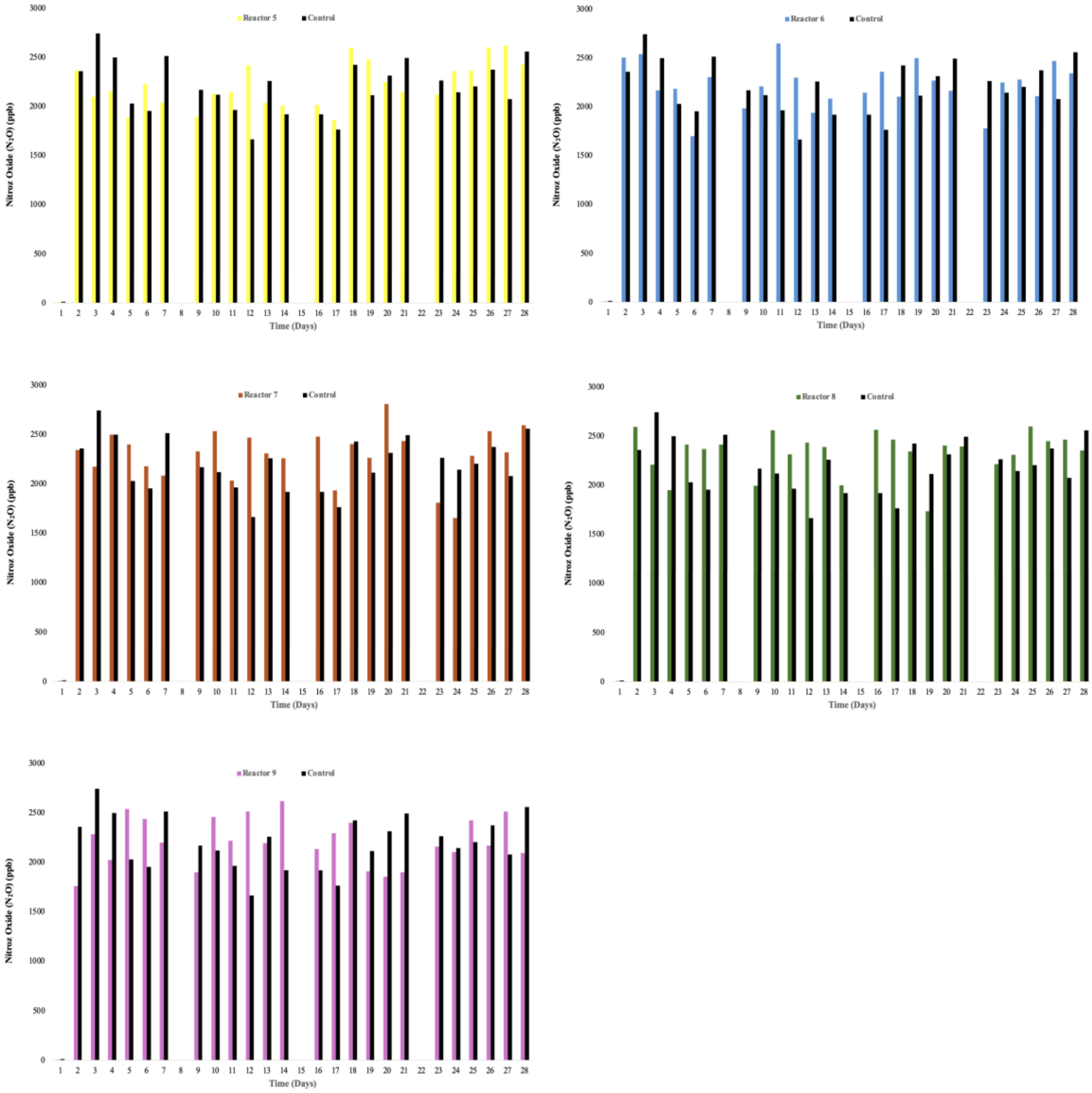


Figure 3. Temporal Changes in Reactors with Different Adsorbent Materials Control Group

3.1 Basic Statistical Analysis

When examining the box plots in Figure 4, it is evident that the median lines of each reactor are very close to one another, and the box distributions overlap.

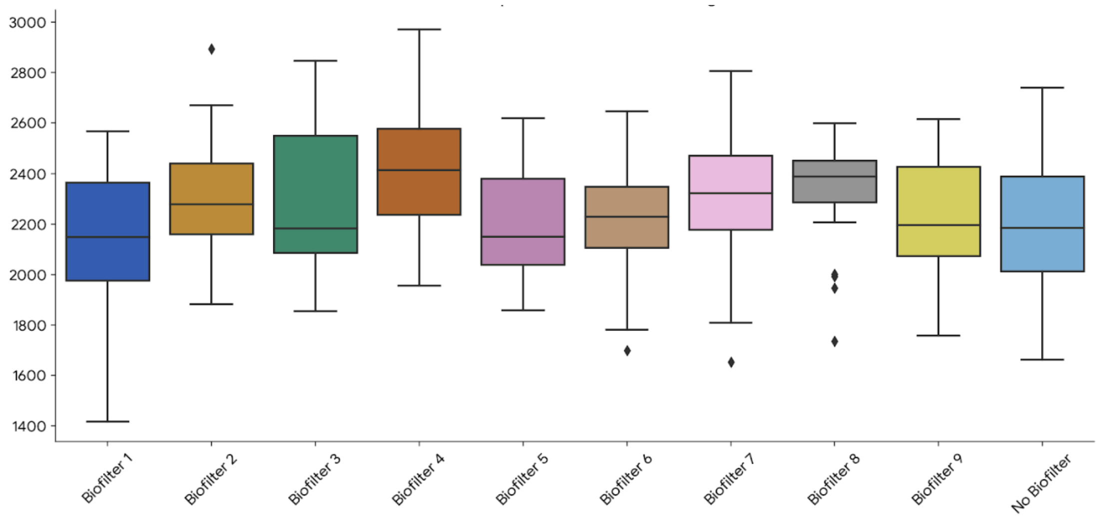


Figure 4. Box Diagram of Biofilters Used in Reactors

Normality was assessed using the Shapiro-Wilk test. The Levene test was employed to evaluate the homogeneity of variance across groups, resulting in a p-value of 0.416, which exceeds the threshold of 0.05. This outcome suggests that the variances are homogeneous, rendering the reactor groups comparable. Subsequently, the Kruskal-Wallis test was applied to determine whether a general difference existed among all reactors. The test statistic of 0.099, each is greater than 0.05, indicates the absence of a statistically significant difference among the reactors. Pairwise comparisons between the control group (Reactor 10) and the other groups were conducted using the Bonferroni correction. No significant differences were observed in comparisons with the control group, except for Reactor 4. However, the difference for Reactor 4 was not statistically significant after correcting for multiple testing errors. Consequently, there is no statistically significant difference between the nine different biofilter groups and the control group. Although numerical differences were noted in Reactors 4 and 8, these differences are not statistically significant. A Dunnett post-hoc test was conducted to compare the control group with the other reactors. The results indicate no significant difference between each reactor and the control group at the 0.05 significance level ($p > 0.05$).

Discriminant analysis offers a more effective framework for distinguishing between groups and demonstrates greater tolerance for limited data. The Wilks' lambda value was determined to be 0.928. Given its proximity to 1, this suggests that the reactor and control groups are not distinctly separated. However, since the significance level (Sig. = 0.041) is less than 0.05, the difference between the reactor and control groups is statistically significant. Upon examining the eigenvalues table to assess the model's explanatory power, the canonical correlation coefficient was found to be 0.269. The square of this coefficient indicates the proportion of variance in N_2O within reactors that is accounted for by the model. Specifically, $R^2 = (0.269)^2 = 0.072$, indicating that 7% of the variance among reactors is explained by the N_2O data, thus reflecting a weak explanatory power of the model. Analysing the group-centred function table to determine each reactor's position on the discriminant function, the z-score for the control group is -0.248. The z-score closest to the control group is that of the 10th reactor group (-0.209), rendering the control group and the 10th reactor group indistinguishable. Conversely, the reactor group most distant from the control group is the 5th reactor (z = 0.536), which is distinctly separated from the control group. Ranking the reactors by their z-scores in relation to their proximity to the control group, the sequence is as follows: -0.209 (Bentonite), -0.183 (Colomite), -0.171 (Activated Carbon), -0.408 (Vermiculite), 0.116 (Graphite), 0.16 (Pumice), 0.165 (Zeolite), 0.243 (Boron Nitride), and 0.536 (Perlite). Consequently, the 10th reactor exerted the greatest influence on the control group, whereas the 5th reactor exerted the least.

3.2 Time Series Clustering

The methodology employed involved comparing the 25-day performance trajectories of N_2Os across 10 reactors. The control reactor was designated as a single cluster, while the remaining reactors were categorized as a second cluster. The dynamic time warping distance was assessed using k-Means Clustering, facilitating the grouping of reactors based on their performance metrics. The k-Means clustering analysis revealed that a p-value of less than 0.05 signifies a statistically significant difference between clusters. Notably, a significant difference was observed between clusters for each variable across all reactors, except for reactors 5 and 8, where no significant difference was detected. Table 3 summarises the basic statistical analyses between reactors.

Table 3. Results of Statistical Analysis between Reactors

Reactors	**Normality Test (Shapiro-Wilks)**			**One Way ANOVA (Dunnett Post-Hoc)**		**Functions at Group Centroids**	**K-Mean Clustering (ANOVA)**	
	W	**p-value**	**Adjusted p-value**	**Mean Difference**	**p-value**	**z score**	**F**	**p-value**
Control	0.989	0.995	1.000	-	-	-0.248	4.576	0.009
1	0.959	0.428	1.000	-41.79	0.998	-0.408	5.582	0.004
2	0.972	0.729	1.000	108.04	0.623	0.165	3.210	0.036
3	0.920	0.059	1.000	106.75	0.636	0.160	13.498	< 0.001
4	0.955	0.352	0.193	204.83	0.049	0.536	2.689	0.063
5	0.950	0.264	1.000	16.92	1.000	-0.183	1.030	0.417
6	0.976	0.808	1.000	20.04	1.000	-0.171	3.769	0.020
7	0.959	0.412	1.000	95.17	0.751	0.116	3.472	0.027
8	0.877	0.007	0.558	128.29	0.428	0.243	1.328	0.296
9	0.962	0.483	1.000	10.29	1.000	-0.209	3.922	0.017

3.3 Random Forest

The Random Forest was used to examine which reactor showed a decrease in N_2O levels during which time period. The reactor with the greatest effect on N_2O removal was investigated. For this purpose, the Random Forest analysis was examined using the Regression Leaner method in Matlab. Figure 5 shows the RMSE (Root Mean Square Error) and Response Plot graph. According to the analysis results, the RMSE value was determined to be 267.62. The Normalized Error (NRMSE) of the model is approximately 17.2% of the data range. Accordingly, it shows that the model's ability to distinguish between the overall performance differences between reactors is at an acceptable level. In other words, the model cannot simulate the high standard deviation in the data. By overlaying the model predictions on the response graph in Figure, an attempt was made to identify which reactor had the deviation. The blue colors represent the measured N_2O values, and the yellow colors represent the predicted values from the Random Forest model. The measured values have a wide range for each reactor and exhibit high variance. According to the graph, the predictions fail to capture the wide distribution of the measured data. This indicates that the model has not learned the instantaneous changes in the reactors. One possible reason for this is that reactor data should consider not only temporal variation but also other influencing factors (such as pH, temperature, etc.). However, it has been successful in simulating the average behavior based on model reactors. In summary, the machine learning algorithm used has shown that it can distinguish the systematic effects of adsorbent materials, rather than instantaneous noise, with a trend parallel to the actual data distribution, such as the decrease in the 7th reactor and the increase in the 4th and 5th reactors.

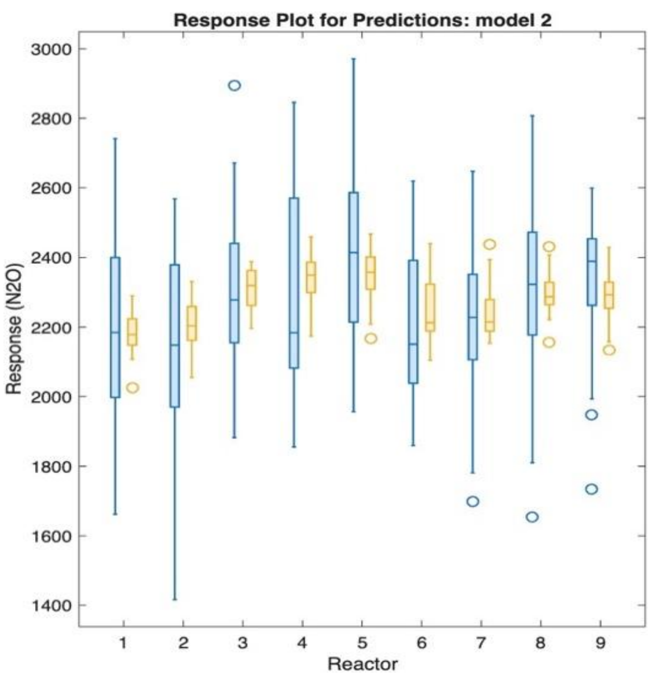


Figure 5. Random Forest

4. Conclusion

Given the efficacy of N_2O as a greenhouse gas, its monitoring and regulation are crucial for mitigating climate change and global warming. Livestock facilities are significant sources of atmospheric N2O emissions, necessitating control measures within these environments. Consequently, a study was conducted under laboratory conditions to evaluate the effectiveness of various natural filters in removing N_2O. Cattle manure served as the N_2O source. Emissions from cattle manure were systematically collected over a 24-day period and treated in a packed column containing a biofilter. The adsorbent materials included bentonite, vermiculite, zeolite, pumice, perlite, colemanite, activated carbon, graphite, and boron nitride. For control purposes, one reactor was devoid of adsorbent material. Upon examining the temporal variation of N_2O over the 24-day period across all reactors, no significant differences were observed that could be attributed to the type of biofilter. This lack of differentiation is attributed to the fluctuations in N_2O levels due to nitrification and denitrification processes over the 90-day period, indicating that the 24-day measurement was insufficient to capture abrupt changes. As the process did not involve composting, parameters such as temperature, humidity, pH, and other pollutants were not monitored, rendering comparisons with composting studies inadequate. Statistical analysis using the Kruskal-Wallis test revealed no significant differences between the nine biofilter groups and the control group. Although numerical differences were noted in pumice and graphite, these were not statistically significant. Discriminant analysis indicated that the control group and boron nitride yielded similar results. Biofiltering with perlite demonstrated the highest N_2O removal efficiency, followed by graphite, zeolite, pumice, activated carbon, vermiculite, colemanite, and perlite. In time series clustering, numerical differences were observed in pumice and graphite, yet these differences lacked statistical significance. The Random Forest analysis identified the reactor with the most substantial impact on N_2O removal. The machine learning algorithm employed was capable of distinguishing trends consistent with the actual data distribution, such as the decrease in the activated carbon reactor and the increase in the pumice and perlite reactors. In conclusion, while the study assessed the relationship between N_2O and adsorbent materials with the available resources, it determined that biofilters should be primarily evaluated concerning temperature, humidity, oxygen, and other pollutant parameters, considering their absorption capacities, and that monitoring should extend for a minimum of three months. In addition, when evaluating the relationship between nitrogen oxides and biofilter types using existing resources, the study concluded that biofilters should be assessed primarily based on temperature, humidity, oxygen, and other contaminant parameters, considering their absorption capacities. Emissions from cow manure contain various concurrent gas components present in high concentrations, including water vapor, ammonia (NH_3), hydrogen sulfide (H_2S), and VOCs. Due to the limitations of the single-gas monitoring system used in this study, the real-time concentrations of these gases could not be quantitatively determined. However, it is widely reported in the literature that molecules with high polarity, such as water vapor and ammonia, exhibit a higher affinity for the active sites and surface functional groups of porous adsorbents compared to the relatively stable N_2O molecule. Therefore, it is thought that other gas components present in the environment may have rapidly saturated the available pores on the adsorbent surface or blocked the active adsorption sites. This competitive adsorption mechanism may have significantly suppressed the N_2O adsorption capacity of all the filter materials examined. Consequently, it is assessed that the most likely explanation for the statistically insignificant effect observed among different filter media is competitive adsorption occurring in a multicomponent gas environment. For future studies, it is recommended to use simultaneous multi-gas analyzers to elucidate this mechanism in detail and to investigate the surface properties of the adsorbent materials using advanced characterization methods such as FTIR and XRD.

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Ethical Approval

The work on the manuscript met all ethical standards required for research publication and no experiments with animals were carried out. Human begins were not studied in this work.

Availability of data and materials

Data available on request from the authors

Generative AI and AI-assisted technologies in the writing process

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References

Ballesteros-Plata D., Cecilia J. A., Barroso-Martín I., Jiménez-Jiménez J., Infantes-Molina A., & Rodríguez-Castellón E. (2022). Materials Design for N_2O Capture: Separation in Gas Mixtures. *Catalysts*, *12*, 1539.

Boggiaa A., Paolottia L., Antegiovannib P., Fagiolia F. F., & Rocchia L. (2019). Managing ammonia emissions using no-litter flooring system for broilers: Environmental and economic analysis. *Environmental Science and Policy*, *101*, 331-340.

Broucek J. (2018). Nitrous Oxide Release from Poultry and Pig Housing. *Pol. J. Environ. Stud.*, *27*(2), 467-479.

Broucek J. (2017). Nitrous oxide production from cattle and swine manure. *Anim Behav Biometeorol, 5,* 13-19.

Cornelissen G., Rutherford D. W., Arp H. P. H., Dörsch P., Kelly C. N., & Rostad C. E. (2013). Sorption of Pure N2O to Biochars and Other Organic and Inorganic Materials under Anhydrous Conditions. *Environ. Sci. Technol.*, *47*, 7704-7712.

Fukumoto A., Suzuki K., Osada T., Kuroda K., Hanajima D., Yasuda T., & Haga K. (2006). Reduction of Nitrous Oxide Emission from Pig Manure Composting by Addition of Nitrite-Oxidizing Bacteria. *Environ. Sci. Technol*., *40*, 6787-6791.

He Y., Inamori Y., Mizuochi M., Kong, H., Iwami N., & Tiehng, S. (2001). Nitrous Oxide Emissions from Aerated Composting of Organic Waste. *Environ. Sci. Technol*., *35*, 2347-2351.

Hernández Huesca R., Pérez Arcos J., Vargas Hernández D., & Pérez Cruz M. A. (2016). Adsorption Kinetics of N_2O on Natural Zeolites. *Rev. Int. Contam. Ambie*., *32*(2), 237-242.

IPCC. (2023). Climate Change 2023 Synthesis Report. (Ed.) H. Lee and J. Romero, Geneva, Switzerland, 184 pp.

Jarraya I., Fourmentin S., Benzina M, & Bouaziz S. (2010). VOC adsorption on raw and modified clay materials. *Chemical Geology*, *275*, 1-8.

Janni, K. A., Jacobson, L. D., Hetchler, B. P., Oliver, J. P., & Johnston, L. J. (2014). Semi-Continuous Air Sampling versus 24-Hour Bag Samples to Evaluate Biofilters on a Swine Nursery in Warm Weather. *Transactions of the ASABE*, 1501-1515. https://doi.org/10.13031/trans.57.10653

Jose V.S., Sejian V., Bagath M., Ratnakaran A.P., Lees A.M.., Al-Hosni Y.A.S., Sullivan M., Bhatta R., & Gaughan J. B. (2016). Modeling of Greenhouse Gas Emission from Livestock. *Fronteries in Environmental Science*, *4*, 1-10.

Kloutse F. A., Gauthier W., Hourri A., Natarajan S., Benard P., & Chahine R. (2020). Study of competitive adsorption of the NN_2O-CO_2-CH_4-N_2 quaternary mixture on CuBTC. *Separation and Purification Technology*, *235*, 116211.

Liu Z., Xi-ren C., Yang Y., Jia H., Bai B., & Zhao Li. (2019). DFT Study of N_2O Adsorption onto the Surface of M-Decorated Graphene Oxide (M = Mg, Cu or Ag). *Materials*, *12*, 2611.

Maia, G. D. N., Gates, R. S., Day V, G. B., & Taraba, J. L. (2011). Ammonia biofiltration and nitrous oxide generation during the start-up of gas-phase compost biofilters. *Atmospheric Environment*, *46*, 659-664.

Manjare S. D., & Ghoshal A. K. (2006). Studies on Adsorption of Ethyl Acetate Vapor on Activated Carbon. *Ind. Eng. Chem. Res*., *45*, 6563-6569.

Meng, X., Sørensen, P., Møller, H. B., & Petersen, S. O. (2023). Greenhouse gas balances and yield-scaled emissions for storage and field application of organic fertilizers derived from cattle manure. *Agriculture Ecosystems & Environment*, *345*, 108327.

Park D., Hong S-H., Kim K.-M., & Lee C.-H. (2020). Adsorption equilibria and kinetics of silica gel for N_2O, O2, N_2, and CO_2. *Separation and Purification Technology*, *251*, 117326.

Peng Y., Zhang F., Xu C., Xiao Q., Zhong Y., & Zhu W. (2009). Adsorption of Nitrous Oxide on Activated Carbons. *J. Chem. Eng. Data*, *54*, 3079-3081.

Schils R. L. M., Eriksen J., Ledgard S. F., Vellinga Th. V., Kuikman P. J., Luo J., Petersen S. O., & Velthof G. L. (2013). Strategies to mitigate nitrous oxide emissions from herbivore production systems. *Animal* (2013), *7*(s1), 29-40.

Sciba U. M., & Rees, R. M. (2014). Nitrous oxide, climate change and agriculture. *CAB Reviews*, *9*(010), 1-7.

Skiba U. M., & Rees R. M. (2014). Nitrous oxide, climate change and agriculture. *CAB Reviews*, *9*(010).

Su-Jin P., Kim Y., & Yeo S. (2008). Vapor Adsorption of Volatile Organic Compounds Using Organically Modified Clay. *Separation Science and Technology*, *43*, 1174-1190.

Tung, N. T., Chiemchaisri, W., Chiemchaisri, C., & Sanguanpak, S. (2021). Removal of greenhouse gas in biofilter using organic and inorganic media. *Ministry of Science and Technology Vietnam*, *63*(1), 83-89.

Utami T. S., Hermansyah H., & Nasikin M. (2012). Biofiltration of Nitrous Oxide Using Cow-Manure Based Compost as Medium Filter. *Journal of Environmental Protection*, *3*, 584-588.

Valdés H., Riquelme A., Solar V. A., Azzolina-Jury F., & Thibault-Starzyk F. (2020). Removal of chlorinated volatile organic compounds onto natural and Cu-modified zeolite: the role of chemical surface characteristics in the adsorption mechanism. *Separation and Purification Technologies*, *258*(2), 118080.

Van der Weerden T. J., Noble A., de Klein C. A. M., Hutchings N., Thorman R. E., Alfaro M. A., Amon B., Beltran I., Grace P., Hassouna M., Krol D. J., Leytem A. B., Salazar F., & Velthof G. L. (2021). Ammonia and nitrous oxide emission factors for excreta deposited by livestock and land-applied manure. *Journal of Environmental Quality*, *50*, 1005-1023.

Yang, L., Wang, X., & Funk, T. L. (2013). Strong influence of medium pH condition on gas-phase biofilter ammonia removal, nitrous oxide generation and microbial communities. *Bioresource Technology*, *152*, 74-79.

Westermann, M., Brackin, R., Robinson, N., Cajas, M. S., Buckley, S., Bailey, T., Redding, M., Kochanek, J., Hill, J., Guillou, S., Freitas, J. C. M., Wang, W., Pratt, C., Fujinuma, R., & Schmidt, S. (2021). Organic Wastes Amended with Sorbents Reduce N2O Emissions from Sugarcane Cropping. *Environments*, *8*(8), 78.

Wu, J., Li, M., Wang, Y., Lin, S., Hu, R., & Xiang, R. (2023). Impact of bentonite on greenhouse gas emissions during pig manure composting and its subsequent application. *Journal of Environmental Management, 344*, 118453.

Zhang, Y., Ji, G., & Wang, R. (2017). Quantitative responses of nitrous oxide accumulation to genetic associations across a temperature gradient within denitrification biofilters. *Ecological Engineering*, *102*, 145-151.

Zhong L., Li G., Qing J., Li J., Xue J., Yan B., Chen G., Kang X., & Rui Y. (2022). Biochar can reduce N_2O production potential from rhizosphere of fertilized agricultural soils by suppressing bacterial denitrification. *European Journal of Soil Biology*, *109*, 103391.

Zhou, Y., Hu, B., Zhang, W., Zhang, Y., Zhang, Y., & Zhang, T. (2020). Nitrous oxide emission from stormwater biofilters in alternating dry and wet weather. *Environmental Research*, *191*, 110137.