CHEMICAL ENGINEERING TRANSACTIONS

VOL. 112, 2024

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Selena Sironi, Laura Capelli
Copyright © 2024, AIDIC Servizi S.r.l.
**ISBN** 979-12-81206-13-7; **ISSN** 2283-9216

DOI: 10.3303/CET24112006

# Experimental Study on Italian Regulatory Wind Tunnel: Performance Evaluation and Critical Aspects

Luca Carrera, Francesca Tagliaferri, Marzio Invernizzi*, Selena Sironi

Politecnico di Milano, Department of Chemistry, Materials and Chemical Engineering “Giulio Natta”, Piazza Leonardo da Vinci 32, 20133 Milano, Italy
marzio.invernizzi@polimi.it

The surge of atmospheric contaminants due to industrial and population expansion has led to increased public concern over olfactory annoyance, particularly in residential areas adjacent to agricultural, industrial, and waste management facilities. Characterizing passive area sources, which lack defined flows, in terms of odor emissions, represents a challenging task, exacerbated by the dual role of wind as both a dispersal agent and driving force for emission. Many sampling devices have been developed over the past decades. In particular, Flux Chambers have a mixed headspace and a non-directional flow, and Wind Tunnels have a directional flow that is predominantly parallel to the inspected surface. Besides the significant differences between the two devices, the issue is further complicated by the variety of designs proposed within the same family. Wind tunnel designs have evolved from large, portable hoods to compact versions to improve portability and fluid dynamic performances. In particular, Low-Speed Wind Tunnels have gained traction due to reduced dilution within the hoods. The aim of this study is to investigate the fluid dynamics and mass transfer of the current Italian regulatory LSWT, mentioned by the Italian legislation, with the purpose of highlighting its strengths and limitations. Fluid dynamic analysis on this device reveals non-homogenous airflow distribution within the hood, indicating the presence of a preferential channel in the central body of the wind tunnel. Mass transfer analysis demonstrates a concentration gradient along the outlet duct’s vertical direction, possibly affecting sample representativeness. Future developments may aim to achieve uniform flow and concentration distribution, ensuring accurate odor emission assessments from passive area sources.

## 1. Introduction

The definition and development of methods to perform odor impact assessment has been the subject of extensive studies considering the increased interest in odor pollution among communities and municipal authorities (Brambilla & Navarotto, 2010; Claeson et al., 2013). Furthermore, since malodors are appearing in residential areas ever closer to the industries, people’s awareness of olfactory nuisances is arising (Henshaw et al., 2006; Zhao et al., 2015).

In this perspective, despite a certain simplicity and a clearly established methodology for the measurement of odor emission from point sources and active area sources, whereby the released airflow is typically conveyed and measurable. odor sampling on passive area sources remains a debated task. Indeed, the emission from passive area sources, such as wastewater treatment tanks, is driven by natural and forced convection enabled by wind (Beghi et al., 2012). In essence, wind drives the emissive process and acts as a dispersal agent in the atmosphere, complicating the study of odor emissions (Invernizzi et al., 2020; Tagliaferri et al., 2021, 2023, 2024) and requiring the design of instruments that can sample emissions without convective fluxes originating straight from the source. For these reasons, in order to estimate the odor emission rate from passive sources, an efficient sampling device should isolate a section of the surface to establish a defined control volume. Additionally, it should create particular fluid dynamic conditions that allow for the sampling of the outlet flow to estimate the specific emission rate.Many sampling devices have been developed over the past decades (Liu et al., 2022; Lotesoriere B.J. et al., 2022). However, the most widely used devices for the characterization of passive area sources are those associated with direct sampling techniques, which involve the use of open-

Paper Received: 31 March 2024; Revised: 10 May 2024; Accepted: 18 May 2024
Please cite this article as: Carrera L., Tagliaferri F., Invernizzi M., Sironi S., 2024, Experimental Study on Italian Regulatory Wind Tunnel: Performance Evaluation and Critical Aspects, Chemical Engineering Transactions, 112, 31-36 DOI:10.3303/CET24112006

bottom hoods that can be placed over the emissive surface and that provide an induced continuous sweep gas flow. These devices can be essentially subdivided into two families: Flux Chabers (FC) with a mixed headspace and a non-directional flow, and Wind Tunnels (WT) with a directional flow that is predominantly parallel to the inspected surface.

The scientific community still disagrees on which of these instruments should be used, which is reflected in various national regulation strategies (Bokowa et al., 2021; Guillot, 2012). Nevertheless, significant differences exist among the instruments. In fact, the choice between WT and FC can result in notably different emission rate estimates, further complicated by the variety of designs proposed within the same family (e.g. WT designs) (Hudson & Ayoko, 2009; Navaratnasamy et al., 2004; Tagliaferri et al., 2020).

Focusing on WT, different designs have been introduced over the years, starting from the devices developed by Lindvall (1970) and Lockyer (1984): early wind tunnels were characterized by high flow rate (exceeding 1 m/s in the central body of the hood) and relatively voluminous devices. In the following years, Jiang (1995) and Frechen (2004) highlighted that high-speed operation leads to excessive dilution within the hood, so the development of the device has transitioned towards the low-speed wind tunnels (LSWT), with velocities in the order of cm/s. On the basis of this observation, Capelli et al. (2009) introduced a WT design with reduced dimensions, currently employed in Italy for passive area source sampling.

The aim of this paper is to investigate the fluid dynamics and mass transfer of the current Italian regulatory WT, proposed by the legislation, with the purpose of highlighting its strength and limitations. Based on these findings, possible improvements are proposed.

## 2. Materials and Methods

### 2.1 Sampling device description

The sampling instrument under investigation is the WT proposed by the Italian regulation (MASE, 2023).

The Italian regulatory WT comprises three primary sections: an inlet portion where air is diverted into the central body via a divergent duct, the central body of the hood, characterized by an open section, that must be located directly above the emission source, and a final section where the air is guided through a convergent conduit towards the outlet.

The divergent duct is designed with a horizontally expanding section while retaining a constant vertical height. Within it, three flow deflectors are installed, creating four vanes through which air flows into uniform, parallel streams. Additionally, a perforated grid at the duct entrance facilitates uniform airflow. The objective of this initial section is to attain a fully developed and uniform flow rate.

The central body is a rectangular parallelepiped with a total sampling area of 0.125 $m^2$. The mass transfer phenomenon takes place within this section of the WT. Given that this part is open and the hood is placed over the emission source to be sampled, the airflow passing through the device simulates the stripping phenomenon induced by atmospheric motion over the emissive surface.

The convergent duct is structured with a diminishing horizontal section, while the vertical portion maintains a consistent height identical to both the central body and the inlet duct. This configuration aids in the transportation of air enriched with the stripped Volatile Organic Compounds (VOCs), facilitating sample collection at the outlet.

### 2.2 Fluid dynamic analysis

In order to explore the fluid dynamic characteristics of the Italian regulatory WT, by measuring the velocity across the entire central section, an appropriate experimental set-up is devised (Figure 1a). The central body of the hood is positioned above a plexiglass sheet to replicate the presence of a liquid level, simulating a real-case sampling scenario. The plexiglass sheet is punctured at nine locations to accommodate the insertion of the anemometer: three holes at the start, three in the middle and three at the end. Each hole along the perimeter is situated 2.5 cm away from the edges. The airflow velocity within the central body of the WT is measured at 27 points: for each of the nine openings, measurements are taken at three distinct heights above the plexiglass sheet, specifically at 1 cm, 4 cm, and 7 cm.

This methodology allows for a detailed characterization of the flow within the central body of the WT, examining the fluid dynamics near the walls and corners, as well as at the center of the hood.

Each test is conducted over two minutes: this timeframe proves to be sufficient for observing velocity trends, as fluctuations around the average value remain relatively stable within the chosen interval.

Velocity measurements are performed using Testo 440 multifunctional tool in conjunction with the Testo hot sphere probe. This instrument features a measuring range of 0-10 m/s and an accuracy of ± 0.03 m/s + 5% of the measured value. The anemometer is configured in Logger mode to gather data at a frequency of 1 Hz.

During the experimental trials, WT is operated with an airflow of 2500 sL/h, aligning with the typical flow rate employed for field sampling, as indicated by Capelli (2018) and Capelli & Sironi (2018). Moreover, this flow rate value ensures that the flow velocity in the central body of the hood is within the range suggested by the regulations in force (MASE, 2023).

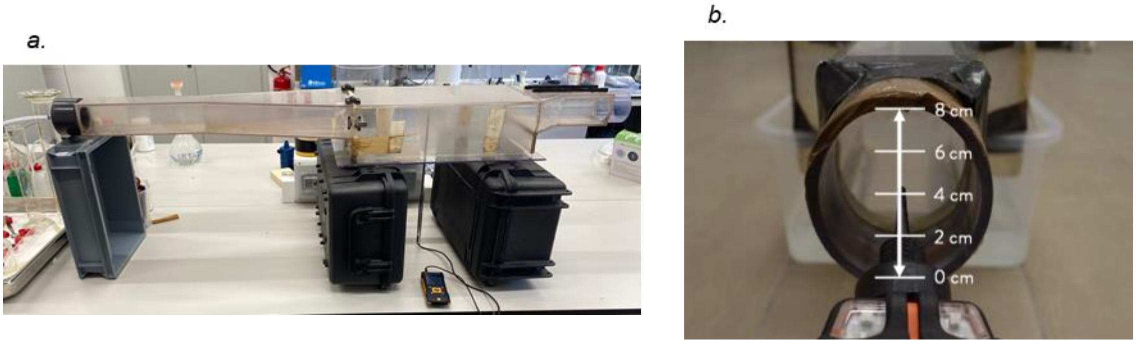


*Figure 1. Experimental set-up for fluid dynamics (a) and mass transfer (b) analysis*

### 2.3 Mass transfer analysis

Mass transfer analysis is conducted to measure the concentration, and consequently the emission rate, at the outlet section, at different heights, to assess the presence of possible vertical concentration gradients.

These tests are carried out using two different compounds: pure water and an aqueous solution of methylethylketone (MEK).

As regards from the first trial, the Italian regulatory WT, with an airflow of 2500 sL/h, is positioned above a basin, containing 26 L of pure water. The water concentration in the air, expressed as relative humidity, is monitored at both the inlet and outlet sections. For the inlet measurement, the hygrometer is inserted into the inlet tube via a glass T-connector. At the outlet, the measuring device is positioned at five different heights along the extremity of the outlet duct: 0 cm, 2 cm, 4 cm, 6 cm, and 8 cm from the bottom (Figure 1b).

The instrument used is the Testo hygrometer 605i, featuring a measurement range from 0 to 100% relative humidity, with a resolution of 0.1%. At a temperature of 25 °C, its precision varies: ±3.0% for relative humidity measurements between 10% and 35%, ±2.0% for measurements between 35% and 65%, ±3.0% for measurements between 65% and 90%, and ±5% for measurements below 10% or above 90%.

For the trial involving the VOC aqueous solution, the experimental setup is the same as the one described for the pure water test. However, in this instance, the solution comprises 13 g of MEK dissolved in 26 L of water, resulting in an initial concentration of the VOC in the liquid phase of 0.5 g/L.

Given that the VOC concentration in the inlet airflow is null, measurements are conducted in the same manner as for water, but solely at the outlet of the hood following the occurrence of the mass transfer phenomenon, where the air becomes enriched with the VOC.

The instrument employed to assess the outlet concentration is the Tiger VOC gas detector, a portable PID (Photoionization Detector). It offers a dynamic detection range spanning from 0 to 20,000 parts per million (ppm), with a minimum resolution of 0.001 ppm (1 ppb). The PID is calibrated with isobutylene, thus the value recorded by the instrument is adjusted using a Response Factor (RF) to convert the calibrated measurement of isobutylene to a measurement of the target volatile compound (MEK).

One crucial precaution, essential for the accurate execution of the tests, involves monitoring and controlling the temperature of both the liquid and the ambient air. Ensuring that the tests are conducted under conditions of thermal equilibrium is critically important, as the chemical and physical properties of VOCs are greatly influenced by temperature. Therefore, it is fundamental to maintain constant temperatures during the test, equal to 23 °C.

## 3. Results

### 3.1 Fluid dynamic analysis

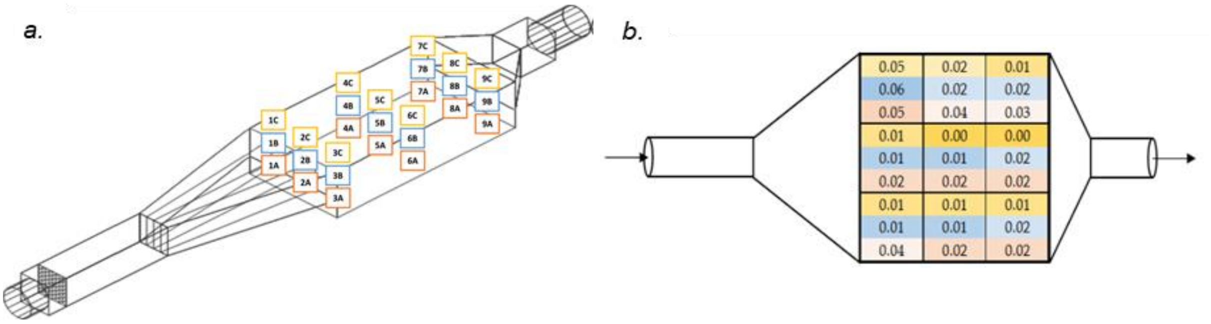
The layout of the sample points and the relative results of the fluid dynamic tests carried out on the WTs are depicted in Figure 2. The three heights for each measurement point are distinguished by different colors: orange represents the height of 1 cm, blue indicates the height of 4 cm, and yellow represents the height of 7 cm. To enhance clarity, conditional formatting is applied to provide a rapid overview of the fluid dynamic behavior: experimental measurements are shaded in colors with increasing intensity as they deviate further from the expected theoretical value. Therefore, lighter colors indicate values closer to the theoretical one, while darker colors signify greater deviations from the expected value:

$$v = \frac{Q_{air}}{A_{WT}} = \frac{Q_{air}}{H_{WT} \cdot B_{WT}} = 0.035\ m/s \quad (1)$$

Where:

- WT subscript refers to Wind Tunnel.
- $Q_{air}$ [$m^3/s$] is the air flowrate, i.e. 2500 sL/h.
- $H_{WT}$ [m] is the height of the central body of the WT, i.e. 0.08 m.
- $B_{WT}$ [m] is the breadth of the central body of the WT, i.e. 0.25 m.

A crucial factor to take into account during the analysis of the results is that the instrument accuracy is ±0.03 m/s. Therefore, the acceptable range for the measured velocities can be considered as 0.01 - 0.06 m/s. Each measurement lasts for two minutes, and the data are collected at a frequency of one datum per second.



| | | |
|---|---|---|
| 0.05 | 0.02 | 0.01 |
| 0.06 | 0.02 | 0.02 |
| 0.05 | 0.04 | 0.03 |
| 0.01 | 0.00 | 0.00 |
| 0.01 | 0.01 | 0.02 |
| 0.02 | 0.02 | 0.02 |
| 0.01 | 0.01 | 0.01 |
| 0.01 | 0.01 | 0.02 |
| 0.04 | 0.02 | 0.02 |

*Figure 2. Scheme of the 27 sample points for the WT (a) and relative results (b) (A = height of 1 cm, B = height of 4 cm, C = height of 7 cm).*

The velocities recorded for the Italian regulatory WT fall within the acceptable range; however, the presence of a preferential channel is evident. This phenomenon is particularly pronounced on the left side at the inlet section of the central body (Figure 2b), where the velocities are higher (around 0.06 m/s) compared to the other points. This behavior may be attributed to an uneven distribution of air within the four channels in the divergent part of the hood. Moreover, it appears that in the middle and final sections, the flow is more homogeneous than in the initial part, as confirmed by the graphs in Figure 3, which show the temporal trends of the measured velocities inside the central body over a time span of two minutes.

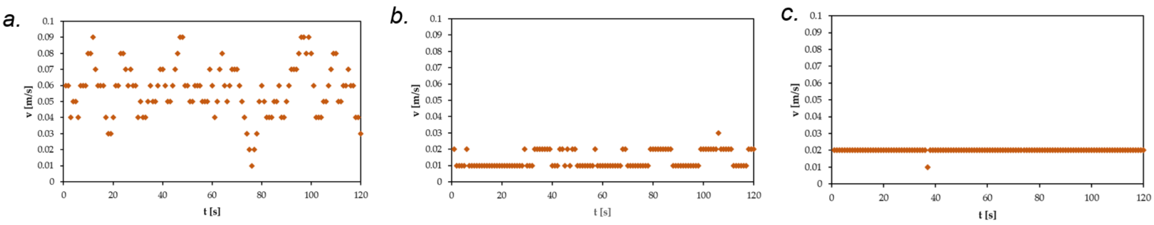


*Figure 3. Examples of velocity trends in the initial section (a), middle section (b) and final section (c) of the central body of the WT*

### 3.2 Mass transfer analysis

The experimental results of the relative humidity at the outlet section of the hood (Figure 4a) reveal non-uniform values along the vertical direction. Measurement demonstrates a decline in relative humidity up to a factor of 2 moving from the bottom to the top of the exit conduit. This presents a potential concern as there is inadequate homogenization in the convergent duct to equalize the outlet concentration. Consequently, varied emission rates might be estimated depending on the height at which the gaseous sample is collected at the exit section.

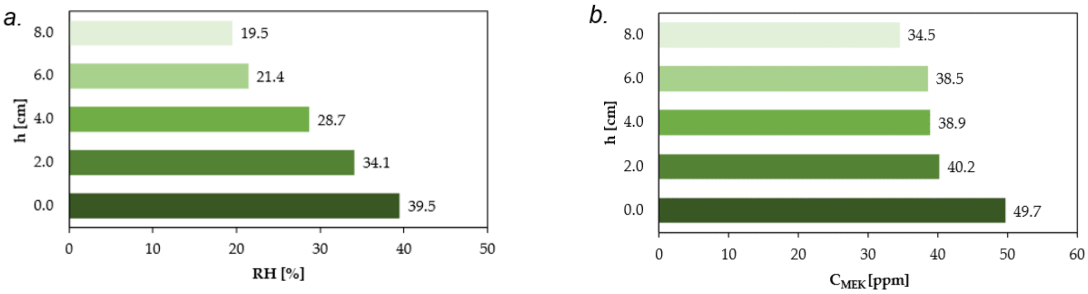


*Figure 4. Mass transfer measurement results for pure water (a) and MEK aqueous solution (b)*

The results obtained for the MEK aqueous solution (Figure 4b) corroborate the observations discussed in the case of water. Figure 4 illustrates that, once again, a downward trend in concentration can be discerned in the WT along the vertical direction, as one moves upwards in the exit duct, from 49.7 ppm to 34.5 ppm.

## 4. Conclusions

The present experimental study discusses an investigation on the Italian regulatory WT device, in terms of fluid dynamic and mass transfer analysis.

According to the results obtained through the fluid dynamic tests, it has been demonstrated that the WT under investigation reveals a non-perfectly homogenous distribution of the flow within the central body of the hood, instead presenting the existence of a preferential channel.

Furthermore, the mass transfer analysis results demonstrate that a significant drawback of the Italian regulatory WT is the existence of a concentration gradient along the outlet duct's vertical direction, pointing out concentration values that vary by up to a factor of two depending on the height of the measurement point.

The conclusions of this experimental work suggest different future perspectives.

Firstly, in order to achieve fluid dynamic improvements within the hood, a possible novel WT design should provide a better distribution system of the incoming airflow, by inserting flow-breaking fittings and filling bodies. In this way, a uniform flow should be possibly achieved within the central body of the hood, without the presence of preferential channel issues.

Furthermore, in order to avoid the presence of a vertical concentration gradient at the outlet section of the WT device, and thus ensure the representativeness of the sample regardless of the location of the sampling point, a possible solution could involve the inclusion of mixing systems, such as static mixers. This should guarantee the mixing of the gaseous outflow and consequently the absence of a concentration gradient.

Finally, in order to provide enhanced portability and ease of use, the development of a novel device could also take into account a potential reduction in weight and size.

### References

Beghi, S. P., Rodrigues, A. C., De Sá, L. M., & Santos, J. M. (2012). Estimating Hydrogen Sulphide Emissions from an Anaerobic Lagoon. 30. www.aidic.it/cet

Bokowa, A., Diaz, C., Koziel, J. A., McGinley, M., Barclay, J., Schauberger, G., Guillot, J. M., Sneath, R., Capelli, L., Zorich, V., Izquierdo, C., Bilsen, I., Romain, A. C., Del Carmen Cabeza, M., Liu, D., Both, R., Van Belois, H., Higuchi, T., & Wahe, L. (2021). Summary and overview of the odour regulationsworldwide. Atmosphere, 12(2). https://doi.org/10.3390/atmos12020206

Brambilla, M., & Navarotto, P. (2010). Sensorial analysis of pig barns odour emissions. Chemical Engineering Transactions, 23, 243–248. https://doi.org/10.3303/CET1023041

Capelli, L., Grande, M., Intini, G., & Sironi, S. (2018). Comparison of field inspections and dispersion modelling as a tool to estimate odour emission rates from landfill surfaces. Chemical Engineering Transactions, 68, 187–192. https://doi.org/10.3303/CET1868032

Capelli, L., & Sironi, S. (2018). Combination of field inspection and dispersion modelling to estimate odour emissions from an Italian landfill. Atmospheric Environment, 191, 273–290. https://doi.org/10.1016/j.atmosenv.2018.08.007

Capelli, L., Sironi, S., Del Rosso, R., & Céntola, P. (2009). Design and validation of a wind tunnel system for odour sampling on liquid area sources. Water Science and Technology, 59(8), 1611–1620. https://doi.org/10.2166/wst.2009.123

Claeson, A. S., Lidén, E., Nordin, M., & Nordin, S. (2013). The role of perceived pollution and health risk perception in annoyance and health symptoms: A population-based study of odorous air pollution. International Archives of Occupational and Environmental Health, 86(3), 367–374. https://doi.org/10.1007/s00420-012-0770-8

MASE 2023. Indirizzi per l'applicazione dell'articolo 272-bis del dlgs 152/2006 in materia di emissioni odorigene di impianti e attività. 28/07/2023 https://www.mase.gov.it/pagina/indirizzi-lapplicazione-dellarticolo-272-bis-del-dlgs-1522006-materia-di-emissioni-odorigene

Frechen, F.-B., Frey, M., Wett, M., & Löser, C. (2004). Aerodynamic performance of a low-speed wind tunnel. Water Science and Technology @IWA Publishing 2004, 50(4), 57–64. https://iwaponline.com/wst/article-pdf/50/4/57/46218/57.pdf

Guillot, J.-M. (2012). Odour Measurement: Focus on Main Remaining Limits Due to Sampling. 30. www.aidic.it/cet

Henshaw, P., Nicell, J., & Sikdar, A. (2006). Parameters for the assessment of odour impacts on communities. Atmospheric Environment, 40(6), 1016–1029. https://doi.org/10.1016/j.atmosenv.2005.11.014

Hudson, N., & Ayoko, G. A. (2009). Comparison of emission rate values for odour and odorous chemicals derived from two sampling devices. Atmospheric Environment, 43(20), 3175–3181. https://doi.org/10.1016/j.atmosenv.2009.03.050

Invernizzi, M., Teramo, E., Busini, V., & Sironi, S. (2020). A model for the evaluation of organic compounds emission from aerated liquid surfaces. Chemosphere, 240. https://doi.org/10.1016/j.chemosphere.2019.124923

Jiang, K., Bliss, P. J., & Schulz, T. J. (1995). The development of a sampling system for determining odor emission rates from areal surfaces: Part i. aerodynamic performance. Journal of the Air and Waste Management Association, 45(11), 917–922. https://doi.org/10.1080/10473289.1995.10467424

Lindvall T. (1970). On sensory evaluation of odorous air pollutant intesities. Nord. Hyg. Tidskr. Suppl. 2, 1–181.

Liu, L., Abdala Prata Junior, A., Fisher, R. M., & Stuetz, R. M. (2022). Measuring volatile emissions from biosolids: A critical review on sampling methods. In Journal of Environmental Management (Vol. 317). Academic Press. https://doi.org/10.1016/j.jenvman.2022.115290

Lockyer, D. R. (1984). A System for the Measurement in the Field of Losses of Ammonia through Volatilisation. In J. Sci. Food Agric (Vol. 35).

Lotesoriere B.J., Invernizzi M., Panzitta A., Uvezzi G., Sozzi R., Sironi S., & Capelli L. (2022). Micrometeorological Methods for the Indirect Estimation of Odorous Emissions. In https://doi.org/10.1080/10408347.2022.2036092 (pp. 1531–1560). Critical Reviews in Analytical Chemistry.

Navaratnasamy, M., Feddes, J. J. R., Edeogu, I. K., & Laurier, F. C. (2004). Comparison of wind tunnel and vented flux chamber in measuring odour emission rates. Written for presentation at the 2004 ASAE/CSAE Annual International Meeting Sponsored by ASAE/CSAE.

Tagliaferri, F., Invernizzi, M., & Sironi, S. (2021). Influence of wind velocity on the emission rate of acetone aqueous solution at different concentrations. Chemical Engineering Transactions, 85, 127–132. https://doi.org/10.3303/CET2185022

Tagliaferri, F., Invernizzi, M., & Sironi, S. (2023). Experimental evaluation on liquid area sources: Influence of wind velocity and temperature on the wind tunnel sampling of VOCs emissions from wastewater treatment plants. Chemosphere, 312. https://doi.org/10.1016/j.chemosphere.2022.137337

Tagliaferri, F., Invernizzi, M., Sironi, S., & Capelli, L. (2020). Influence of modelling choices on the results of landfill odour dispersion. Detritus, 12, 92–99. https://doi.org/10.31025/2611-4135/2020.13998

Tagliaferri, F., Panzeri, F., Invernizzi, M., Manganelli, C., & Sironi, S. (2024). Characterization of diffuse odorous emissions from lignocellulosic biomass storage. Journal of the Energy Institute, 112. https://doi.org/10.1016/j.joei.2023.101440

Zhao, Y., Lu, W., & Wang, H. (2015). Volatile trace compounds released from municipal solid waste at the transfer stage: Evaluation of environmental impacts and odour pollution. Journal of Hazardous Materials, 300, 695–701. https://doi.org/10.1016/j.jhazmat.2015.07.081