

Air pollutant emission factors from wood-fired pizza ovens<sup>☆</sup>

Andrea Bergomi<sup>a,\*</sup>, Gabriele Migliavacca<sup>b,\*\*</sup>, Silvia Bertagna<sup>b</sup>, Mattia Borelli<sup>a</sup>,  
Salvatore Chiavarini<sup>c</sup>, Valeria Comite<sup>a</sup>, Iliaria D'Elia<sup>d</sup>, Paola Fermo<sup>a</sup>,  
Teresa M.G. La Torretta<sup>d</sup>, Antonio Piersanti<sup>d</sup>, Milena Stracquadanio<sup>d</sup>

<sup>a</sup> University of Milan, Department of Chemistry, Via Golgi 19, 20133, Milan, Italy

<sup>b</sup> Innovhub Stazioni Sperimentali per l'Industria, Area Combustibili, Via Galilei 1, San Donato Milanese, 20097, Milan, Italy

<sup>c</sup> ENEA, Division Anthropic and Climate Change Impacts, Via Anguillarese, Santa Maria di Galeria, 30100123, Rome, Italy

<sup>d</sup> ENEA, Laboratory Models and Measurements for Air Quality and Climate Observations, Via dei Mille 21, 40121, Bologna, Italy

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## ABSTRACT

Wood combustion is a well-known source of harmful gaseous air pollutants and particulate matter. As a result, emissions from various wood-burning appliances, such as small-scale residential heating and cooking devices, are regulated. However, similar appliances, such as wood-fired ovens used in pizzerias, are not subject to the same regulations, leaving the sector largely unstandardized. Additionally, there is a lack of experimental studies evaluating the emission profiles of these devices, making their impact on air pollution and air quality uncertain. This study assesses the emission profile of three wood-fired pizza ovens burning both beechwood logs and briquettes. Emissions of NO<sub>x</sub>, CO, OGC, TSP, PM<sub>10</sub>, PM<sub>2.5</sub>, and PAHs were tested across all key operational phases of the ovens, and emission factors were calculated by accounting for each phase's contribution to typical oven management (NO<sub>x</sub>: 85 ± 3 g GJ<sup>-1</sup>; CO: 1038 ± 59 g GJ<sup>-1</sup>; OGC: 71 ± 10 g GJ<sup>-1</sup>; TSP: 233 ± 21 g GJ<sup>-1</sup>; PM<sub>10</sub>: 162 ± 16 g GJ<sup>-1</sup>; PM<sub>2.5</sub>: 157 ± 16 g GJ<sup>-1</sup>; ∑PAHs: 1482 ± 883 mg GJ<sup>-1</sup>). Statistical analysis revealed a significant influence of oven type and operational phase on emissions, emphasizing the critical role of the baking process together with wood combustion in defining the emission profile of these devices. Hence, emission factors were calculated for each pollutant, which more accurately represent the actual emissions of these devices, as opposed to the emission factors of manually operated wood boilers, which are currently used as proxies for wood-fired ovens in the European emission inventory. Their use is thus proposed for updating the emission inventories.

## 1. Introduction

Wood-fired ovens are devices designed for food preparation which can be used to cook bread, meat, vegetables and other types of food. Pizza is probably one of the most popular dishes that can be prepared using these appliances due to the characteristic flavor and texture that can be achieved exclusively by using wood-fired ovens (Falciano et al., 2022; Grand View Research, 2021). Following the COVID-19 pandemic, there has been an expansion of the pizza market, which is projected to rise from USD 197 billion in 2023 to USD 499.5 billion in 2032 (Business Research Insights, 2025). Consequently, the global pizza oven market is also expected to increase between 2022 and 2030 at a compound annual growth rate (CAGR) of 5.3 %. In 2022, wood-fired ovens represented

41.0 % of appliances worldwide, constituting a greater share than both gas-fired and electric alternatives (Grand View Research, 2021).

The increase in the number of wood-fired ovens, especially in large cities, prompted several local authorities to investigate the potential impacts on air pollution (Hugony, 2020). The concern is driven by the fact that similar wood burning devices employed in residential heating and cooking, such as woodstoves and fireplaces, have a significant impact on the emissions of particulate matter (PM) and other gaseous pollutants including, but not limited to, nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), and organic gaseous carbon (OGC) (Ozgen et al., 2014). For instance, while constituting only 2.6 % of the total energy consumption, residential biomass combustion contributes to 36 % of PM<sub>2.5</sub> emissions in the European Union (EU) (Wolters, 2018). Moreover,

<sup>☆</sup> This paper has been recommended for acceptance by Admir Créso Targino.

\* Corresponding author.

\*\* Corresponding author.

E-mail addresses: [andrea.bergomi@unimi.it](mailto:andrea.bergomi@unimi.it) (A. Bergomi), [gabriele.migliavacca@mi.camcom.it](mailto:gabriele.migliavacca@mi.camcom.it) (G. Migliavacca).

incomplete combustion of wood is also one of the major emitters of polycyclic aromatic hydrocarbons (PAHs), another class of dangerous air pollutants that can be found in both the particulate and gaseous phase (Patel et al., 2020).

For this reason, the EU introduced source-specific requirements for devices employed in domestic combustion, setting emission limits for PM, NO<sub>x</sub>, CO and OGC (Regulation (EU) No 2015/1185). Instead, to date, pollutant emissions of wood-fired ovens remain unregulated. This is mainly due to the lack of data on the emission profile of these appliances, which refrains from introducing source-specific legislation. A recent study conducted by the Metropolitan City of Milan estimated that a non-negligible percentage of atmospheric PM found in large cities can be attributed to emissions deriving from the combustion of solid biomass for uses other than heating (Hugony, 2020). In fact, the number of stoves and fireplaces in urban areas is rather low compared to rural and mountainous areas; nevertheless, the measured contribution of biomass burning is also high in metropolitan areas (INEMAR - ARPA Lombardia, 2024). This is therefore attributed to the large concentration of pizzerias with wood-burning ovens, which are active in both summer and winter, although experimental measurements of the emission factors of these ovens have never been performed in practice (Bergomi, 2025).

The interest of public administrations, including the Italian Ministry of the Environment and Energy Security, and control bodies in pollutant emissions produced by pizzerias equipped with wood-fired ovens is therefore high, as these administrations are, on the one hand, driven to counteract a potentially relevant pollutant source, but on the other hand they are cautious about affecting an important economic sector and a product particularly appreciated by consumers (Bergomi, 2025). Despite these concerns, different local authorities have already started to enact legislation regulating the use and emissions of wood-fired ovens in pizzerias, rotisseries, bakeries, and other similar establishments (NYC Environmental Protection, 2016; Falciano et al., 2024).

The 2023 Air Pollutants Emission Inventory Guidebook (AEIG) of the European Monitoring and Evaluation Programme (EMEP), published by the European Environment Agency (EEA), does not provide distinct emission factors for wood-fired pizza ovens; instead, it uses those for wood-fired boilers as proxies (European Environment Agency, 2023). Having realistic values for this type of source is important to feed Air Quality Models and to deliver Air Quality plans (Directive, 2024/2881/EU). To date, no studies are available on experimental assessments of the emission factors of wood-fired ovens. A literature study focused on the characterization of particles emitted by pizzerias burning wood was conducted in the city of Sao Paulo (Mota Lima et al., 2020). Other studies in this field focus on the determination of the environmental impacts of wood-fired ovens by evaluating the performance characteristics (Falciano et al., 2022) and the carbon footprint of the final product (Moresi et al., 2024), without an emphasis on the emissions of major air pollutants. An innovative sampling system was implemented to characterize the emissions of PM and major gaseous pollutants, with a preliminary evaluation of the emissions of wood-fired pizza ovens. Moreover, the results highlighted a non-negligible impact of the baking process, in combination with wood combustion, in defining the emission profile of these devices (Bergomi et al., 2022).

Building on these preliminary results, the current study aimed to determine for the first time experimental emission factors for major air pollutants from wood-fired ovens used in pizzerias and similar establishments. Specifically, the study focused on emissions of total suspended particulate matter (TSP), PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>x</sub>, CO, and OGC, based on experimental testing conducted on three different ovens. A sampling protocol was developed to replicate the operating conditions of a real-life establishment, accounting for the impact of various operational phases, including ignition, cooking, and shutdown. Beechwood was chosen as the fuel type, and tests were performed using both logs and briquettes. Finally, the influence of fuel type, operational phase, and oven type on the emissions of all the investigated air pollutants was evaluated and final emission factors of each pollutant were calculated

and compared to the values currently present in the AEIG (European Environment Agency, 2023).

## 2. Materials and methods

### 2.1. Appliances and fuels

Considering the diverse range of pizza ovens in use, experimental tests were conducted on three different ovens to capture the heterogeneity of the landscape and assess potential differences in emission profiles (Fig. 1).

The first oven (Base MEC80, Ambrogi – oven 1) was a traditional fixed-top wood-fired pizza oven with a capacity of 5–6 pizzas which had never been used prior to testing. The second oven (Vesuvio Igloo, Valoriani – oven 2) was a hybrid model, also with a capacity of 5–6 pizzas, operated as a wood-fired oven, and, like the first, was unused before testing. Finally, the third oven (Festival, Ambrogi – oven 3) was another traditional fixed-top wood-fired pizza oven, but an older and larger version with a capacity of 8–10 pizzas, which had been in use for over ten years. The ovens selected for this study, produced by Ambrogi Forni and Valoriani, come from two of the leading pizza oven manufacturers in Italy. Moreover, the typical internal diameter of wood-fired pizza ovens offered by these and other top manufacturers used in pizzerias ranges between 100 and 150 cm. The ovens tested in this study were therefore chosen to represent different sizes within this commonly used range (oven 1: 130 cm; oven 2: 120 cm; oven 3: 145 cm).

Two different types of fuelwoods were used to carry out experimental tests: beechwood logs and beechwood briquettes. Beechwood was selected because it is the most used fuel in standard testing of small-scale wood-burning appliances (Caserini et al., 2014), which are the devices most comparable to wood-fired pizza ovens. Moreover, beechwood is by far the most used in Italian wood-fired ovens. It is widely regarded in pizzerias as the preferred option due to its ability to heat the oven quickly, produce minimal smoke, and offer high fuel efficiency. Wood logs are the more traditional type of fuel, whereas briquettes are currently being proposed as a viable alternative due to several advantages in terms of transportation, handling, and storage costs (Roy and Corscadden, 2012). Both the logs and the briquettes were certified for food use and the technical characteristics are the same as the ones outlined in Bergomi et al. (2022). The fuels were analyzed for their calorific properties, water content, and elemental composition following the relative technical standards (Table S1).

### 2.2. Sampling and measurement of air pollutants

The innovative sampling system described in Bergomi et al. (2022) was used to carry out experimental tests on all three wood-fired ovens. The use of a dilution tunnel was made due to the potentially significant impact of the condensation of organic gaseous compounds on particle emissions (Schön et al., 2013; Ozgen et al., 2014). For this reason, the temperature of the diluted fumes, the draught, and the flow rate in the dilution tunnel were kept under control during the execution of the experimental tests. These parameters can influence the emission profile of the oven by affecting the combustion process and the degree of condensation of organic gaseous compounds. Specifically, the temperature was kept between 40 and 60 °C, the draught between –17 and –19 Pa and the velocity between 3 and 10 m s<sup>-1</sup>.

Sampling and measurements were conducted for the following air pollutants: CO, NO<sub>x</sub>, OGC, TSP, PM<sub>10</sub>, PM<sub>2.5</sub>, and PAHs. In addition, parameters essential for determining emission factors, such as oxygen (O<sub>2</sub>) and carbon dioxide (CO<sub>2</sub>), were monitored upstream and downstream of dilution. Gaseous pollutants were measured in the hot flue gases, while particle emissions were assessed in both the hot and cold flue gases. Also, a dedicated sampling line for PAHs was positioned along the dilution tunnel with a separate probe. For each parameter whose concentration in the flue gases was determined, all

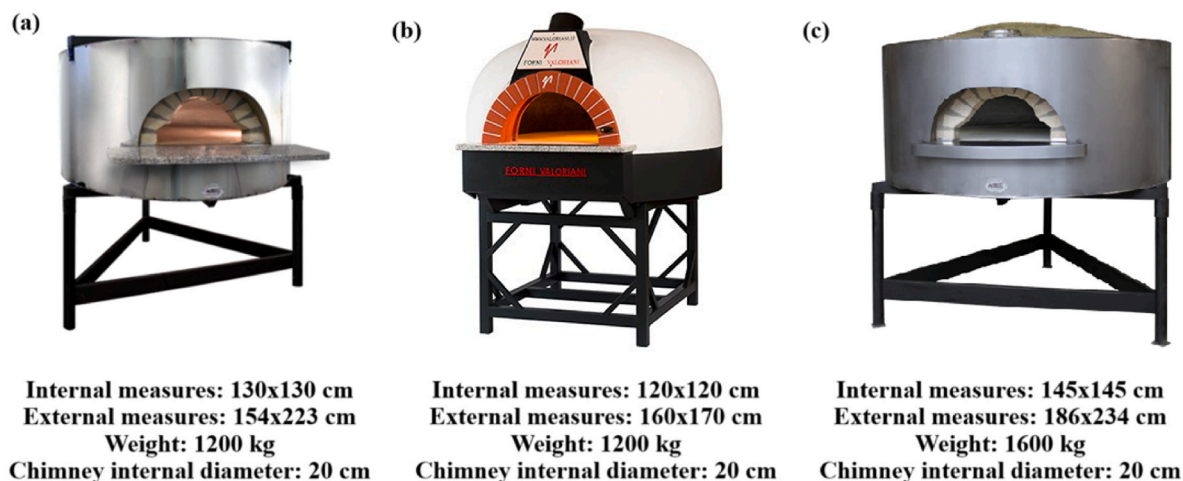


Fig. 1. Wood-fired ovens and their technical characteristics: (a) Base MEC80, Ambrogi; (b) Vesuvio Igloo, Valoriani; (c) Festival, Ambrogi.

instrumentation (Table S2) was operated according to the provisions of UNI EN 16510-1, and following the additional specifications outlined in Bergomi et al. (2022).

PAH sampling was performed in accordance with the ISO 11338-1:2003 method, with a separate collection of the three phases: particulate, condensate, and gaseous. Given the substantial amount of particulate matter emitted by the wood-fired ovens, sampling was conducted from the dilution tunnel, and the particulate phase was collected using quartz fiber thimbles. After completing the experimental trials, the sampling line was washed with three different solvents (acetone, toluene, and dichloromethane), which were then added to the condensate phase. Lastly, volatile PAHs were captured in the gaseous phase using a polyurethane foam (PUF).

Quantitative analysis of PAHs was carried out separately on the particulate, condensate, and gaseous phase. The compounds selected for analysis were the 16 PAHs classified by the EPA as priority pollutants (Bojes and Pope, 2007): acenaphthene, acenaphthylene, anthracene, fluoranthene, fluorene, naphthalene, phenanthrene, pyrene, benz[a]anthracene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[ghi]perylene, benzo[a]pyrene, chrysene, dibenz[a,h]anthracene, and indeno[1,2,3-cd]pyrene. Detailed information on PAH analysis is provided in the supplementary material.

### 2.3. Experimental tests

Due to the absence of technical standards concerned with emission testing on wood-fired ovens, a new sampling protocol was devised to carry out experimental tests. Preliminary trials were important in defining the operational phases of oven management and different combustion cycles were tested to evaluate potential impacts on emissions (Bergomi et al., 2022). The best compromise between representativity of real-life conditions and reproducibility of the experimental testing was selected in defining the final sampling protocol. Combustion cycles were defined for each of the representative operational phases: cold ignition, hot reignition, and cooking. Details on the operational phases are outlined in the supplementary materials.

Experimental tests were conducted separately for each operational phase, excluding the shutdown phase, which preliminary testing showed did not generate significant emissions. To evaluate the impact of the baking process, additional tests were performed during the cooking phase without baking and this phase was designated as the *Stationary* phase.

The duration of the experimental tests was set to 2 h to maximize representativity of the results while acknowledging instrumental limitations. Instead, to avoid filter overload, TSP sampling on the hot flue

gases ( $TSP_{conc}$ ) was carried out for 30 min and  $PM_{10}/PM_{2.5}$  sampling with the impactor was carried out for 15 min. To fully evaluate the impact of condensable PM on emissions, parallel sampling between  $TSP_{conc}$  and TSP sampled after dilution ( $TSP_{dil}$ ) was performed in trials conducted on the third oven (Festival, Ambrogi). Due to instrumental limitations, 30-min sampling was carried out for both  $TSP_{conc}$  and  $TSP_{dil}$ . In all cases where sampling times were shortened, three repetitions were made during the 2 h of experimental testing and, to maximize repeatability, sampling started concurrently with the introduction of a new fuelwood load. The setup of the experimental trials and the pollutants measured are summarized in Tables S3, S4, and S5.

### 2.4. Emission factors

The results of this study are expressed as emission factors of the investigated air pollutants. The measured concentrations from each of the experimental trials were reported as  $mg\ Nm^{-3}$  (13 %  $O_2$ ), this being the reference parameter for the limit values defined in national and European regulations for wood-burning appliances, whereas final emission factors were expressed as  $g\ GJ^{-1}$ , since these are the units commonly used in emission inventories.

To report all measured emission data under the same conditions, the degree of dilution achieved in the tunnel was determined by using the measured concentration of  $CO_2$  both upstream and downstream of dilution and correcting for the ambient air background concentration (Bergomi et al., 2022). The dilution factor was calculated every 10 s and then averaged to achieve the final value.

The calculation of dilution factors using  $CO_2$  proved impractical in the experimental trials conducted on the third wood-fired oven (Festival, Ambrogi) due to very low concentrations in the dilution tunnel. This was caused by higher oxygen concentrations in the combustion chamber compared to the other two ovens, which led to significantly diluted hot flue gases. As a result,  $CO_2$  concentrations in the dilution tunnel fell below the instrument's limit of detection, complicating accurate measurement. Therefore, the degree of dilution ( $d$ ) in these trials was calculated using  $NO_x$  concentrations measured upstream ( $[NO_x\ upstream]$ ) and downstream ( $[NO_x\ downstream]$ ) of the dilution tunnel, as shown in Equation (1).

$$d = \frac{[NO_x\ upstream]}{[NO_x\ downstream]} \quad (1)$$

Also in this case, the dilution factor was calculated punctually based on  $NO_x$  concentrations reported every 10 s and then averaged to achieve the final value.

Concentrations were expressed as  $mg\ Nm^{-3}$  (13 %  $O_2$ ) by

normalizing the pollutant's mass per dry volume of flue gases at STP for a reference oxygen content of 13 %, which was chosen as this is the value commonly used for wood-burning appliances. Due to the large amount of air present in the oven chamber, the fumes were already highly diluted in the hot flue gases with oxygen concentrations between 17 and 19 %. Therefore, concentrations in the dilution tunnel were close to ambient air values, meaning that normalization would potentially lead to a large error in emission factor calculation. For this reason, the concentrations of the emitted pollutants ( $EC$ ) measured from the dilution tunnel were determined by initially calculating the corresponding concentration in the hot fumes using the dilution factor and later normalizing for the oxygen concentration measured on the hot flue gases. All values were calculated using Equation (2):

$$EC_x = C_x \times d \times \frac{(21 - O_{2,ref})}{(21 - O_{2,exp})} \quad (2)$$

where  $C_x$  is the concentration obtained from the experimental tests expressed in  $mg\ Nm^{-3}$ ,  $d$  is the dilution factor,  $O_{2,ref}$  is the reference oxygen value and  $O_{2,exp}$  is the oxygen percentage in the hot flue gases.

The results from the experimental trials were then used to calculate emission factors ( $EF$ ) for each pollutant, which are representative of wood-fired ovens, based on Equation (3):

$$EF_x = \frac{1}{8}EF_{HR} + \frac{5}{8}EF_{COOK} + \frac{2}{8}EF_{STAT} \quad (3)$$

where,  $EF_{HR}$  is the mean emission factor of the hot-reignition phase,  $EF_{COOK}$  is the mean emission factor of the cooking phase, and  $EF_{STAT}$  is the mean emission factor of the stationary phase. The ratios are derived from observations of oven operations in a typical pizzeria setting (see Section 3.4) and reflect the relative contribution of each representative operational phase over a standard 8-h workday: 1 h for the hot reignition phase, 5 h for the cooking phase, and 2 h for the stationary phase.

The final emission factors were then converted to  $g\ GJ^{-1}$  or  $mg\ GJ^{-1}$  using  $0.68\ Nm^3\ GJ^{-1}$  as the conversion factor (Ufficio Federale dell'Ambiente UFAM, 2018). Although wood-fired pizza ovens are not primarily used for energy production, the emission factors have been expressed in  $g\ GJ^{-1}$  or  $mg\ GJ^{-1}$ , in line with the standard units used in European emission inventories. This is consistent with the classification of these ovens as non-residential cooking appliances, under the 'non-residential heating' category in the AEIG.

### 2.5. Statistical analysis

Emission factors of wood-fired ovens are potentially influenced by three factors: oven type, operational phase, and fuel type. To assess the individual impact of these three variables, main-effects ANOVA analysis was performed using the Statistica software, selecting *oven type*, *operational phase*, and *fuel type* as the independent variables and *emission factors* as the dependent variables. The results are reported expressing the degrees of freedom for the main effect, the degrees of freedom for error, the  $F$  value, and the  $p$  value in APA style (Hanover College, ). If significant main effects were found, post-hoc pairwise comparisons were performed using the Scheffe test to identify differences between individual groups. Descriptive statistics, including means and standard errors, were calculated prior to conducting the ANOVA and the results from both elaborations were compared to further evaluate the impact of the independent variables on the emission factors.

## 3. Results and discussion

Experimental tests were conducted to evaluate the emissions of the major air pollutants from wood-fired ovens. The results were compared to the values currently listed in the EMEP/EEA AEIG, which acknowledges traditional wood-fired pizza ovens in restaurants and artisan bakeries as potential sources of pollutant emissions within the non-

residential cooking sector (Fig. 2). Lacking experimental literature data, the guidebook currently proposes manual boilers burning wood (<1 MWh) as proxies for traditional wood-fired ovens (European Environment Agency, 2023).

### 3.1. Gaseous pollutant emissions

The results indicate that the majority of the experimental concentrations of air pollutants fall within the confidence intervals reported in the AEIG for manually operated wood-burning boilers, suggesting good representativity of the values currently proposed in the guidebook. However, the emission factors presented in the AEIG exhibit considerable variability, largely due to the manual operation of the devices, where combustion conditions are difficult to control, leading to significant differences from one device to another. A similarly high level of variability was observed for all gaseous pollutants emitted from the tested wood-fired ovens. Among these,  $NO_x$  and CO emissions showed the lowest variability and were generally consistent with the values reported in the AEIG.

Like CO and  $NO_x$ , OGC emissions showed substantial variability, consistent with findings in the literature on small-scale residential heating appliances using wood as fuel (Klauser et al., 2018; Ozgen et al., 2014; Ozgen and Caserini, 2018). Indeed, the emissions of volatile carbonaceous compounds are influenced by the type of appliance (stove, fireplace, boiler, etc.), the quality of the appliance (traditional, advanced) and the type of fuel (spruce, oak, beech, etc.). On top of that, OGC is highly sensitive to combustion conditions and therefore often presents the highest variability amongst gaseous pollutants (Klauser et al., 2018). Overall, the values observed in this study are lower than the ranges observed for open fireplaces (Ozgen et al., 2014), which are the small-scale appliances that most resemble wood-fired ovens. Instead, they are comparable to OGC emissions from modern and advanced stoves burning firewood (Klauser et al., 2018).

Direct comparison with the AEIG cannot be made in this case because, unlike CO and  $NO_x$ , emission factors are reported only for non-methane volatile organic compounds (NMVOCs) and not for OGC. However, significant conclusions can still be drawn considering that experimental OGC emissions were constantly below the value listed in the AEIG for NMVOCs. Indeed, since OGC includes both NMVOCs and  $CH_4$ , with the latter accounting for around 50 % of total emissions deriving from biomass combustion (Schön et al., 2013), it is safe to conclude that the emissions of volatile species from the wood-fired ovens are lower than the value currently found in the AEIG.

From the results of the experimental trials, a main-effects ANOVA was conducted to assess the impact of oven type, fuel type, and operational phase on the emissions of the different air pollutants. The main effect of oven type was found to be significant for all gaseous pollutants:  $NO_x$  ( $F(2,39) = 6.161, p = 0.005$ ), CO ( $F(2,39) = 9.188, p = 0.005$ ), and OGC ( $F(2,39) = 3.901, p = 0.029$ ). Post-hoc Scheffé tests revealed significant differences between the third oven (Festival, Ambrogi) and the other two ovens (Base MEC80, Ambrogi and Vesuvio Igloo, Valoriani) for all the species. Descriptive statistics helped quantify these differences.

The third oven, being larger and older than the other two, required more fuelwood per load, which likely contributed to higher emissions of CO and OGC. In contrast,  $NO_x$  emissions from this oven were lower, despite the increased fuelwood consumption, an outcome that appears counterintuitive, as  $NO_x$  emissions are typically positively correlated with the fuel nitrogen content (Ozgen et al., 2021). Similarly, other key factors influencing  $NO_x$  formation, namely combustion temperature and oxygen availability, did not account for the observed decrease. The temperature was controlled and kept consistent across all ovens, while the larger mouth of the third oven allowed for increased airflow, and thus higher oxygen availability, which typically promotes  $NO_x$  formation rather than suppressing it. Therefore, lower  $NO_x$  emissions from this oven were likely due to the higher CO concentrations in the combustion

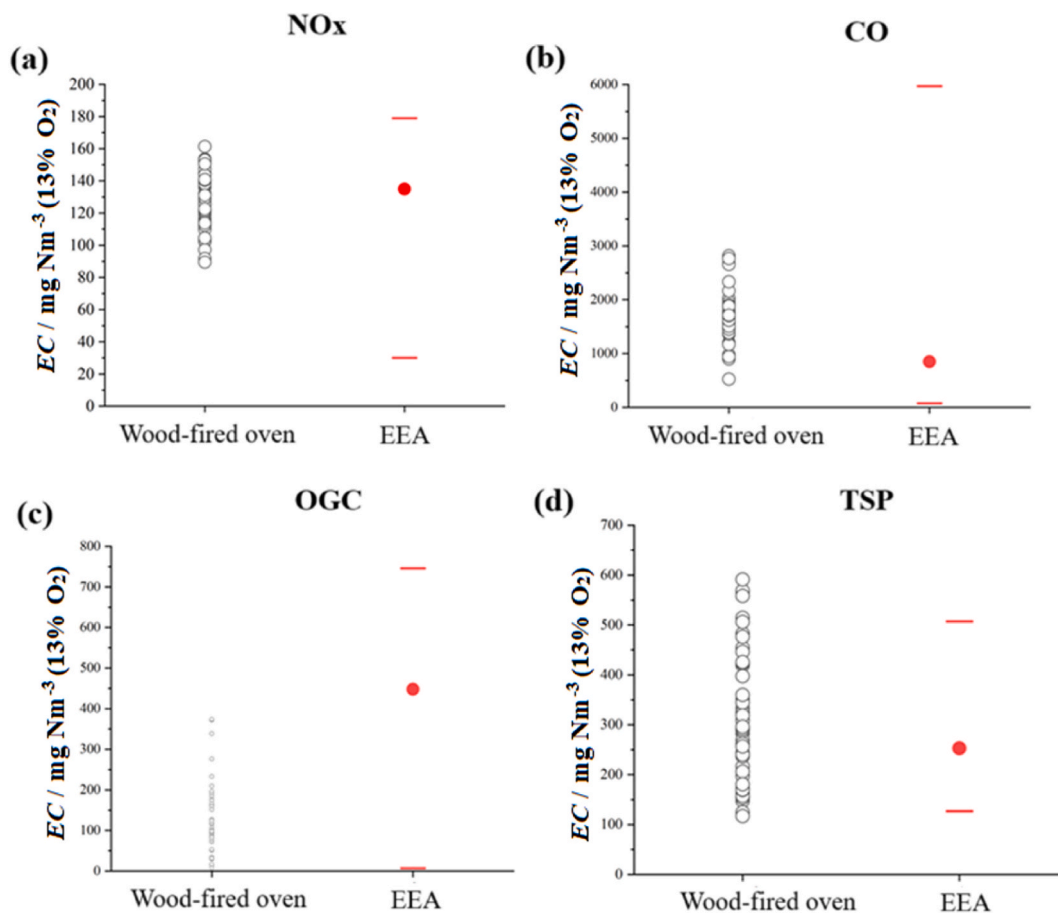


Fig. 2. Experimental air pollutant concentrations (white circles) compared to the EMEP/EEA AEIG values for manual boilers burning wood (<1MWth) (red dot) and the 95th confidence interval (red lines): (a) NO<sub>x</sub>, (b) CO, (c) OGC, (d) TSP. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

chamber, which created a more reducing environment thus inhibiting NO<sub>x</sub> formation. Overall, the differences in gaseous pollutant emissions were most pronounced during the ignition phases, while emissions during the cooking phase were similar across the ovens.

Moving on, the main effect of the operational phase was significant for emissions of CO and OGC (respectively,  $F(3,39) = 5.404, p = 0.003$ ; and  $F(3,39) = 6.999, p < 0.001$ ), but not for NO<sub>x</sub>. Post-hoc Scheffé tests revealed significant differences between the stationary phase and the other three phases for both CO and OGC. On average, the stationary phase was associated with lower emissions compared to all other phases

(Fig. 3).

These differences can be attributed to the higher emissions typically observed during the ignition phases, which are characterized by a greater degree of incomplete combustion (Krumal et al., 2023). Additionally, the combustion conditions within the chamber during the cooking phase may have been influenced by the operations related to the introduction and cooking of pizzas, which require heat for cooking and, consequently, affect the uniformity of temperature distribution and therefore the quality of combustion. Moreover, mechanical turbulence and the input of cold air caused by the loading of the pizza may also have

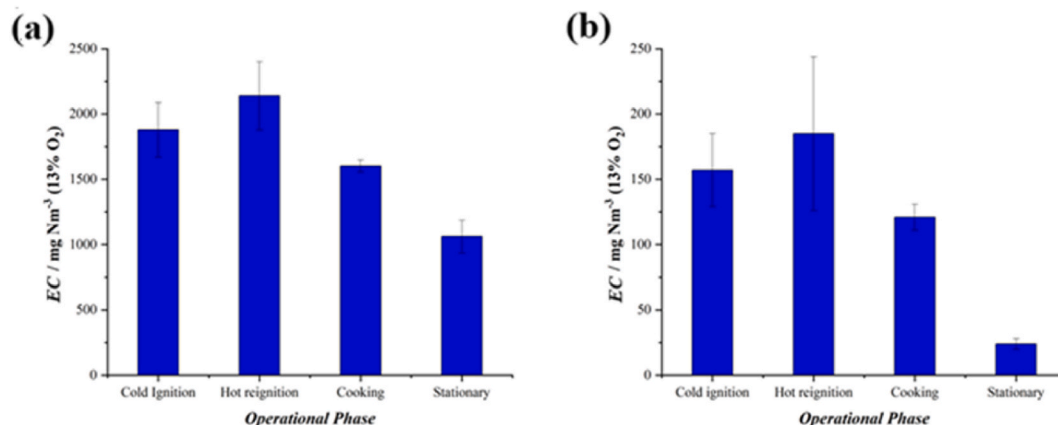


Fig. 3. Mean concentrations in the different operational phases of (a) CO and (b) OGC.

contributed to the alteration in the fluid dynamics and combustion kinetics. The differences were particularly pronounced for OGC, indicating a strong impact of the baking process on emissions. Indeed, the introduction of each new batch of pizzas was associated with characteristic peaks in OGC concentration, similar in intensity to those observed with each new fuelwood load (Fig. 4). This may be due to a direct and/or indirect effect of the baking process which modifies combustion conditions within the chamber by sequestering part of the heat for cooking. Nevertheless, these results highlight the significant role that cooking operations play in shaping the emission profile of wood-fired ovens.

Finally, no significant impact on the emissions of any air pollutants was observed based on fuel type. However, a weak global effect was detected for  $\text{NO}_x$  ( $F(1,39) = 4.222, p = 0.047$ ), with a  $p$ -value very close to the threshold for significance. Despite this, the Scheffe post-hoc test did not reveal a significant difference between the means of beechwood logs and briquettes ( $p = 0.214$ ). This lack of difference is likely due to both fuel types being derived from the same wood species, sharing similar compositional characteristics. While several studies have demonstrated that emissions from small-scale wood-burning appliances are heavily influenced by the type of fuel used (Ozgen et al., 2021), few studies have compared the emissions from wood logs versus briquettes. One such study (Schön and Hartmann, 2012) found that burning briquettes in wood stoves was linked to higher particulate emissions, though gaseous emissions were similar. These findings are in line with the literature, as no differences were observed in the emissions of gaseous pollutants.

### 3.2. Particulate matter emissions

To account for the impact of the condensation of organic gaseous compounds on particle emissions of wood-fired ovens, TSP was collected from the dilution tunnel ( $\text{TSP}_{\text{dil}}$ ). The values observed (Fig. 1) ranged between  $117 \text{ mg Nm}^{-3}$  (13 %  $\text{O}_2$ ) and  $592 \text{ mg Nm}^{-3}$  (13 %  $\text{O}_2$ ), falling within the wide range of emissions observed for similar biomass combustion systems without abatement technologies (Ghafghazi et al., 2011). However, the results of the experimental tests show a larger variability to the literature data of the AEIG, probably due to the impact of batch loadings of fuelwood in wood-fired ovens.

Main effects ANOVA was performed to evaluate the impact of the fuel type, oven type, and operational phase also on the emissions of  $\text{TSP}_{\text{dil}}$  and the only significant effect was observed for oven type ( $F(2,44) = 14.1012, p < 0.001$ ). The Scheffe test indicates differences between the third oven (Festival, Ambrogi) and the other two (respectively,  $p < 0.001$  and  $p < 0.001$ ), with higher TSP emissions from the

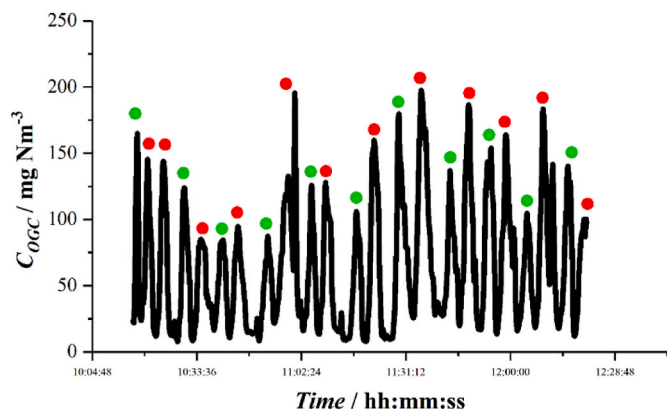


Fig. 4. OGC concentrations during a representative 2-h trial conducted on the Valoriani – Vesuvio Igloo oven during the cooking phase: the red dots indicate a fuelwood load, whereas the green dots indicate a pizza load. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

former (Fig. 5). This is most probably due to greater amounts of fuelwood used which led to greater amounts of emitted particles and highlights a common trend with CO and OGC, in contrast to the one seen for  $\text{NO}_x$ .

TSP sampling was conducted also on the hot flue gases to study the contribution of the condensable fraction on emissions by comparing the mean of the three  $\text{TSP}_{\text{conc}}$  measurements to the corresponding  $\text{TSP}_{\text{dil}}$  values downstream of dilution (Table S6). The results do not indicate a clear impact of condensation on the emissions of TSP. Rather, pairwise  $t$ -Test indicates a difference between the two groups ( $p = 0.017$ ) with higher values associated with  $\text{TSP}_{\text{conc}}$ . These results can be explained by the fact that the values that are being compared were not sampled perfectly in parallel. Indeed, as part of the protocol, sampling on the hot flue gases started in correspondence to a new fuelwood load, which is associated with a peak in emissions of PM. This means that sampling might have missed the final parts of the load in which the emissions of particles are lower, resulting in an overall imbalance in the concentrations in favor of  $\text{TSP}_{\text{conc}}$ .

To avoid the issue of not having parallel sampling on the hot and the cold flue gases, the sampling time of  $\text{TSP}_{\text{dil}}$  was shortened to 30 min on experimental trials conducted on the third wood-fired oven (Table 1).

By comparing the data pairs, it is possible to highlight an important contribution of secondary PM, as indicated by the results of the pairwise  $t$ -Test which shows a significant difference between the two groups ( $p < 0.001$ ). This could be in part due to the greater amounts of volatile species emitted by the third oven, which are then able to condense in the tunnel, and in part due to the new parallel set up of the experiment which eliminated any external factors influencing results.

Moving on, the dimensional speciation of the particles (Table S7) highlighted a significant contribution of fine particulates. Regardless of oven type, operational phase, or fuel type, between 84 and 100 % of emitted particles fall within the category of  $\text{PM}_{2.5}$ . This means that wood-fired ovens emit mostly fine particles, which is in line with the observations made in other studies on biomass combustion (McDonald et al., 2000). This resulted in no significant differences between the concentrations of  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$ , since almost all the particles falling under the former category are also included in the latter. Consequently, mean  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  concentrations from wood-fired ovens fall within a similar range to the one observed for TSP: between  $125 \text{ mg Nm}^{-3}$  (13 %  $\text{O}_2$ ) and  $416 \text{ mg Nm}^{-3}$  (13 %  $\text{O}_2$ ). For this reason, no additional data elaboration is presented since the same considerations made for TSP also apply in this case.

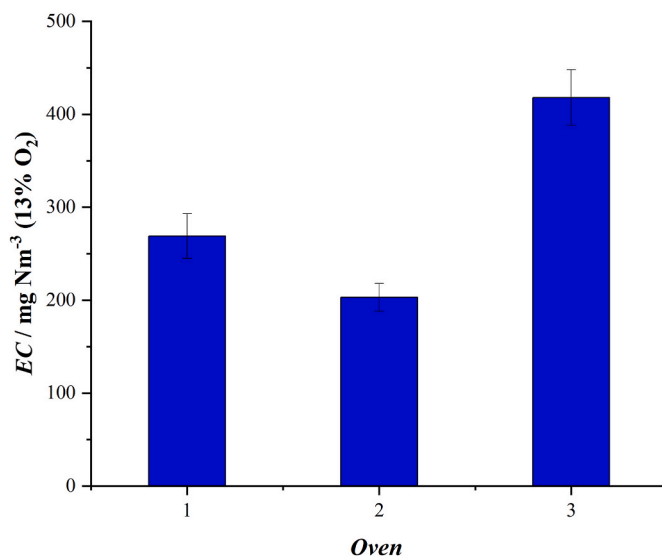


Fig. 5. Mean TSP concentrations of the three ovens tested.

**Table 1**

TSP<sub>conc</sub> and TSP<sub>dil</sub> concentrations in experimental trials conducted on the third oven.

Date	Operational Phase	Fuel	TSP <sub>conc</sub> / mg Nm <sup>-3</sup> (13 %O <sub>2</sub> )	TSP <sub>dil</sub> / mg Nm <sup>-3</sup> (13 %O <sub>2</sub> )
22/04/24	Cold Ignition	Beechwood Logs	239	454
22/04/24	Cold Ignition	Beechwood Logs	257	292
22/04/24	Cold Ignition	Beechwood Logs	186	181
23/04/24	Cooking	Beechwood Logs	229	256
23/04/24	Cooking	Beechwood Logs	250	319
23/04/24	Cooking	Beechwood Logs	195	296
24/04/24	Hot reignition	Beechwood Logs	322	514
24/04/24	Hot reignition	Beechwood Logs	422	423
24/04/24	Hot reignition	Beechwood Logs	558	568
02/05/24	Cold Ignition	Beechwood Logs	270	566
02/05/24	Cold Ignition	Beechwood Logs	139	237
02/05/24	Cold Ignition	Beechwood Logs	202	262
03/05/24	Cooking	Beechwood Logs	283	483
03/05/24	Cooking	Beechwood Logs	240	360
03/05/24	Cooking	Beechwood Logs	280	476
07/05/24	Cooking	Beechwood Logs	406	591
07/05/24	Cooking	Beechwood Logs	245	397
07/05/24	Cooking	Beechwood Logs	375	558
09/05/24	Hot reignition	Beechwood Logs	523	823
09/05/24	Hot reignition	Beechwood Logs	232	345
10/05/24	Cooking	Beechwood Logs	375	506
10/05/24	Cooking	Beechwood Logs	322	446
10/05/24	Cooking	Beechwood Logs	271	426

### 3.3. Polycyclic aromatic hydrocarbons emissions

PAH emissions were initially assessed by summing the contribution of all 16 EPA-PAHs in the particulate, condensate and gaseous phases, and expressed as Total PAH-sum (Table S8).

Main effects ANOVA statistical analysis highlighted a significant effect of the operational phase ( $F(2,22) = 4.27218$ ;  $p = 0.027$ ), whereas oven type ( $F(1,22) = 1.75013$ ;  $p = 0.199$ ) and fuel type ( $F(1,22) = 0.66876$ ;  $p = 0.422$ ) did not have a significant impact on Total PAH-sum emissions. Greater emissions were associated with cold ignition, as opposed to the stationary and cooking phases (Fig. 6).

This is probably due to a greater amount of incomplete combustion during the cold ignition phase, which is known to generate PAHs (European Environment Agency, 2023). Specifically, the lower temperatures in the combustion chamber during ignition may have favored the formation of these compounds. This is like what was observed for CO and OGC, which are also formed primarily from incomplete combustion of wood. However, unlike OGC, cooking operations did not have a significant impact on total PAH emissions, as highlighted by the lack of difference between the emissions of the stationary and the cooking phase, suggesting a primary role of fuel combustion. Moreover, a great variability was also associated with the emissions of PAHs, once again underscoring the nature of batch working systems in which the emissions of most pollutants are highly dependent on the combustion quality of each fuelwood load.

Moving on, Table S9 shows the individual contribution of the particulate, condensate, and gaseous phase to the total emissions of PAHs from wood-fired ovens. The results show that most of the PAHs emitted are partitioned in the gaseous phase, regardless of the operational phase. However, whereas the relative contribution of PAHs in the particulate, gaseous and condensate phases is similar during ignition and cooking, their distribution changes during the stationary phase in which there is a lower relative contribution of PAHs in the gaseous phase (63 %) and a higher contribution of PAHs in the particulate phase (33 %). This is in line with the results obtained for OGC, in which the stationary phase was associated with lower emissions of this class of pollutants. Evidently, the better quality of combustion during the stationary phase decreases the amount of volatile organic compounds emitted, including PAHs.

Finally, concentrations of individual PAHs were calculated to evaluate the relative impact of each species (Tables S10 and S11). Naphthalene was the most abundant PAH emitted, making up 49 % of total PAH emissions during the cold-ignition phase, 56 % during the stationary phase, and 64 % during the cooking phase. Other notable

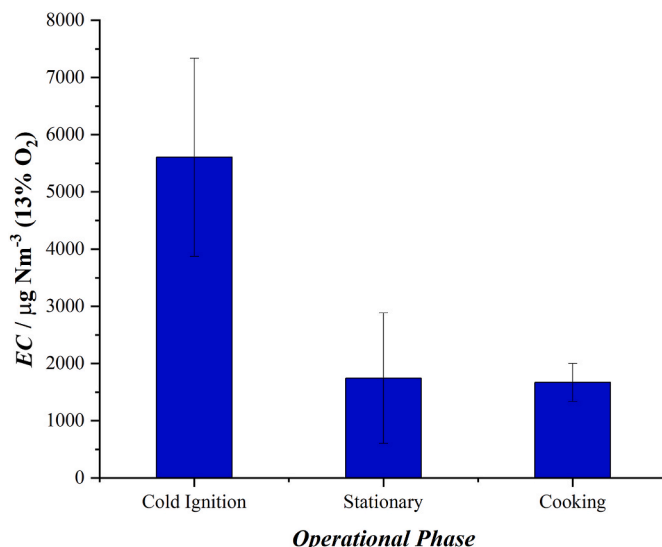


Fig. 6. Mean Total PAH-sum concentrations in each operational phase studied.

contributors included acenaphthylene, phenanthrene, fluoranthene, and pyrene, each accounting for between 4 and 18 % of total emissions. All other PAHs contributed minimally, with each accounting for less than 3 % of the total emissions.

Overall, the most abundant PAHs emitted by wood-fired ovens were low- and medium-molecular weight compounds (LMW and MMW), which were primarily found in the gaseous and/or condensate phases (Fig. 7). Specifically, naphthalene, acenaphthylene, and phenanthrene were almost exclusively present in the gaseous phase, while fluoranthene and pyrene were distributed more evenly between the condensate and particulate phases, with a small contribution from the gaseous phase. Overall, emissions from the wood-fired oven were dominated by LMW-PAHs, which accounted for over 80 % of total emissions, followed by MMW-PAHs contributing between 11 and 14 %. High molecular weight (HMW) PAHs made up only 2–6 % of the total emissions.

### 3.4. Air pollutant emission factors

Assigning a single emission factor, along with its associated error, is crucial for compiling emissions inventories and provides valuable information for regulatory agencies to assess the impact of the source under investigation on air pollution; in this case, wood-fired ovens. Considering that commercial establishments may operate the ovens in different ways and have different daily and weekly usage times, it is difficult to obtain one single value that is representative of emissions. Indeed, there are establishments which are open daily and make constant use of the oven, whereas in other cases the use of the oven is only sporadic. This means that the relative contribution of the different operational phases may be different from case to case and therefore the emission factors may vary. However, a reasonable assumption is that most establishments use the oven regularly (six days a week) with a daily operation of 8 h: 4 h during lunch service and 4 h during dinner service.

In this scenario, the wood-fired oven remains inactive only during the closing day of the commercial activity, meaning that it never cools down completely to room temperature. Most pizza chefs leave the embers from the last days of operation and close the oven to ensure that the temperature remains between 80 and 180 °C when operations are ready to resume after the day of rest. In terms of emission factor calculation, this means that the cold-ignition phase is almost never performed. Instead, hot-reignition is carried out daily to bring the oven back up to temperature (350–400 °C), lasting around 30 min. Once the oven reaches the operating temperature, pizza cooking begins and, depending on the daily clientele and pizza requests, the oven operates around 75 % of

the time with pizza cooking inside and the remaining 25 % solely with wood-burning to maintain the temperature.

Based on these considerations, final emission factors were calculated for each air pollutant investigated, using Equation (3) (Table 2).

These values are proposed for inclusion in emission inventory guidebooks, as they more accurately reflect the actual emissions from wood-fired ovens compared to the currently listed values, which pertain to similar but not identical appliances. Indeed, the observed differences can be directly attributed to the specific characteristics of wood-fired ovens. For example, the proposed CO emission factor for wood-fired ovens is nearly double the current guidebook value, largely due to higher emissions during the ignition and cooking phases, the latter being distinctive to these appliances. In contrast, the proposed NO<sub>x</sub> emission factor is lower than the current AEIG value, partly due to the elevated CO concentrations typically present in the oven chamber, another unique aspect of wood-fired ovens. A significant difference is also observed in emissions of volatile compounds: the proposed emission factor for OGC is substantially lower than the guidebook value and aligns more closely with those reported for modern, advanced firewood stoves (Klauser et al., 2018).

**Table 2**  
Air pollutant emission factors of wood-fired ovens.

Pollutant	Emission Factor	Standard Error	Unit
NO <sub>x</sub>	85	3	g GJ <sup>-1</sup>
CO	1038	59	g GJ <sup>-1</sup>
OGC	71	10	g GJ <sup>-1</sup>
TSP	233	21	g GJ <sup>-1</sup>
PM <sub>10</sub>	162	16	g GJ <sup>-1</sup>
PM <sub>2.5</sub>	157	16	g GJ <sup>-1</sup>
Total PAH-sum	1482	883	mg GJ <sup>-1</sup>
Naphthalene	852	249	mg GJ <sup>-1</sup>
Acenaphthylene	153	55	mg GJ <sup>-1</sup>
Acenaphthene	4	1	mg GJ <sup>-1</sup>
Fluorene	24	10	mg GJ <sup>-1</sup>
Phenanthrene	194	57	mg GJ <sup>-1</sup>
Anthracene	24	9	mg GJ <sup>-1</sup>
Fluoranthene	84	26	mg GJ <sup>-1</sup>
Pyrene	68	23	mg GJ <sup>-1</sup>
Benz[a]anthracene	13	5	mg GJ <sup>-1</sup>
Chrysene	13	5	mg GJ <sup>-1</sup>
Benzo[b]fluoranthene	20	8	mg GJ <sup>-1</sup>
Benzo[k]fluoranthene	5	2	mg GJ <sup>-1</sup>
Benzo[a]pyrene	12	5	mg GJ <sup>-1</sup>
Indeno[1,2,3-cd]pyrene	10	5	mg GJ <sup>-1</sup>
Dibenz[a,h]anthracene	1	1	mg GJ <sup>-1</sup>
Benzo[ghi]perylene	7	3	mg GJ <sup>-1</sup>

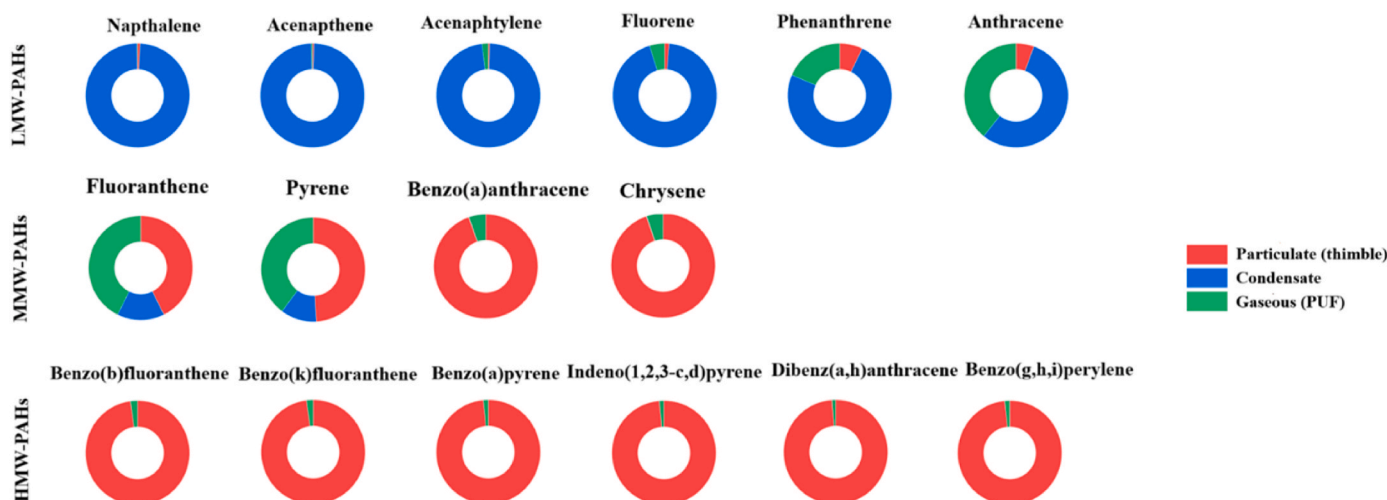


Fig. 7. Distribution of each PAH emitted from the wood-fired ovens in the particulate (thimble), condensate, and gaseous (PUF) phase.

Turning to particulate matter, the TSP emission factor is higher than the AEIG value, primarily due to the greater quantity of fuelwood consumed in larger ovens, such as the third oven tested in this study. Regarding PAH emission factors, comparisons with AEIG values are possible only for benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, and indeno(1,2,3-cd)pyrene. For all but the latter, the emission factors reported in this study are consistent with the values currently listed in the guidebook, whereas the emission factor for indeno(1,2,3-cd)pyrene is slightly lower. When compared to a similar study on small-scale wood-burning appliances (Ozgen et al., 2014), the emission factors for these four PAHs are generally lower than those associated with most beechwood-fueled devices and are comparable to the average emissions observed for closed fireplaces.

#### 4. Conclusions

In this study, the emission factors for the major air pollutants emitted by wood-fired ovens were determined for the first time through experimental tests, replicating the operating conditions of a real-life establishment. As is typical with batch-operated appliances, a wide range of values was observed for all macropollutants and PAHs. The operational phase and the oven type played an important role in this regard, affecting the emissions of most pollutants and underscoring the need to accurately weight each phase's contribution when calculating final emission factors. To reflect territorial diversity, results from all oven types tested were incorporated into the final analysis. While most values fell within the broad range observed in existing literature, some discrepancies were noted when compared to the values currently proposed in the AEIG. The experimental emission factors from this study are therefore suggested as alternatives to those currently found in the guidebook and can be used by regulatory agencies to evaluate public health risks associated with wood-fired ovens in different areas and, if necessary, enact targeted measures for the abatement of specific pollutants.

#### CRedit authorship contribution statement

**Andrea Bergomi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation. **Gabriele Migliavacca:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Silvia Bertagna:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation. **Mattia Borelli:** Data curation. **Salvatore Chiavarini:** Formal analysis. **Valeria Comite:** Data curation. **Ilaria D'Elia:** Writing – review & editing, Formal analysis, Data curation. **Paola Fermo:** Writing – review & editing, Resources. **Teresa M.G. La Torretta:** Writing – review & editing, Validation, Investigation, Formal analysis, Data curation. **Antonio Piersanti:** Writing – review & editing, Data curation. **Milena Stracquadanio:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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#### 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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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envpol.2025.126948>.

#### Data availability

I have shared the link to my data at the Attach Files step.

#### References

- Bergomi, A., 2025. *Characterization of Air Pollution and Air Quality Using Innovative Sampling Methods and Analytical Techniques for Regulated and Non-regulated Pollutants*. University of Milan, Milan, Italy. Doctoral dissertation.
- Bergomi, A., Morreale, C., Fermo, P., Migliavacca, G., 2022. Determination of pollutant emissions from wood-fired pizza ovens. *Chem. Eng. Trans.* 92, 499–504. <https://doi.org/10.3303/CET2292084>.
- Bojes, H.K., Pope, P.G., 2007. Characterization of EPA's 16 priority pollutant polycyclic aromatic hydrocarbons (PAHs) in tank bottom solids and associated contaminated soils at oil exploration and production sites in Texas. *Regul. Toxicol. Pharmacol.* 47, 288–295. <https://doi.org/10.1016/j.yrtph.2006.11.007>.
- Business Research Insights, 2025. Pizzas market size, share, growth, and industry analysis by type (9 inches, 12 inches, 14 inches & other) by application (supermarket, restaurant, retail store & other) regional forecast by 2033. <https://www.businessresearchinsights.com/market-reports/pizzas-market-102575>. (Accessed 27 January 2025).
- Caserini, S., Ozgen, S., Galante, S., Giugliano, M., Hugony, F., Migliavacca, G., Morreale, C., 2014. Fattori di emissione dalla combustione di legna e pellet in piccoli apparecchi domestici. *IDA* 1, 27–46. <https://hdl.handle.net/11311/874754>.
- Directive 2881/2024, 2024. Directive (EU) No 2881/2024 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe. <https://eur-lex.europa.eu/eli/dir/2024/2881/oj/eng>. (Accessed 7 July 2025).
- European Environment Agency, 2023. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023 – Technical Guidance to Prepare National Emission Inventories. Publications Office of the European Union. Report 06/2023. <https://data.europa.eu/doi/10.2800/795737>. (Accessed 15 July 2025).
- Falciano, A., Masi, P., Moresi, M., 2022. Performance characterization of a traditional wood-fired pizza oven. *J. Food Sci.* 87, 4107–4118. <https://doi.org/10.1111/1750-3841.16268>.
- Falciano, A., Masi, P., Moresi, M., 2024. Unlocking the secrets of Neapolitan pizza: a concise review of wood-fired, electric, and gas pizza ovens. *J. Food Sci.* 89, 6966–6984. <https://doi.org/10.1111/1750-3841.17417>.
- Ghafghazi, S., Sowlati, T., Sokhansanj, S., Bi, X., Melin, S., 2011. Particulate matter emissions from combustion of wood in district heating applications. *Renew. Sustain. Energy Rev.* 15, 3019–3028. <https://doi.org/10.1016/j.rser.2011.04.001>.
- Grand View Research, 2021. Pizza oven market size, share & trends analysis report by type, by fuel used, by end use (residential, commercial), by distribution channel, by region, and segment forecasts, 2023 – 2030. <https://www.grandviewresearch.com/industry-analysis/pizza-oven-market-report>. (Accessed 27 January 2025).
- Hanover College, n.d. Main effects and Interactions. [https://psych.hanover.edu/classes/researchmethods/readings/main\\_effects\\_and\\_interactions.pdf](https://psych.hanover.edu/classes/researchmethods/readings/main_effects_and_interactions.pdf) (accessed 27 January 2025).
- Hugony, F., 2020. Progetto Metropizza (Incontro Conclusivo). ENEA, Città Metropolitana di Milano. <https://www.energiaenergetica.enea.it/vi-segnaliamo/milano-28-gennaio-2020-meeting-conclusivo-del-progetto-metro-pizza.html>. (Accessed 28 January 2025).
- INEMAR - ARPA Lombardia, 2024. INEMAR, Inventario Emissioni in Atmosfera: emissioni in Regione Lombardia nell'anno 2021 - versione in revisione pubblica.

- ARPA Lombardia Settore Monitoraggi Ambientali. <https://inemar.arpalombardia.it/inemar/webdata/main.seam>. (Accessed 28 January 2025).
- Klauser, F., Carlon, E., Kistler, M., Schmid, C., Schwabl, M., Sturmlechner, R., Haslinger, W., Kasper-Giebl, A., 2018. Emission characterization of modern wood stoves under real-life oriented operating conditions. *Atmos. Environ.* 192, 257–266. <https://doi.org/10.1016/j.atmosenv.2018.08.024>.
- Krumal, K., Mikuska, P., Horak, J., Jaroch, M., Hopan, F., Kubonova, L., 2023. Gaseous and particulate emissions from the combustion of hard and soft wood for household heating: influence of boiler type and heat output. *Atmos. Pollut. Res.* 14, 101801. <https://doi.org/10.1016/j.apr.2023.101801>.
- McDonald, J.D., Zielinska, B., Fujita, E.M., Sagebiel, J.C., Chow, J.C., Watson, J.G., 2000. Fine particle and gaseous emission rates from residential wood combustion. *Environ. Sci. Technol.* 34, 2080–2091. <https://doi.org/10.1021/es9909632>.
- Moresi, M., Falciano, A., Cimini, A., Masi, P., 2024. Unveiling the carbon footprint of True Neapolitan Pizza: paving the way for eco-friendly practices in pizzerias. *Ital. J. Food Sci.* 35, 106–119. <https://doi.org/10.15586/ijfs.v36i4.2598>.
- Mota Lima, F.D., Perez-Martinez, P.J., de Fatima Andrade, M., Prashant, K., de Miranda, R.M., 2020. Characterization of particles emitted by pizzerias burning wood and briquettes: a case study at Sao Paulo, Brazil. *Environ. Sci. Pollut. Res.* 27, 35875–35888. <https://doi.org/10.1007/s11356-019-07508-6>.
- NYC Environmental Protection, 2016. New York city air pollution control Code. <https://www.nyc.gov/assets/dep/downloads/pdf/air/air-pollution-control-code.pdf>. (Accessed 27 January 2025).
- Ozgen, S., Caserini, S., 2018. Methane emissions from small residential wood combustion appliances: experimental emission factors and warming potential. *Atmos. Environ.* 189, 164–173. <https://doi.org/10.1016/j.atmosenv.2018.07.006>.
- Ozgen, S., Caserini, S., Galante, S., Giugliano, M., Angelino, E., Marongiu, A., Hugony, F., Migliavacca, G., Morreale, C., 2014. Emission factors from small scale appliances burning wood and pellets. *Atmos. Environ.* 94, 144–153. <https://doi.org/10.1016/j.atmosenv.2014.05.032>.
- Ozgen, S., Cernuschi, S., Caserini, S., 2021. An overview of nitrogen oxides emissions from biomass combustion for domestic heat production. *Renew. Sustain. Energy Rev.* 135, 110113. <https://doi.org/10.1016/j.rser.2020.110113>.
- Patel, A.B., Shaikh, S., Jain, K.R., Desai, C., Madamwar, D., 2020. Polycyclic aromatic hydrocarbons: sources, toxicity, and remediation approaches. *Front. Microbiol.* 11, 562813. <https://doi.org/10.3389/fmicb.2020.562813>.
- Regulation 1185/2015, 2015. Regulation (EU) No 1185/2015 of 24 April 2015 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for solid fuel local space heaters. <http://eur-lex.europa.eu/eli/reg/2015/1185/oj/eng>. (Accessed 7 July 2025).
- Roy, M.M., Corscadden, K.W., 2012. An experimental study of combustion and emissions of biomass briquettes in a domestic wood stove. *Appl. Energy* 99, 206–212. <https://doi.org/10.1016/j.apenergy.2012.05.003>.
- Schön, C., Hartmann, H., 2012. Combustion of wood briquettes in stoves. In: 20<sup>th</sup> European Biomass Conference and Exhibition, 18–22 June. Milan, Italy. [https://www.tfz.bayern.de/mam/cms08/festbrennstoffe/dateien/cp\\_combustion\\_of\\_wood\\_briquettes\\_in\\_stoves\\_-\\_eu\\_bc\\_e\\_milan\\_2012.pdf](https://www.tfz.bayern.de/mam/cms08/festbrennstoffe/dateien/cp_combustion_of_wood_briquettes_in_stoves_-_eu_bc_e_milan_2012.pdf).
- Schön, C., Hartmann, H., Turowski, P., 2013. Measurement strategies influencing the results of total particle emission from biomass combustion. In: 21<sup>st</sup> European Biomass Conference and Exhibition, 3–7 June. Copenhagen, Denmark. [https://www.tfz.bayern.de/mam/cms08/festbrennstoffe/dateien/cp\\_measurement\\_strategies\\_influencing\\_the\\_results\\_of\\_total\\_particle\\_emission\\_from\\_biomass\\_combustion\\_-\\_eu\\_bc\\_e\\_copenhagen\\_2013.pdf](https://www.tfz.bayern.de/mam/cms08/festbrennstoffe/dateien/cp_measurement_strategies_influencing_the_results_of_total_particle_emission_from_biomass_combustion_-_eu_bc_e_copenhagen_2013.pdf).
- Ufficio Federale dell'Ambiente UFAM, 2018. Misurazione delle emissioni degli impianti a combustione alimentati con olio, gas o legna – Raccomandazioni per la misurazione delle emissioni degli impianti a combustione, second ed. Confederazione Svizzera [www.bafu.admin.ch/uv-1319-i](http://www.bafu.admin.ch/uv-1319-i). (Accessed 28 January 2025).
- Wolters, R., 2018. *EU Policy regarding Emission Reduction from Domestic Combustion* (DG ENV/C3 Clean Air). European Commission.