environments

MDPI

Article

Evaluation of PM2.5 Excess Pollution in Ambient Air from Different Wood Heating Systems, Using Optical Sensors in Individual Houses in France

Jean-Baptiste Renard [1,*], Jérémy Surcin [2], Tony Renucci [3], Eric Poincelet [4], Thomas Bourdrel [5] and Isabella Annesi-Maesano [6]

[1] LPC2E-CNRS, 45000 Orléans, France
[2] AirCityWeather, 41300 Salbris, France; jeremy.surcin@protonmail.com
[3] Respire, 75010 Paris, France; tony@respire-asso.org
[4] Pollutrack, 75020 Paris, France; e.poincelet@gmail.com
[5] ICube, 67000 Strasbourg, France; thomasbourdrel@yahoo.fr
[6] Department of Environmental and Prevention Sciences, University of Ferrara, 44121 Ferrara, Italy; isabella.annesi-maesano@inserm.fr
* Correspondence: jean-baptiste.renard@cnrs-orleans.fr

Abstract

Wood-burning fireplaces with inserts, wood-burning stoves, and pellet stoves are widely used as heating systems and as alternatives to fossil-fuel-based heating, although the particulate matter they emit can pose a significant risk to public health. A field campaign was conducted in France during the 2025–2026 winter season using several optical sensors (Pollutrack, LOAC2, and bcMeter) deployed in 44 individual houses to better characterize PM2.5 concentrations, particle size distributions, and the proportion of black carbon in emissions from these three heating systems. The measurement strategy relies on an original approach to estimating excess pollution, defined as the additional contribution of heating-related emissions to background ambient air pollution, using sensors strategically positioned both inside and around the houses. Emissions from fireplaces with inserts and wood-burning stoves can locally increase PM2.5 concentrations to several tens of $\mu g.m^{-3}$. Pellet stoves exhibit the lowest PM2.5 mass concentrations, although particle number concentrations for particles between 0.15 and 1 µm are similar across the different heating systems. Pellet stoves may also contribute to local increases in secondary aerosol concentrations. On a daily average, these emissions contribute a few $\mu g.m^{-3}$ to ambient PM2.5 concentrations. Finally, the ratio of PM2.5 mass concentration to black carbon mass concentration is approximately 10 indoors and does not appear to be a reliable indicator for distinguishing between the different heating systems. A measurement strategy is also proposed to improve the quantification of excess pollution attributable to residential heating.

Keywords: fireplaces; wood stoves; pellet stoves; individual houses; PM2.5; mass concentrations; number concentrations; black carbon

Academic Editor: William A. Anderson

Received: 14 October 2026
Revised: 10 November 2026
Accepted: 11 November 2026
Published: 14 November 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Wood is one of the main sources of residential heating and is often presented as an alternative to fossil-fuel combustion [1]. For example, in eastern France, wood energy accounts for approximately 20% of domestic energy consumption [2]. Nevertheless, this

 https://doi.org/10.3390/environments13110625

energy source generates significant quantities of chemical compounds that contribute to air pollution. These emissions depend on the combustion device, the type of biomass used, and how the devices are operated by users [3,4]. Because combustion is more or less incomplete, depending on the combustion device and the characteristics of the wood, a variety of pollutants are emitted. The main pollutants are carbon monoxide (CO) and fine particulate matter (PM), followed by polycyclic aromatic hydrocarbons (PAHs) and trace metals [5–7]. PM is generally composed of a central core of black carbon, surrounded by a mixture of light-absorbing organic compounds, commonly referred to as brown carbon [8–10], and a surface containing polycyclic aromatic hydrocarbons (PAHs), metals, and sulfates. Under poor combustion conditions, such as those encountered in open fireplaces burning damp wood, PM is primarily composed of black carbon and PAHs. Conversely, under more favorable combustion conditions, such as those in stoves burning dry wood or pellets, PM contains lower proportions of black carbon and organic carbon. In these cases, PM formation depends primarily on the potassium salt content, which acts as a condensation nucleus for other molecules, thereby promoting secondary particle formation [11]. Such particles are mainly smaller than 1 μm, with a concentration peak in the 0.1–0.2 μm size range [12,13].

For example, in France, residential wood heating contributes, on average, approximately 40% of ambient PM2.5 (particulate matter with an aerodynamic diameter of less than 2.5 μm) emissions by mass [14]. Similarly, a field campaign conducted in Copenhagen, Denmark [15], found that emissions from wood heating were of the same order of magnitude as those from road traffic.

Air pollution from residential wood heating poses a significant public health risk, comparable to that associated with traffic-related emissions [16]. The health risks associated with exposure to wood-burning emissions, as well as the increase in mortality associated with increased PM mass concentrations from wood combustion, have been demonstrated for both outdoor and indoor air pollution [17–20]. These concerns range from short-term effects, such as asthma and cardiovascular diseases, to long-term effects, including cancer.

Field campaigns have been used to estimate the average mass contribution of wood combustion to PM concentrations at the city or regional scale [21–23]. These studies have shown substantial spatial variability in PM concentrations, resulting, as for other PM sources, from the heterogeneous spatial distribution of emission sources, population density, and residential characteristics in urban, suburban, and rural environments. Modeling studies can help investigate the dynamic processes controlling such variability, as well as the transport of PM emitted by wood-burning stoves [24]. Analyses of these field campaigns have shown that different fuel types and combustion-device types can affect PM mass concentrations, particle number concentrations, and particle size distributions, as well as the abundance of nanoparticles. In particular, more recent wood-burning devices may generate higher particle number concentrations in the nanoparticle size range while emitting lower PM mass concentrations than older devices [25].

Measurements can be conducted both outdoors and indoors. Indoor air can be directly contaminated by pollutants emitted from open-hearth fireplaces, but also through leaks from chimneys or the infiltration of outdoor air into houses [26]. Different measurement techniques can be used for this purpose. The most conventional approach relies on mass-concentration instruments used by air-quality monitoring networks to provide regulatory measurements [27]. However, different types of sensors and instruments can also be used for research purposes, including low-cost optical sensors [28], optical instruments such as aethalometers [29], aerosol particle counters [30], and sampling devices for subsequent laboratory analysis [31].

Here, we present a field campaign conducted in France at the single-household scale, using a novel methodological approach based on optical sensors to evaluate the amount of PM2.5 to which inhabitants are exposed when using different residential wood-heating systems: fireplaces with inserts, wood-burning stoves, and pellet stoves. The novelty of the instrumental approach lies in estimating the excess pollution produced by the heating device in each house by subtracting the background PM2.5 mass concentration originating from other sources and influenced by meteorological conditions. For example, high wind speeds can disperse pollutants and thereby dilute their concentrations, whereas anticyclonic conditions can favor pollutant accumulation [32].

2. Materials and Methods

2.1. Instrumentation

Three different instruments are used to monitor the temporal evolution of PM concentrations. The first is the optical aerosol counter Pollutrack, a medium-cost sensor that provides real-time PM2.5 mass concentrations via a 4G connection. The reported values are corrected for ambient relative humidity and, therefore, for the possible hygroscopic growth of the particles [33]. The reproducibility of the sensors for daily averages is 0.4 $\mu g.m^{-3}$, while the absolute accuracy of individual sensors is better than 3 $\mu g.m^{-3}$ [31]. Approximately 50 Pollutrack sensors were used throughout the campaign. In the present study, measurements were conducted using a relative approach based on differences between several Pollutrack sensors operating simultaneously. Given the large number of measurements and the use of this relative approach, a relative accuracy better than 0.4 $\mu g.m^{-3}$ can be assumed. Although the instrument was initially developed for mobile measurements (e.g., on cars or buses [34]), it can also be used at fixed monitoring stations [33]. In the present study, Pollutrack sensors are installed outdoors on the walls of the houses and indoors on furniture, at average human breathing height, in order to characterize the PM concentrations in the air inhaled by the inhabitants.

The second instrument is the low-cost bcMeter, an optical absorption photometer designed to measure black carbon. The instrument is provided by bcMeter (https://bcmeter.org/). It provides measurements of black carbon mass concentrations, with a typical root-mean-square error (RMSE) of approximately 0.1 $\mu g.m^{-3}$ for daily averages, as demonstrated during validation campaigns [35]. It is used for indoor measurements and has a typical operating lifetime of approximately one week, depending on the black carbon concentration, after which the sampling filter becomes excessively loaded.

The third instrument is the LOAC2 aerosol counter, which provides particle number concentrations in 30 size classes over the 0.5–90 μm size range, together with information on particle typology based on measurements performed at four different light-scattering angles [36]. The instrument can distinguish between black carbon, organic particles, various mineral particle families (depending on their optical transparency), and liquid droplets. However, it is not specifically designed to provide a detailed characterization of PM composition. In the present study, LOAC2 is used for indoor measurements only and is installed close to the Pollutrack sensor. In this version of the LOAC2 instrument, data are recorded onboard and processed at the end of the measurement campaign. The error bars associated with the reproducibility between different instruments are estimated at ±20%. The overall counting uncertainty should also include the contribution from Poisson counting statistics, ranging from approximately 60% for aerosol concentrations of 10^{-2} cm^{-3} to approximately 6% for concentrations higher than 1 cm^{-3}.

Finally, meteorological parameters, primarily wind speed and direction, are obtained from the ERA5 reanalysis provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) [37]. However, the 0.1° × 0.1° spatial resolution of the dataset is

insufficient to capture wind speed and direction at the building scale. Therefore, these parameters are considered indicative only.

2.2. Conditions of Measurements

The measurement campaign was conducted in 53 houses in France during the heating periods in late winter 2025 and throughout the 2025–2026 winter. The houses are individual units, limiting contamination from adjacent houses. The campaign involved seven measurement rotations, each including between 5 and 12 houses, with a measurement period of at least three weeks per rotation. The changing meteorological conditions throughout these periods highlight the need for developing an analysis method that is as insensitive as possible to weather conditions. Nine houses were excluded from the analysis because of an insufficient number of measurements, occasional sensor failures, poor 4G connectivity, difficulties in identifying the heating source, or contamination associated with cigarette smoke. Thus, measurements from 44 houses were considered, corresponding to a success rate of 83%. Such a large number of different houses is necessary to statistically identify potential pollution excesses, even though individual measurements may vary due to differences in local conditions.

Figure 1 shows the geographical distribution of the measurement sites in France and the heating systems used by the inhabitants. The selected locations were chosen to represent a range of population densities and geographical conditions, including cities and their suburbs, small villages, and regions ranging from oceanic climates (Atlantic and Mediterranean) with relatively mild winter temperatures to more continental climates with colder winters.

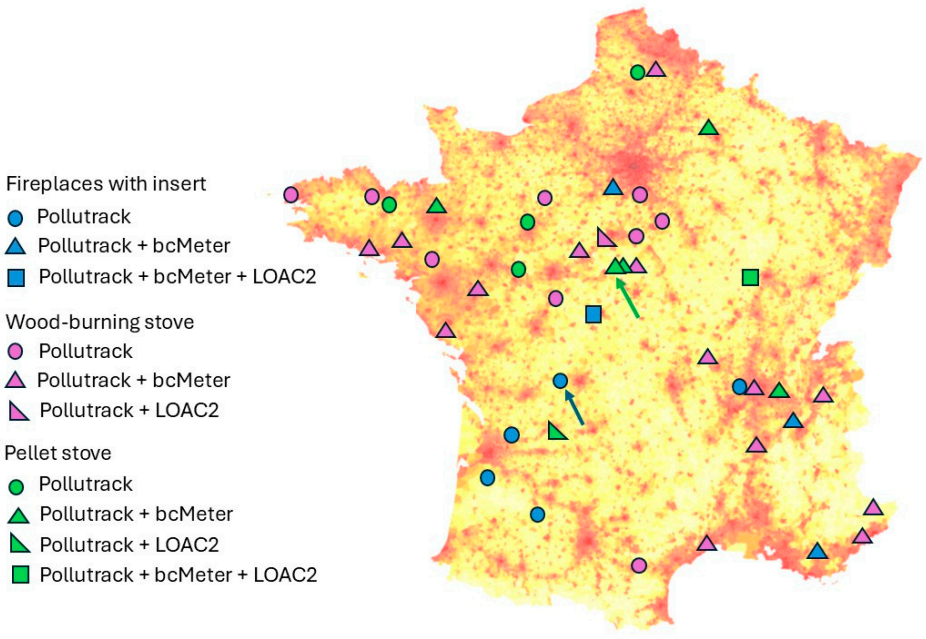


Figure 1. Locations of the measurement sites and associated instruments and heating systems during the field campaign conducted in France during the 2025 and 2026 winter seasons. The background color represents population density, ranging from 5 inhabitants km^{-2} (yellow) to more than 15,000 inhabitants km^{-2} (dark red). The blue arrow indicates the city of Saint-Junien, and the green arrow indicates the city of Salbris, for which examples of measurements are presented further on

Between 2 and 4 Pollutrack sensors were installed at approximately human breathing height on the exterior walls of the selected houses (Figure 2a), with the sensors evenly distributed and positioned close to the cardinal directions (North, East, South, and West).

The number of sensors installed and operated depended on the available mounting locations and the quality of the 4G connection. This approach helps mitigate the influence of wind direction on the local measurement of smoke emitted by wood-burning heating systems. Fine particles in the smoke plume tend to be transported with the wind, and PM2.5 mass concentrations may therefore vary substantially between Pollutrack sensors. At a given time, the PM2.5 concentration measured by the sensor located upwind of the house provides an estimate of the background PM2.5 concentration in the ambient air, outside the local smoke plume. When the smoke plume passes over one of the sensors, a concentration peak can be observed, while the other sensors remain little or unaffected. The excess pollution is therefore estimated at a given time by subtracting the minimum PM2.5 concentration measured simultaneously by the outdoor sensors from the maximum concentration. It should be noted that the background PM2.5 mass concentrations were often relatively low because of the generally windy and rainy weather conditions observed during the 2025 and 2026 winter seasons.

A limitation of this method is that the number of sensors is still too small to ensure that the smoke plume is systematically intercepted by one of the sensors. Consequently, the probability of detecting the plume depends on the continuously changing wind direction. In addition, during strong anticyclonic conditions, which fortunately occurred only rarely during the campaign, the smoke plume could be insufficiently dispersed and could therefore encompass the entire house. Consequently, the outdoor excess pollution attributable to PM2.5 in the smoke plume should be regarded as a lower estimate of the actual excess concentrations.

Another Pollutrack sensor was installed inside each house, close to the heating device (Figure 2b). To estimate the indoor PM2.5 concentration potentially originating from the heating system, the minimum PM2.5 concentration measured simultaneously by the outdoor sensors was subtracted from the indoor concentration. The resulting excess concentration may originate from several processes, including leakage from the heating system or its exhaust system, infiltration of outdoor air into the house, or other indoor human activities. In some houses, a bcMeter and a LOAC2 instrument were also installed indoors to further characterize the particles.



(**a**) (**b**)

Figure 2. Pollutrack sensors installed at a house in the city of Salbris. (**a**) Outdoor sensor installed on an exterior wall. (**b**) Indoor sensor installed on a table close to a pellet stove. The location of the Pollutrack sensor is indicated by a red arrow.

The different measurement sites were grouped into 3 categories (Figure 1): fireplaces with inserts, wood-burning stoves, and pellet stoves. In total, 240 days of Pollutrack measurements were obtained for fireplaces with inserts, 564 days for wood-burning stoves, and 235 days for pellet stoves. For the bcMeter, 50 days of measurements were obtained for fireplaces with inserts, 132 days for wood-burning stoves, and 73 days for pellet stoves. Finally, two LOAC2 instruments were used during four measurement sessions at the end of the campaign: one session for a fireplace with an insert, one for a wood-burning stove, and two for pellet stoves, corresponding to 13, 47, and 50 days of measurements, respectively. These figures illustrate the overall scale of the study and provide a substantial statistical basis for investigating the different measurement conditions and their associated variability.

2.3. Data Analysis

2.3.1. Outdoor Measurements

Pollutrack data are available at one-minute intervals and are aggregated at two different temporal resolutions. The first involves calculating hourly mean values to match the temporal resolution of the meteorological data. The second involves calculating daily mean values, allowing comparisons with regulatory limits and recommended PM2.5 concentration guidelines.

Figure 3 presents the results obtained for a house in the city of Saint-Junien, in southwestern central France, from 26 February to 19 March 2025, equipped with a fireplace with an insert, and for a house in the city of Salbris, in north-central France, from 12 January to 11 February 2026, equipped with a pellet stove. The measurements in Saint-Junien include the highest pollution episodes recorded during the campaign. The effects of fireplace ignition are clearly visible at the end of each weekday as high-concentration peaks, suggesting that the ignition process was not always properly controlled. These events produced the highest PM2.5 concentrations both indoors and outdoors, with the outdoor Pollutrack sensors approaching saturation under the most polluted conditions. In contrast, the measurements in Salbris, where a pellet stove was used, are relatively stable, although a few peaks are observed. These peaks are of lower magnitude than those recorded in Saint-Junien and could be associated with stove ignition phases or with activities unrelated to heating carried out by the inhabitants.

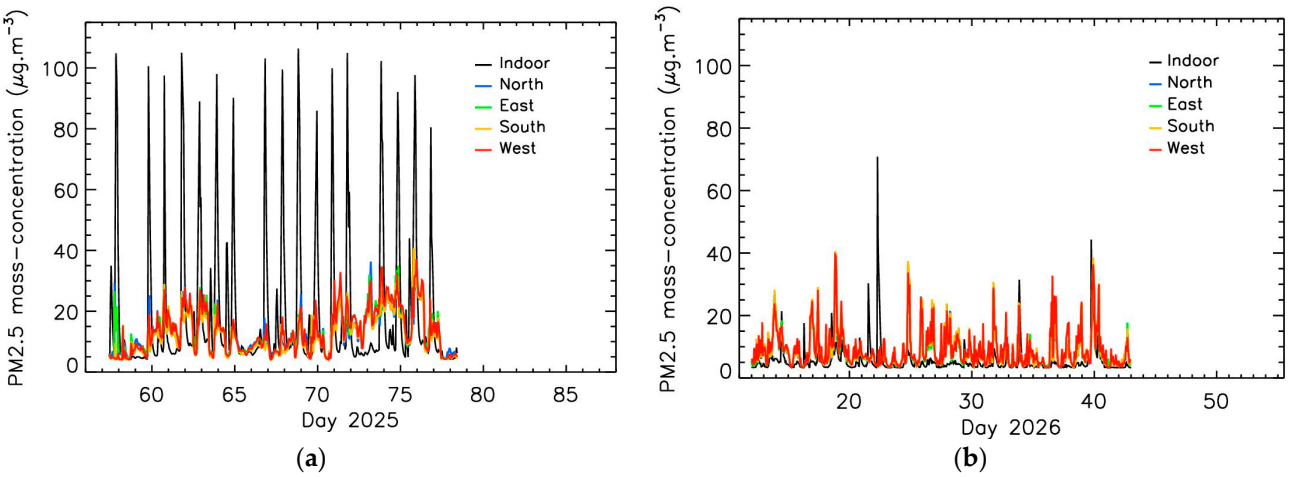


Figure 3. Hourly measurements from the Pollutrack sensors, shown according to their positions relative to the cardinal directions. The values of some measurements are close together and may be difficult to distinguish. (**a**) House located in Saint-Junien (fireplace with insert). (**b**) House located in Salbris (pellet stove).

For each hour, the concentration measured by each outdoor Pollutrack sensor is compared with the concentrations simultaneously recorded by the other sensors located at the different cardinal points. This produces one pairwise difference when only two sensors are operating and six pairwise differences when four sensors are operating. The largest difference, defined as the maximum concentration minus the minimum concentration, is then identified for each hour. Because the wind direction can change over time, the largest difference is not necessarily obtained between the same pair of sensors. As a first approximation, this procedure provides an estimate of the excess PM2.5 concentration within the smoke plume relative to the background ambient-air concentration, which may itself vary over time. It should be noted that the maximum concentration within the plume may occur between two sensors and therefore may be only partially detected or may not be detected at all. Consequently, as discussed above, the excess PM2.5 concentrations derived using this approach should be considered as lower estimates of the actual excess concentrations.

This approach may be subject to uncertainties arising from surrounding pollution sources or local airflow conditions. Pollution from surrounding sources is likely to affect all sensors similarly, primarily contributing to the background concentration, which is removed by the subtraction procedure. Local airflow conditions, on the other hand, may indeed influence the measurements. However, these conditions are expected to vary from one house to another, depending on local topography and the surrounding environment. Such variations should be statistically compensated for and, therefore, should tend to average out when combining data from multiple houses. Finally, higher pollution concentrations were statistically observed for sensors mounted on the side of the house downwind of the chimney, suggesting that the measurements do indeed capture a very localized increase in pollution caused by the chimney plume.

If this relative measurement approach, based on comparisons between different sensors, effectively removes the influence of wind direction and wind speed on the measurements, no systematic relationship should be observed between the mean wind speed derived from ERA5 reanalysis and the detected excess PM2.5 concentration. Otherwise, the excess PM2.5 mass concentration would be expected to decrease as wind speed increases, as is generally observed for total PM2.5 mass concentrations. For example, in Paris (France), the total PM2.5 mass concentration decreases from 20 to 5 $\mu g.m^{-3}$ as wind speed increases from 0 to 12 $m.s^{-1}$ [30]. Although the data analyzed here naturally exhibit some scatter due to local wind effects, the statistical analysis indeed shows no significant dependence of the maximum detected excess PM2.5 concentration on wind speed, within the associated uncertainties, regardless of the heating system considered. The excess PM2.5 concentration remains at 2.1 ± 0.6 $\mu g.m^{-3}$ (1σ) across the wind speed range of 0–12 $m.s^{-1}$. This value could therefore provide a first estimate of the excess pollution attributable to heating systems.

Figure 4 presents the results of these pairwise differences for the Saint-Junien and Salbris houses, based on hourly averages. The differences are generally smaller and less dispersed in Salbris than in Saint-Junien, which may indicate that the excess PM2.5 concentrations within the plume are lower and/or less spatially heterogeneous in the Salbris case.

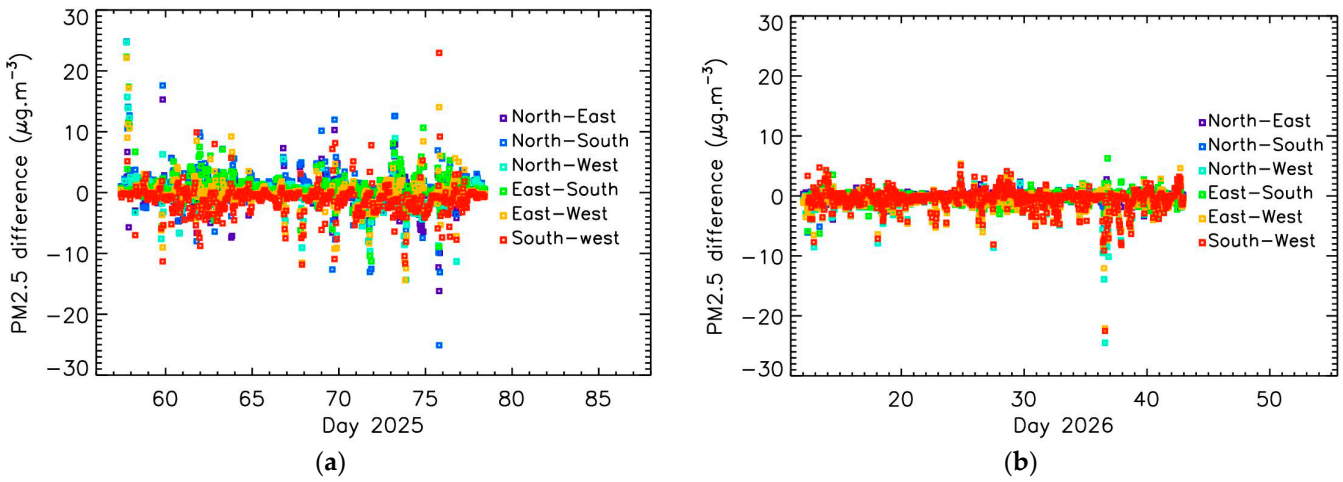


Figure 4. Hourly differences in outdoor PM2.5 concentrations between the various sensors for the same houses as in Figure 3. (**a**) Saint-Junien. (**b**) Salbris.

The same approach is applied to the Pollutrack data aggregated over 24 h. This procedure naturally smooths the fluctuations observed in the hourly values, but it provides an estimate of the daily excess PM2.5 concentration attributable to the smoke plume.

2.3.2. Indoor Measurements

A similar standardized approach to that used for outdoor air is applied to assess the presence of smoke inside the houses. As before, the analysis is performed using both hourly and daily averages. The method consists of estimating the background contribution from outdoor air using the lowest PM2.5 concentration recorded by the outdoor sensors. This value is then subtracted from the corresponding indoor concentration measured over the same time period, either hourly or daily. In a well-ventilated house with no significant indoor pollution sources, similar PM2.5 concentrations would be expected indoors and outdoors. Higher indoor concentrations may result from other activities taking place inside the house. However, if short-duration and intense PM2.5 peaks are temporally correlated between outdoor and indoor air, a heating-related origin may be the most likely explanation. Conversely, lower PM2.5 concentrations indoors than outdoors may indicate either effective ventilation in the house or the presence of a local outdoor source of PM2.5 near the house.

Figure 5 shows the hourly temporal evolution of the excess PM2.5 concentrations inside the houses in the cities of Saint-Junien and Salbris. Saint-Junien is one of the most striking cases of severe indoor air contamination during fireplace ignition. While the indoor concentrations corrected for the outdoor background are generally close to zero, as expected, pronounced pollution peaks reaching several tens of µg.m^{-3} can be observed. In contrast, in Salbris, apart from a few sporadic peaks, the values remain close to zero.

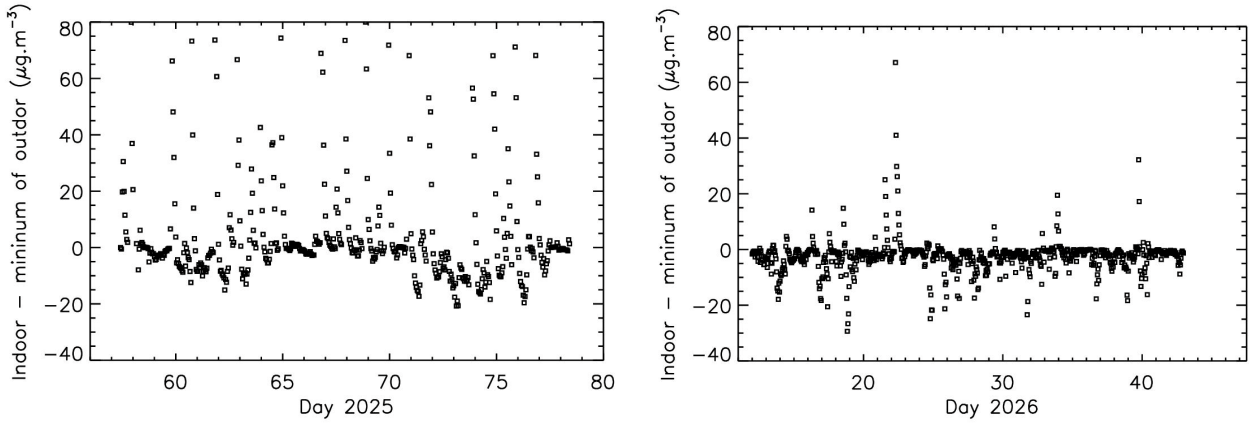


Figure 5. Hourly differences between indoor PM2.5 mass concentrations and background outdoor PM2.5 concentrations for the same houses as in Figure 3. (**a**) Saint-Junien. (**b**) Salbris.

3. Results

3.1. Excess PM2.5 Pollution in Outdoor Air

The results from the Pollutrack sensors vary considerably depending on the type of heating system. Figure 6a,b show the hourly average excess PM2.5 concentrations for sites equipped with a fireplace with an insert or a wood-burning stove, respectively, as well as the mean of the hourly averages. The high variability from one site to another could be explained not only by the position of the sensors relative to the smoke plume, but also by combustion practices, for example, whether or not optimal lighting and combustion practices are followed.

At some sites equipped with a fireplace with an insert or a wood-burning stove, the excess PM2.5 concentration exceeds 5 μg.m^{-3} and can even exceed 15 μg.m^{-3}. The overall average across all sites using these two heating systems is around 3 μg.m^{-3}, with a frequent increase in the early evening. This level of excess pollution may appear low, but it represents an estimate for a single heating device and should be considered a lower-bound estimate. When this excess pollution is added to ambient air pollution, the WHO daily guideline value of 15 μg.m^{-3} (published on 22 September 2021) may be exceeded in many cases, even in areas where ambient air pollution levels are relatively low.

Figure 6c shows the same analysis for pellet stoves. In this case, the results are very similar and stable from one location to another and throughout the day. The overall average excess pollution is around 2 μg.m^{-3}, with little dispersion and no significant hourly variations. This lower value compared with those obtained for the other heating systems is significant in view of the relative accuracy of the Pollutrack sensors. This confirms that, in terms of the mass of PM2.5 emitted, pellet stoves perform better than fireplaces with inserts and wood-burning stoves, at least when considering only PM2.5 mass concentrations [25].

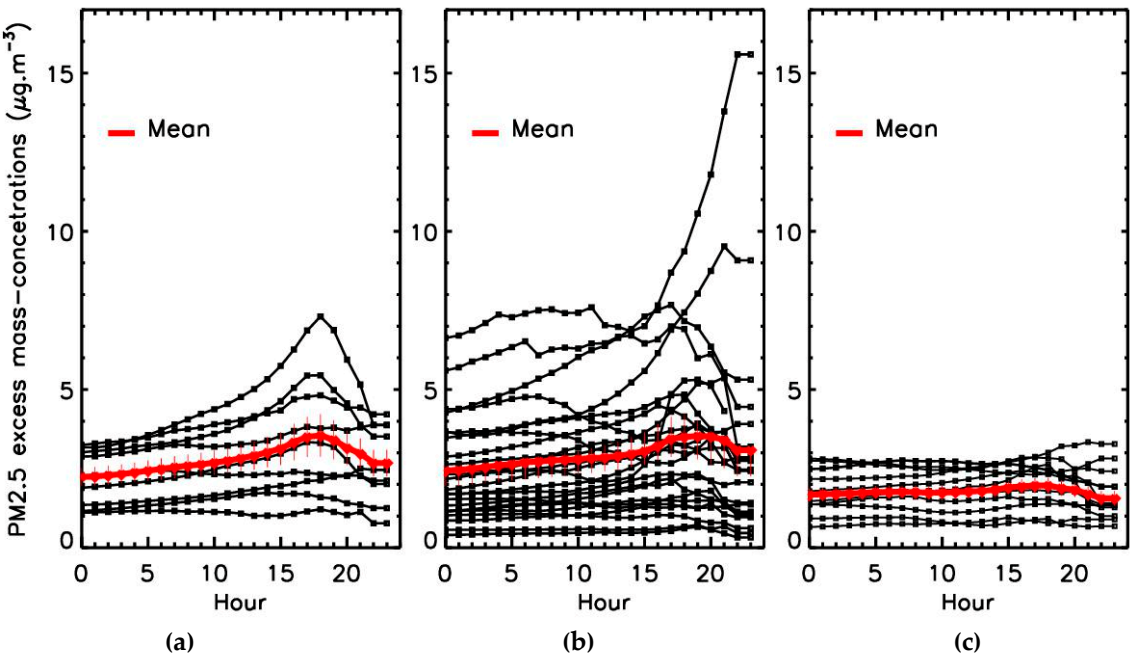


Figure 6. Hourly average excess PM2.5 concentrations in outdoor air: (**a**) fireplace with insert; (**b**) wood-burning stove; (**c**) pellet stove.

Figure 7 presents a histogram of the distribution of hourly mean excess concentrations. For each heating source, the percentage is calculated by dividing the number of values within each concentration range by the total number of measurement hours and multiplying the result by 100. The y-axis is displayed on a logarithmic scale to clearly highlight high-pollution episodes, whose occurrence remains low due to measurement conditions that do not always allow the PM2.5 plume to be captured.

Up to 5 μg.m^{-3}, the curves for the three types of heating are similar. For higher concentrations, similar trends are observed for the excess pollution associated with fireplaces with inserts and wood-burning stoves, with some values exceeding 20 μg.m^{-3}. In contrast, pellet stoves produce virtually no excess pollution above 15 μg.m^{-3}, and the percentages of concentrations between 10 and 15 μg.m^{-3} are approximately three times lower than those observed for the other two types of heating. For values below 2 μg.m^{-3}, the percentage appears to be slightly higher for pellet stoves than for the other two heating types, whereas the trend is reversed above 2 μg.m^{-3}. This could indicate that nanoparticle concentrations, which contribute only weakly to PM2.5 mass concentrations, may be higher for pellet stoves than for the other heating devices [25].

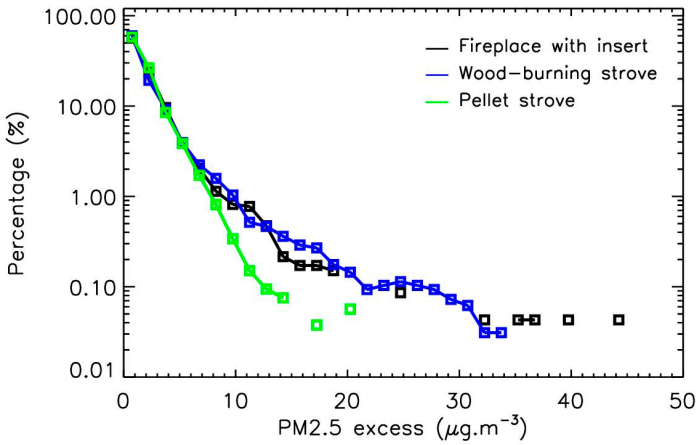


Figure 7. Histogram of hourly averaged excess PM2.5 concentrations in outdoor air.

3.2. Excess PM2.5 Pollution in Indoor Air

The behavior of particles in indoor air may differ from that in outdoor air due to the absence of wind when windows and doors are closed. Larger particles, typically those larger than a few μm, settle rapidly in a room unless an event, such as the presence or movement of a person, causes them to be resuspended [38].

A daily cycle can readily appear in the measurements, related to the activities of the occupants, in addition to possible periods when fireplaces and stoves are relit. This cycle is characterized by periods when indoor air is more polluted than outdoor air and periods when it is less polluted. Accurately describing indoor–outdoor exchanges is complex [39] and is beyond the scope of the present analysis. Nevertheless, under ideal conditions and when considering all local effects, it could be expected that the values of excess indoor pollution relative to outdoor air would be broadly centered around zero, with the values showing a more or less Gaussian distribution.

Thanks to the large number of houses studied and the large number of measurement days, the mean values tend to converge as more data from different houses are included. The histograms of indoor excess pollution generally show a distribution with the most probable value close to 0 μg.m^{-3}. If indoor activities, ventilation, air infiltration, and other processes were the dominant factors influencing indoor excess pollution, similar results would be expected regardless of the heating system used. However, significant differences emerge for positive values depending on the type of heating system (Figure 8a), indicating that indoor air can be globally more polluted than outdoor air. As before, the curves for fireplaces with inserts and wood-burning stoves are similar, with excess pollution reaching up to 100 μg.m^{-3} and approximately 15% of the values exceeding 15 μg.m^{-3}. This indicates that either there are leaks in the smoke evacuation system or that outdoor PM2.5 pollution may partly enter the house, particularly through air intakes and various openings.

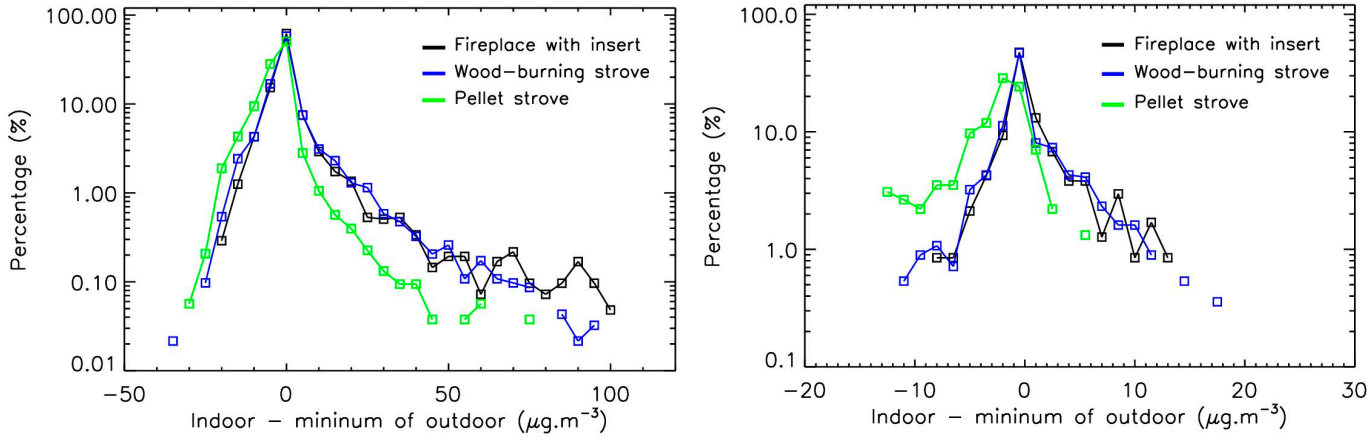


Figure 8. Histogram of excess PM2.5 pollution in indoor air compared to outdoor air: (**a**) hourly average; (**b**) daily average.

For pellet stoves, the curve is much more symmetrical, once again showing that excess pollution is lower. Nevertheless, the maximum percentage is no longer centered around zero, but rather around negative values. This effect is even more apparent for the daily averages (Figure 8b), for which the most probable value occurs around −2 μg.m^{-3}, with values reaching as low as −15 μg.m^{-3}. This indicates that outdoor air may be more polluted than indoor air, a phenomenon that was not observed with the other types of heating. One possible explanation is that secondary aerosols are produced in the immediate outdoor environment around the house and detected by the Pollutrack sensors,

originating from ultrafine particles and gaseous emissions such as volatile organic compounds and PAHs [40,41]. This is consistent with the high combustion efficiency of pellets, which tend to be converted predominantly into gaseous products and ultrafine particles [25], whereas the less efficient combustion associated with fireplaces with inserts and wood-burning stoves produces larger amounts of coarse PM due to incomplete combustion [12]. Nevertheless, this hypothesis assumes that the emitted gases and the subsequently formed secondary aerosols are more or less equally distributed around the house, which needs to be confirmed.

3.3. Size Distribution in Indoor Air

The LOAC2, which counts particles, provides access to particle size distributions, i.e., the number of particles as a function of their size across 19 size classes. Note that, due to calibration issues, the lower size limit of the distributions differs among the two LOAC2 units used in this study. First, the intercomparison between the PM2.5 mass concentrations measured by LOAC2 and Pollutrack indoors shows that, as expected, the data from the two sensors are in good agreement on a daily average basis, with the values falling within their respective error bars. It should be recalled that these measurements include the contribution from ambient air in the absence of heating, to which the contribution from heating-related particles is added.

Then, the time evolution of the concentrations in the 19 size classes shows that daily cycles appear in the LOAC2 measurements, with the highest values during the daytime and the lowest values at night, when the occupants are sleeping, combustion intensity decreases, or when the house is unoccupied. Figure 9 shows the average particle size distributions for the four houses studied, considering all measurements regardless of daily variations. The size-distribution curves only show the descending part of the distributions, indicating that, as expected [42], the maximum concentrations occur below 0.15 µm.

The typological information provided by LOAC2 shows the presence of carbonaceous particles, as well as a strong presence of hydrated particles across almost all size ranges, probably related to the high humidity conditions during the winter of 2025–2026. Some of these particles could also be secondary aerosols that have condensed and are optically transparent, but which LOAC2 cannot distinguish from water droplets.

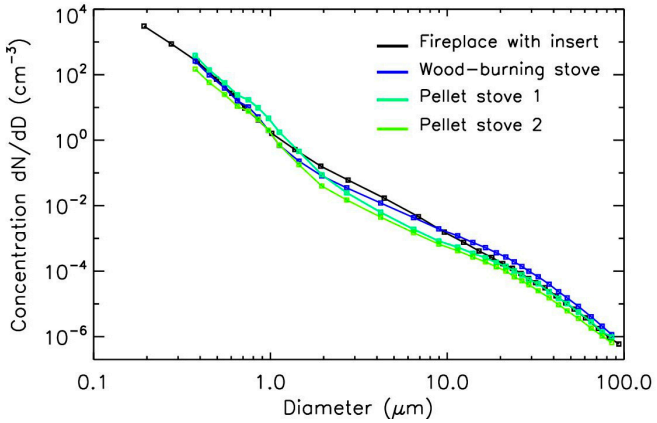


Figure 9. Particle size distributions in indoor air according to the heating system (note that measurements were conducted in two different houses equipped with pellet stoves).

The concentrations of particles smaller than 1 µm are relatively high, which may indicate the presence of fine particles emitted by the heating systems in addition to those already present in ambient air. The coarse mode clearly appears from approximately 2 µm, as indicated by a change in the slope of the concentration decrease. This mode persists

up to approximately 10 μm, followed by a third mode of large particles centered at about 30 μm. This last mode includes both the "grey" dust typically found in indoor air, such as the dust collected in a vacuum cleaner bag, and, in some cases, droplets associated with ambient humidity.

The size-distribution curves for the 4 measurement sites are similar, indicating that daily variations effectively disappear when the measurements are integrated over sufficiently long periods. Nevertheless, due to the small number of houses studied, these results should be considered indicative and require confirmation through additional measurement campaigns.

The values for submicron particles and for particles larger than 10 μm are very similar, within the uncertainty ranges, regardless of the type of heating. However, a significant difference appears between 2 and 10 μm in the coarse mode, with values almost three times lower for pellet stoves than for wood heating. If converted into mass concentrations, these results would indicate that pellet stoves produce fewer large particles and, therefore, lower PM2.5 mass concentrations than wood-burning stoves and fireplaces with inserts, and could thus be considered less polluting. However, this would be an incorrect way of interpreting the results because, when considering particle number concentrations—the parameter that may be more relevant for certain human health assessments [43]—no obvious difference is observed between the three types of heating systems for the most numerous particles detected by LOAC2, i.e., those smaller than 1 μm but larger than 0.2 μm. On the other hand, if pellet stoves produce an excess of ultrafine particles compared with other heating devices, these particles may be too small to be detected by LOAC2.

3.4. Blach Carbon Detection

The ratio of the total PM2.5 concentration to the black carbon concentration resulting from combustion is generally between 5 and 100 (i.e., black carbon accounts for 1–20% of the PM2.5 mass) in environments influenced by a mixture of primary particulate matter and secondary aerosols, such as those produced by combustion-related heating emissions and rapidly dispersed into the ambient air [44–47]. Figure 10 presents the ratios over time between the Pollutrack and bcMeter mass concentration measurements recorded in the house in Salbris (presented in Figure 2), which is equipped with a pellet stove. The ratios are necessarily scattered due to the low concentrations involved and possible indoor activities unrelated to the pellet stove. Nevertheless, the ratios between the two measurements are generally between 10 and 30.

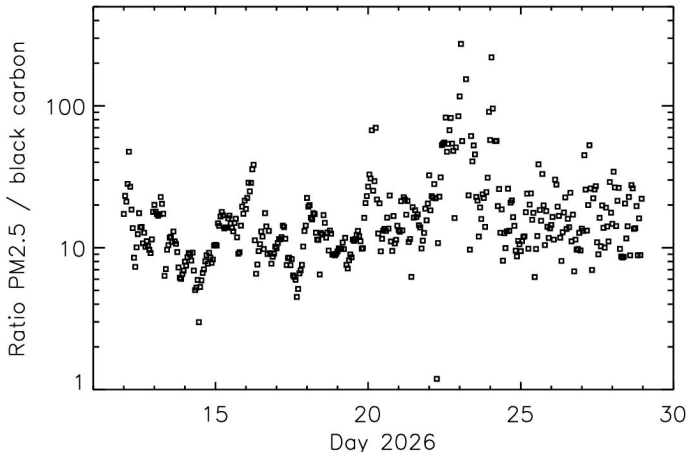


Figure 10. Ratio over time between the Pollutrack and bcMeter mass concentration measurements recorded in a house in Salbris (presented in Figure 2) equipped with a pellet stove.

The histograms of the Pollutrack/bcMeter ratios show very similar behavior for the three types of heating, with mean values between 15 and 25, median ratios between 10 and 14, and most probable values between 8 and 12 (Figure 11), in agreement with typical values reported for such conditions [44–47]. Thus, these ratios based on mass concentrations do not appear to be a relevant indicator for distinguishing between the different types of heating, although they provide robust information on the amount of black carbon that may be inhaled by the occupants of the houses.

A secondary mode appears for ratios between 2 and 4, approximately ten times less frequent than the main mode and therefore accounting for only a few percent of the observations. Such low ratios, detected for both types of stoves, could indicate that occasional emission bursts with a high fraction of black carbon may occur. One possible explanation could be leaks in the smoke-extraction system or excess carbon production during ignition. Nevertheless, these results require confirmation through further measurements and studies to identify their origin.

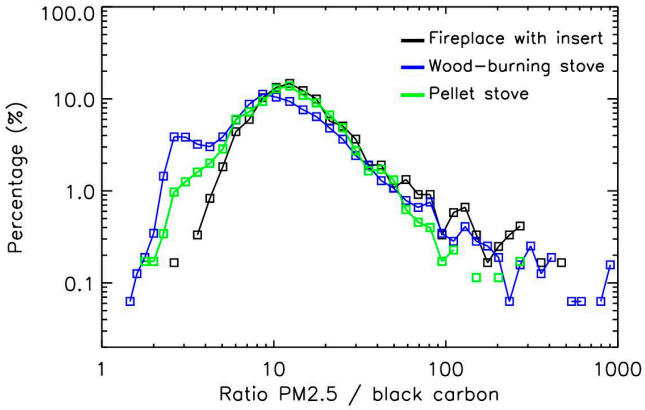


Figure 11. Distribution of the Pollutrack/bcMeter ratios for indoor air for the three different heating systems.

4. Discussion

This measurement campaign has enabled us to propose an original approach for estimating excess pollution, defined as the contribution of heating-related emissions to background ambient air pollution. This new strategy uses sensors strategically positioned around and inside the houses under study. It differs from previous studies based on sampling devices [3,5], which do not allow the short-term evolution of smoke emissions to be investigated, from dedicated optical instruments designed to identify carbonaceous particles from wood burning at several sites [48] and from modelling approaches based on emission inventories combined with data from air quality monitoring networks [8].

Emissions from fireplaces with inserts and wood-burning stoves can locally generate PM2.5 concentrations of up to several tens of $\mu g.m^{-3}$ over hourly periods. On a daily average basis, these emissions amount to a few $\mu g.m^{-3}$ and are therefore added to the PM2.5 concentrations already present in ambient air. Pellet stoves, on the other hand, exhibit the lowest increase in PM2.5 mass concentrations. However, they may still contribute to local increases in outdoor PM2.5 concentrations of a few $\mu g.m^{-3}$ relative to indoor levels through the formation of secondary aerosols. Indoor air quality is also affected, with pollution increments of several tens of $\mu g.m^{-3}$ on an hourly scale compared with background air. These increments may result either from leaks in the fine-particle and gas exhaust system or from outdoor air entering the houses, particularly through various openings. It should be noted that all the values given here are average values for a single household. If houses using these heating systems are relatively far apart, natural atmospheric

dispersion will dilute their effects. Conversely, if the houses are close to one another, for example, in an urban area, a significant cumulative effect may occur in the immediate environment, resulting in a local increase in PM2.5 concentrations.

This initial study shows that the various wood- and pellet-burning heating systems are not without impacts in terms of fine particulate pollution and that the resulting pollution increments are not negligible compared with the WHO guideline value for overall PM2.5 concentrations. It also shows that, if only PM2.5 mass concentrations are considered—which are strongly influenced by larger particles—emissions from pellet stoves would appear to result in lower pollution levels than those from wood-burning stoves and fireplaces with inserts. However, this interpretation may be incomplete because, although pellet stoves produce fewer particles in the 2–10 μm size range, they may generate comparable numbers of fine particles, at least particles between approximately 0.15 and 1 μm. Furthermore, the present study focuses exclusively on particle mass and number concentrations and should be complemented by chemical analyses to better characterize the composition of particulate matter emitted by residential heating systems.

5. Conclusions

The results obtained here should be considered as a lower limit, as the smoke plume could not always be detected by the Pollutrack sensors. A possible next step would be to select one representative house for each type of heating system from the current sample and equip each house with an array of sensors. Typically, twenty or more Pollutrack sensors could be deployed around the house to establish a local map of the direction and intensity of the smoke plume.

Next, ultrafine particles in the 10–500 nm size range should be investigated in both indoor and outdoor air using, for example, a portable SMPS-type instrument. The cost and operational constraints associated with this type of instrument require the continuous presence of an operator, who could move the instrument according to the results obtained from the Pollutrack sensors. In addition, several strategically positioned LOAC2 instruments, both indoors and outdoors, would make it possible to better characterize particulate matter in the 0.15–100 μm size range, identify the types of particles emitted, and assess more precisely the differences in particle-size distributions associated with the various heating systems.

Finally, further work should be carried out to assess the cumulative effects of emissions, which could become significant when houses are located close to one another and use fireplaces or wood-burning stoves. This would make it possible to better estimate the actual exposure to particulate pollution experienced by both the inhabitants of the houses and their neighbors.

Author Contributions: Conceptualization, J.-B.R. and T.R.; methodology, J.-B.R. and J.S.; validation, J.-B.R., J.S. and E.P.; formal analysis, J.-B.R. and J.S.; investigation, J.-B.R., J.S. and T.R.; resources, E.P. and T.R.; data curation, J.S. and T.R.; writing—original draft preparation, J.-B.R.; writing—review and editing, J.S. E.P., T.R., T.B. and I.A.-M.; visualization, J.-B.R.; supervision, J.-B.R., T.R., J.S., E.P., T.B. and I.A.-M.; project administration, T.R.; funding acquisition, T.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Climate Foundation, with grant numbers G-2510-71107 and G-2411-69359, the Clean Air Fund, with grant number 001756, and La Poule Rousse, with grant numbers PR286 and PR448.

Data Availability Statement: The raw datasets generated and analyzed during the current study are available at https://drive.proton.me/urls/56ADQGGRAG#sAaTQEqBIXqm.

Acknowledgments: The authors warmly thank the Verian society for conducting the selection and recruitment of the participating households. We express our deepest gratitude to all the inhabitants of the studied houses for their valuable involvement, operational follow-up, and warm welcome during the 2025 and 2026 winter campaigns.

Conflicts of Interest: Author Jérémy Surcin was employed by the AirCityWeather, Author Eric Poincelet was employed by the Pollutrack. The remaining author declare no conflicts of interest.

References

1. Thomson, H.; Liddell, C. The suitability of wood pellet heating for domestic households: A review of literature. *Renew. Sustain. Energy Rev.* **2015**, *42*, 1362–1369.
2. Zgheib, M.; Quaranta, G.; Tschamber, V.; Trouvé, G. Global warming and human health effects of wood heating life cycle in the Grand-Est region in France. *Biomass Bioenergy* **2023**, *175*, 106879.
3. Mcdonald, J.D.; Zielinska, B.; Fujita, E.M.; Sagebiel, J.C.; Chow, J.C.; Watson, J.G. Fine particle and gaseous emission rates from residential wood combustion. *Environ. Sci. Technol.* **2000**, *34*, 2080–2091.
4. Ozgen, S.; Caserini, S.; Galante, S.; Giugliano, M.; Angelino, E.; Marongiu, A.; Hugony, F.; Migliavacca, G.; Morreale, C. Emission factors from small scale appliances burning wood and pellets. *Atmos. Environ.* **2014**, *94*, 144–153.
5. Orasche, J.; Seidel, T.; Hartmann, H.; Schnelle-Kreis, J.; Chow, J.C.; Ruppert, H.; Zimmermann, R. Comparison of emissions from wood combustion. Part 1: Emission factors and characteristics from different small-scale residential heating appliances considering particulate matter and polycyclic aromatic hydrocarbon (PAH)—Related toxicological potential of particle-bound organic species. *Energy Fuels* **2012**, *26*, 6695–6704.
6. Bari, A.; Baumbach, G.; Brodbeck, J.; Struschka, M.; Kuch, B.; Dreher, W.; Scheffknecht, G. Characterisation of particulates and carcinogenic polycyclic aromatic hydrocarbons in wintertime wood-fired heating in residential areas. *Atmos. Environ.* **2011**, *45*, 7627–7634.
7. Ozgen, S.; Becagli, S.; Bernardoni, V.; Caserini, S.; Caruso, D.; Corbella, L.; DellAcqua, M.; Fermo, P.; Gonzalez, R.; Lonati, G.; et al. Analysis of the chemical composition of ultrafine particles from two domestic solid biomass fired room heaters under simulated real-world use. *Atmos. Environ.* **2017**, *150*, 87–97.
8. Johansson, L.S.; Tullin, C.; Leckner, B.; Sjövall, F. Particle emissions from biomass combustion in small combustors. *Biomass Bioenergy* **2023**, *25*, 435–446.
9. Gonçalves, C.; Alves, C.; Fernandes, A.P.; Monteiro, C.; Tarelho, L.; Evtyugina, M.; Pio, C. Organic compounds in PM2.5 emitted from fireplace and woodstove combustion of typical Portuguese wood species. *Atmos. Environ.* **2011**, *45*, 4533–4545.
10. Zhang, Y.; Albinet, A.; Petit, J.-E.; Jacob, V.; Chevrier, F.; Gille, G.; Pontet, S.; Chrétien, E.; Dominik-Sègue, M.; Levigoureux, G.; et al. Substantial brown carbon emissions from wintertime residential wood burning over France. *Sci. Total Environ.* **2020**, *743*, 140752.
11. Janssen, N.A.H.; Hoek, G.; Simic-Lawson, M.; Fischer, P.; van Bree, L.; ten Brink, H.; Keuken, M.; Atkinson, R.W.; Anderson, H.R.; Brunekreef, B.; et al. Black carbon as an additional indicator of the adverse health effects of airborne particles compared with PM10 and PM2.5. *Environ. Health Perspect.* **2011**, *119*, 1691–1699. https://doi.org/10.1289/ehp.1003369. PMID: 21810552; PMCID: PMC3261976.
12. Bäfver, L.S.; Leckner, B.; Tullin, C.; Berntsen, M. Particle emissions from pellets stoves and modern and old-type wood stoves. *Biomass Bioenergy* **2011**, *35*, 3648–3655.
13. Kleeman, M.J.; Schauer, J.J.; Cass, G.R. Size and Composition Distribution of Fine Particulate Matter Emitted from Wood Burning, Meat Charbroiling, and Cigarettes. *Environ. Sci. Technol.* **1999**, *33*, 3516–3523.
14. Lugon, L.; Kimmerlin, C.; Kim, Y.; Pousset, P.; Achille, J.; Joly, F.; Couvidat, F.; Collet, S.; Cuniasse, B.; Redaelli, M.; et al. Multi-pollutant contribution of wood heating to emissions, concentrations and population exposure during winter time down to the street levels. *J. Hazard. Mater.* **2026**, *506*, 141603.
15. Glasius, M.; Ketzel, M.; Wåhlin, P.; Jensen, B.; Mønster, J.; Berkowicz, R.; Palmgren, F. Impact of wood combustion on particle levels in a residential area in Denmark. *Atmos. Environ.* **2006**, *40*, 7115–7124.
16. Yang, Y.; Ruan, Z.; Wang, X.; Yang, Y.; Mason, T.G.; Lin, H.; Tian, L. Short-term and long-term exposures to fine particulate matter constituents and health: A systematic review and meta-analysis. *Environ. Pollut.* **2019**, *247*, 874–882.
17. Karanasiou, A.; Alastuey, A.; Amato, F.; Renzi, M.; Stafoggia, M.; Tobias, A.; Reche, C.; Forastiere, F.; Gumy, S.; Mudu, P.; et al. Short-term health effects from outdoor exposure to biomass burning emissions: A review. *Sci. Total Environ.* **2021**, *781*, 146739.

18. Borchers-Arriagada, N.; Hoorn, S.V.; Cope, M.; Morgan, G.; Hanigan, I.; Williamson, G.; Johnston, F.H. The mortality burden attributable to wood heater smoke particulate matter (PM2.5) in Australia. *Sci. Total Environ.* **2024**, *921*, 171069.
19. Mehta, S.S.; Hodgson, M.E.; Lunn, R.M.; Ashley, C.E.; Arroyave, W.D.; Sandler, D.P.; White, A.J. Indoor wood-burning from stoves and fireplaces and incident lung cancer among Sister Study participants. *Environ. Int.* **2023**, *178*, 108128.
20. Riddervold, I.S.; Bønløkke, J.H.; Olin, A.C.; Grønborg, T.K.; Schlünssen, V.; Skogstrand, K.; Hougaard, D.; Massling, A.; Sigsgaard, T. Effects of wood smoke particles from wood-burning stoves on the respiratory health of atopic humans. *Part. Fibre Toxicol.* **2012**, *9*, 12.
21. Fuller, G.W.; Tremper, A.H.; Baker, T.D.; Espen Yttri, K.; Butterfield, D. Contribution of wood burning to PM10 in London. *Atmos. Environ.* **2014**, *87*, 87–94.
22. Desservettaz, M.; Phillips, F.; Naylor, T.; Price, O.; Samson, S.; Kirkwood, J.; Paton-Walsh, C. Air quality impacts of smoke from hazard reduction burns and domestic Wood heating in Western Sydney. *Atmosphere* **2019**, *10*, 557.
23. van Pinxteren, D.; Engelhardt, V.; Mothes, F.; Poulain, L.; Wadinga Fomba, K.; Spindler, G.; Cuesta-Mosquera, A.; Tuch, T.; Müller, T.; Wiedensohler, A.; et al. Residential wood combustion in Germany: A twin-site study of local village contributions to particulate pollutants and their potential health effects. *ACS Environ. Au* **2024**, *4*, 12–30.
24. Wolf, T.; Pettersson, L.H.; Esau, I. Dispersion of particulate matter (PM2.5) from wood combustion for residential heating: Optimization of mitigation actions based on large-eddy simulations. *Atmos. Chem. Phys.* **2021**, *21*, 12463–12477.
25. Trojanowski, R.; Fthenakis, V. Nanoparticle emissions from residential wood combustion: A critical literature review, characterization, and recommendations. *Renew. Sustain. Energy Rev.* **2019**, *103*, 515–528.
26. Frasca, D.; Marcoccia, M.; Tofful, L.; Simonetti, G.; Perrino, C.; Canepari, S. Influence of advanced wood-fired appliances for residential heating on indoor air quality. *Chemosphere* **2018**, *211*, 62–71.
27. Allen, G.; Sioutas, C.; Koutrakis, P.; Reiss, R.; Lurmann, F.W.; Roberts, P.T. Evaluation of the TEOM® method for measurement of ambient particulate mass in urban areas. *J. Air Waste Manag. Assoc.* **1997**, *47*, 682–689.
28. Hassani, A.; Schneider, P.; Vogt, M.; Castell, N. Low-cost particulate matter sensors for monitoring residential wood burning. *Environ. Sci. Technol*. **2023**, *57*, 15162–15172.
29. Wang, Y.; Hopke, P.K.; Rattigan, O.V.; Xia, X.; Chalupa, D.C.; Utell, M.J. Characterization of residential wood combustion particles using the two-wavelength aethalometer. *Environ. Sci. Technol.* **2011**, *45*, 7387–7393.
30. McNamara, M.L.; Noonan, C.W.; Ward, T.J. Correction factor for continuous monitoring of wood smoke fine particulate matter. *Aerosol Air Qual. Res.* **2011**, *11*, 315–322.
31. Bari, M.A.; Baumbach, G.; Kuch, B.; Scheffknecht, G. Air pollution in residential areas from wood-fired heating. *Aerosol Air Qual. Res.* **2011**, *11*, 749–757.
32. Renard, J.-B.; Surcin, J. PM2.5 pollution decrease in Paris, France, for the 2013–2024 period: An evaluation of the local source contributions by subtracting the effect of wind speed. *Sensors* **2025**, *25*, 6566.
33. Renard, J.-B.; Poincelet, E.; Annesi-Maesano, I.; Surcin, J. Spatial distribution of $PM_{2.5}$ mass and number concentrations in Paris (France) from the Pollutrack network of mobile sensors during 2018–2022. *Sensors* **2023**, *23*, 8560.
34. Renard, J.-B.; Becker, G.; Nodorft, M.; Tavakoli, E.; Thiele, L.; Poincelet, E.; Scholz, M.; Surcin, J. High-spatial resolution maps of PM2.5 using mobile sensors on buses: A case study of Teltow city, Germany, in the suburb of Berlin, 2023. *Atmosphere* **2024**, *15*, 1494.
35. Doldi, A.; Pagliarulo, L.; Bolzacchini, E.; Ferrero, L.; Freitag, S.; Schute, L.; Junk, K.; Todea, A.M.; Asbach, C. Evaluating the performance of the low-cost black carbon sensor bcMeter at an urban background site. *Gefahrstoffe Reinh. Luft* **2025**, *85*, 5–11.
36. Renard, J.-B.; Berthet, G.; Jeannot, M.; Jacquet, P.; Langerome, B.; Lecas, T.; Chevrier, S.; Briaud, E.; Chalumeau, G.; Grenard, F.; et al. LOAC2: The improved version of the Light Optical Aerosols Counter for measurements at ground level and within the atmosphere under balloons. *Sensors* **2026**, *26*, 3786.
37. Available online : https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview (accessed on 1 July 2026).
38. Estokova, A.; Stevulov, N. Investigation of suspended and settled particulate matter in indoor air. In *Atmospheric Aerosols—Regional Characteristics—Chemistry and Physics*; Abdul-Razzak, H., Ed.; IntechOpen: London, UK, 2012.
39. Bekierski, D.; Kostyrko, K.B. The Influence of outdoor particulate matter $PM_{2.5}$ on indoor air quality: The implementation of a new assessment method. *Energies* **2021**, *14*, 6230.
40. Eriksson, A.C.; Nordin, E.Z.; Nystrom, R.; Pettersson, E.; Swietlicki, E.; Bergvall, C.; Westerholm, R.; Boman, C.; Pagels, J.H. Particulate PAH emissions from reside, combustion: Time-resolved analysis with aerosol mass spectrometry. *Environ. Sci. Technol.* **2014**, *48*, 7143–7150.

41. Bruns, E.A.; Krapf, M.; Orasche, J.; Huang, Y.; Zimmermann, R.; Drinovec, L.; Močnik, G.; El-Haddad, I.; Slowik, J.G.; Dommen, J.; et al. Characterization of primary and secondary wood combustion products generated under different burner loads. *Atmos. Chem. Phys.* **2015**, *15*, 2825–2841.
42. Boman, C.; Pettersson, E.; Westerholm, R.; Boström, D.; Nordin, A. Stove performance and emission characteristics in residential wood log and pellet combustion, Part 1: Pellet stoves. *Energy Fuels* **2011**, *25*, 307–314.
43. Schraufnagel, D.E. The health effects of ultrafine particles. *Exp. Mol. Med.* **2020**, *52*, 311–317.
44. Tiwari, S.; Srivastava, A.K.; Bisht, D.S.; Parmita, P.; Srivastava, M.K.; Attri, S.D. Diurnal and seasonal variations of black carbon and PM2.5 over New Delhi, India: Influence of meteorology. *Atmos. Res.* **2013**, *125*, 50–62.
45. Viidanoja, J.; Sillanpää, M.; Laakia, J.; Kerminen, V.-M.; Hillamo, R.; Aarnio, P.; Koskentalo, T. Organic and black carbon in PM2.5 and PM10: 1 year of data from an urban site in Helsinki, Finland. *Atmos. Environ.* **2002**, *36*, 3183–3193.
46. Taheri, A.; Aliasghari, P.; Hosseini, V. Black carbon and PM2.5 monitoring campaign on the roadside and residential urban background sites in the city of Tehran. *Atmos. Environ.* **2019**, *218*, 116928.
47. Zhang, Y.; Wang, J.; Wu, N.; Ouyang, X.; Li, G.; Cheng, Y.; Zhang, Q.; Ding, A.; Su, H. The contribution of black carbon-containing particles to PM2.5: Variability, drivers, and impacts. *Environ. Sci. Technol.* **2025**, *59*, 5155–5163.
48. Herich, H.; Hueglin, C.; Buchmann, B. A 2.5 year's source apportionment study of black carbon from wood burning and fossil fuel combustion at urban and rural sites in Switzerland. *Atmos. Meas. Technol.* **2011**, *4*, 1409–1420.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.