Literature review: report on indoor air quality associated with woodburning

Executive Summary

This paper reviews recent studies to assess the contribution from wood stoves to indoor particulate matter (PM) in comparison with other common household activities. There are wide variations in reported concentrations of PM, however the 24hr average concentrations reported are typically below WHO recommended exposure values. Peak values of PM over short timescales are higher than the 24hr average values, and are attributed to re-fuelling of stoves and removal of ash during cleaning. These peak values can be mitigated if users follow manufacturer's instructions/ best practice. Other factors that could play a role in the PM concentrations are identified including stove construction, climatic factors, air settings and the characteristics of the fuel burned, but these parameters are rarely reported in the literature. No scientific evidence was found for adverse health impacts from exposure to the indoor air typically associated with modern enclosed wood burning stoves, however data in the context of developed world studies is extremely limited. The studies showed that other sources of particulate matter in the home, in particular cooking derived emissions, can release much higher levels of PM compared to enclosed wood stoves. There are limitations regarding the quantity of research studies and consistency of the research methods used, with different analyser types reporting variable concentrations. Standard test protocols and measurement methods for domestic indoor PM should be devised for further research in this area. These should take into account that the length of exposure may be different for the different cases, for instance a short cooking or ash removal activity compared to longer stove operation activity. The rate of air changes and ventilation needs to also be defined in a quantitative way.

1. Introduction

Exposure to high levels of particulate matter (PM) has been linked to a variety of serous health impacts including lung cancer, Chronic obstructive pulmonary disease (COPD) and other cardiovascular (CV) disease [Ali et al 2021]. Sources of exposure are most commonly via inhalation, but harmful components of the particulate can also be absorbed via skin contact with contaminated surfaces and by ingestion [Kristensen 2019]. There are many sources of particulates associated with normal domestic activities such as cleaning, cooking, use of candles and use of fragranced personal care products. Recent concern has been focussed on the degree to which particulate can be released from wood burning stoves to the indoor air, and whether these concentrations are significant in terms of health impact. This paper reviews recent studies into indoor air pollution to assess the contribution from wood stoves in comparison with other common household activities. The scope of this paper is focused towards developed world PM concentrations using enclosed wood burning stoves rather than open fires in developing world areas, although an acknowledgement of issues in the wider world context is made.

1.1 Particulate Matter

Domestic particulate matter can come from a wide range of sources such as cleaning products, personal care products, cooking, incense, candles, human skin shedding as well as wood burning stoves. These sources are discussed further in the sections below. PM can be formed in the air from other emissions as Secondary Organic Aerosol (SOA) during complex atmospheric reactions such as the oxidation of gas phase volatile organic compounds (VOC) The composition of particulate matter varies according to source but can include condensed organic species, solid carbon 'soot' spherules and solid inorganic material.

PM is usually measured according to its aerodynamic diameter. The definition of coarse particles or 'PM_{10}' is particulate with average aerodynamic diameters below 10 µm, fine particles or '$PM_{2.5}$' are diameters below 2.5µm and ultrafine particles (UFP) are <0.1µm (100nm). Figure 1 shows a comparison to the size of a human hair [EPA, 2021]

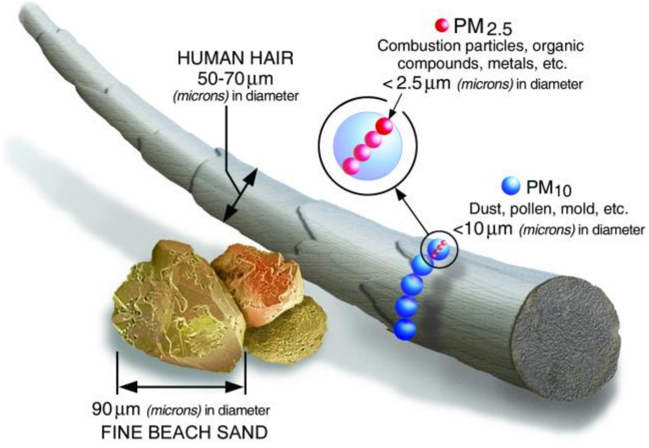


Figure 1: Size comparisons for PM particles [EPA, USA- 2021]

When particles are first emitted from combustion sources, they are spherules of carbon typically 10-50nm in diameter. These primary particles rapidly agglomerate into chains with organic species condensed onto them, resulting in a larger measurable particle diameter. The solid carbon component is either Black Carbon (BC) or Elemental Carbon (EC) depending on how the measurement is conducted. Thermo-optical analysis is needed to determine BC whilst techniques such as thermogravimetric analysis (TGA) will give EC. A wide variety of semi-liquid combustion products and incompletely burned fuel fragments condense onto the solid carbon cores and contribute to the measurable mass. These are Volatile Organic Compounds (VOC), Semi- Volatile Organic Compounds (SVOC) and Intermediary Volatile Organic Compounds (IVOC), according to their volatility- i.e., how readily they condense.

Another significant component of PM from combustion sources is inorganic material, which is the incombustible ash associated with trace elements in the fuel. Wood typically contains a wide range of inorganic material, such as calcium, silicon, magnesium, phosphorus and potassium. Whilst much of the inorganic material will remain in the stove grate as ash, some will be carried with the combustion flue gases- especially minerals such as potassium which are more volatile. There is ongoing research to see whether potassium acts as a condensation nucleus for carbonaceous particulate matter to form around.

Guidelines are given for recommended mass-based exposure to PM, corelating to 25 µg/m^3 PM2.5 in the EU as shown in Table 1 [Ali 2021]. There are still unanswered research questions regarding safe levels of exposure to PM and the degree to which size and composition matters. With this in mind, The World Health Organisation (WHO) have stated that there is no evidence of a safe level of exposure to PM or a threshold below which no adverse health effects occur [WHO, 2013]. Concentrations are measured as peak values or averages over a specific time period such as 24hrs or a year. The short peak concentrations will record a maximum concentration according to specific activities such as igniting a stove whereas the average values give an indication of ongoing exposure.

Pollutant	WHO	EU
$PM_{2.5}$	10 µg/m^3(1yr)	25 µg/m^3 (24hr)
	25 µg/m^3 (24hr)	
PM_{10}	20 µg/m^3(1yr)	50 µg/m^3(1yr)
	50 µg/m^3(24hr)	40 µg/m^3(24hr)

Table 1: Particulate Recommended Average Exposure limits [Adapted from Ali, 2021]

2. Stove Indoor PM Exposure

2.1 Developing world

The focus of this review is the UK and developed countries with similar levels of technology, however it is useful to place this in the context of wider Global impacts. The impact of pollution by ambient fine particulate matter in 2015 resulted in ~4.2 million deaths globally, representing ~4.2% of disability-adjusted life years [Cohen et al, 2017]. This impact is most strongly seen in Asian and African countries where many communities rely on simple systems of solid fuel combustion for cooking and heating such as '3 stone fires' which can be made by the householder.

Figure 2 shows the extent of premature deaths worldwide attributed to indoor pollution from solid fuels between 1981 and 2020 [Ali 2021]. The contrast between persistently high levels of impact in developing world, especially Asia, can be contrasted with a gradually improving picture in the developed world areas such as Europe and North America.

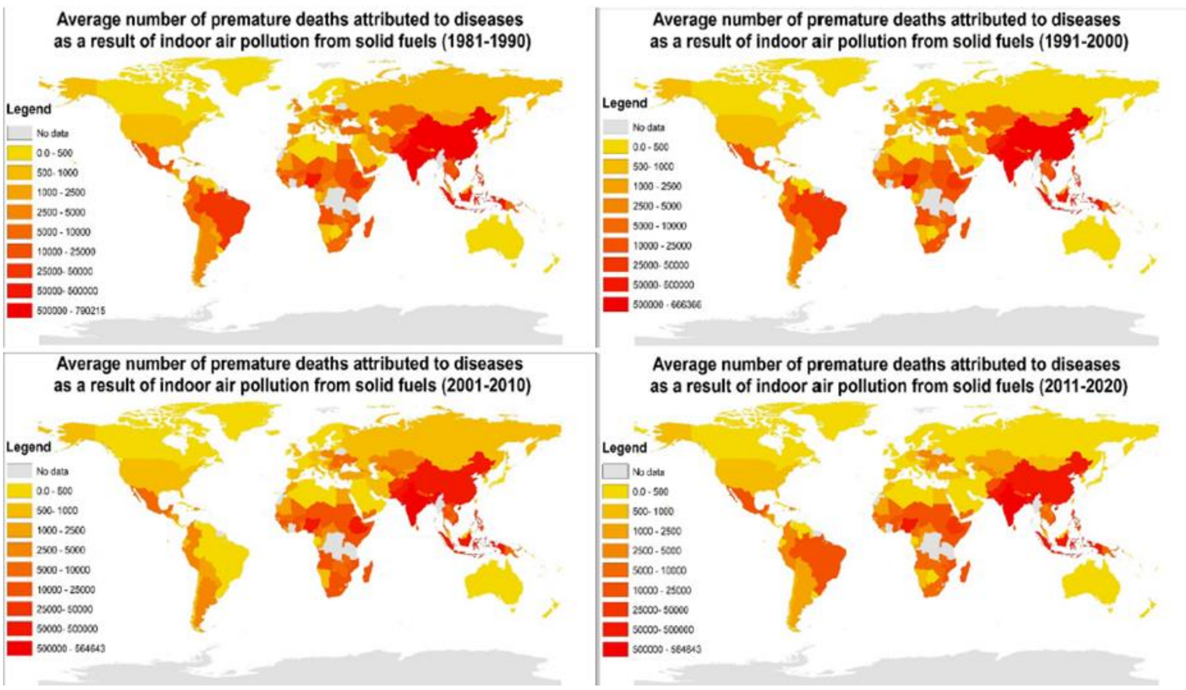


Figure 2; Average premature deaths attributed to diseases as a result of indoor air pollution from solid fuel [Ali, 2021]

The detailed analysis of pollution studies in the developing world is outside the scope of this paper. It can be noted that the combustion sources are usually open fires or simple cookstoves have limited ventilation to the outside. There are many studies available in the literature regarding the levels of indoor air pollution in these countries, many of which highlight the disproportional impact that is felt by women in these areas, who typically spend more time adjacent to the particulate sources when cooking [Cohen, 2017; Ali, 2021] . The combustion technology of these basic cooking systems is not comparable with a modern developed world enclosed woodstove and hence cannot be used to inform risk factors in a typical developed world setting.

2.2 Stove Indoor air studies in the developed world

In comparison to developing world studies, there is much less literature information available regarding the concentrations of stove related indoor PM for developed world countries. There are inconsistencies between measurement protocols between studies, such as whether peak values of average values are recorded, and different analysis techniques. The most significant studies are listed below.

Salthammer et al assessed indoor air quality associated with seven wood burning stoves/fireplaces in private homes, located in Germany [Salthammer, 2014]. The study measured concentration of particulate in terms of UFP (5.6-55nm), FP (0.3-20µm) and $PM_{2.5}$. Selected gases and VOC were also measured in this study. The tests were conducted over a three-day period; with day one as background measurements, day two included ignition and 4 hours burning, then day three to evaluate residual air quality afterwards. It is noted that no smoking or candles were permitted during the testing period and the cumulative effects of a typical winter pattern of stove use was not studied. The study found inconsistent PM results between the stoves, but concluded that the PM guidelines as defined by the German Federal Environment Agency (and WHO) were not generally exceeded during the trials, with the average $PM_{2.5}$ being ~22µg/m^3 (24 average) during firing. The levels of finest particles were seen to increase and could be attributed to opening the fire chamber door for re-loading. During adverse weather for one of the tests- a atmospheric temperature inversion resulted in reduced draft during ignition and lead to high levels of indoor CO and NOx. The report identified that other factors could play a role in the PM concentrations that were identified including stove construction, climatic factors, air settings and the characteristics of the fuel burned, but that these were outside the scope of the research study [Salthammer, 2014].

Vicente et al looked at the impact of wood combustion on indoor air quality, including a comparison of an enclosed wood stove with an open fireplace. Samples of PM10 were taken and characterised in terms of the inorganic species, organic carbon and elemental carbon. Vicente noted that although a standard sequence of ignition, air setting and operation was followed, there was still a very high degree of variability in the results.

Similarly to the Salthammer analysis, the Vincente work showed the highest peak concentrations were associated with the ignition phase and with reloading of the wood, as shown in Figure 3 [Vicente, 2020]

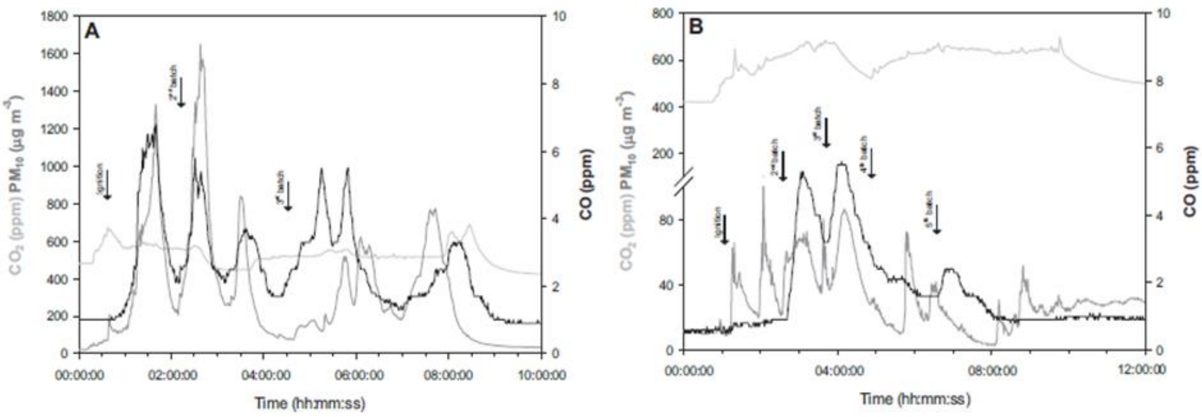


Figure 3: Indoor profiles of PM_{10}, CO_2 and CO measured during (A)fireplace and (B)wood stove operation [Vicente, 2020]

A marked difference was shown in air quality between the enclosed stove and open fireplace as shown in Figure 4. In this analysis, indoor PM_{10} emissions had roughly a two-fold increase compared to a twelve-fold increase with the fireplace.

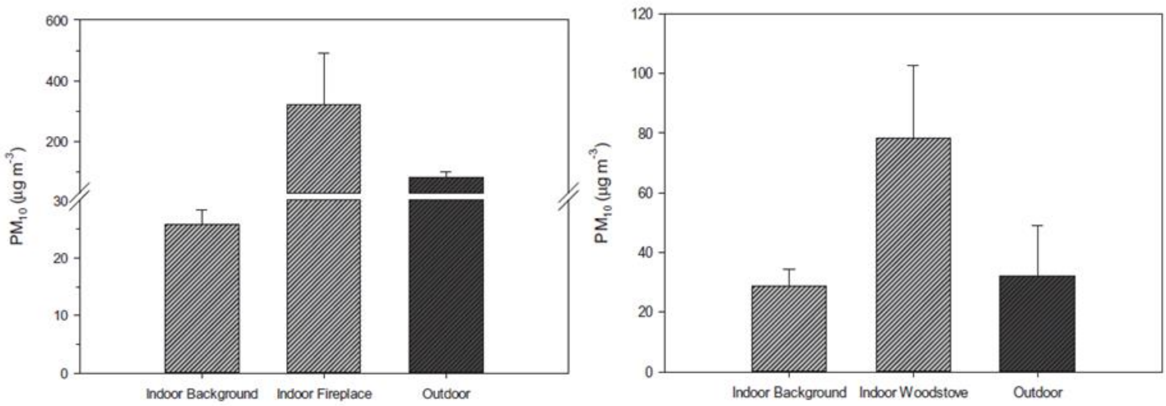


Figure 4: PM_{10} concentrations indoors- background air, using combustion appliances and outdoor air [Vicente, 2020]

The values of peak PM measured by Vicente et al are given in Table 2, noting that the peak values for the woodstove correlate with refuelling. The average room concentration during operation was higher in this study with an average PM_{10} of ~79 µg/m^3 for the woodstove compared to 319~ µg/m^3 for the fireplace, noting a wide degree of uncertainty as shown below.

	Open fire PM_{10} µg/m^3	Woodstove PM_{10} µg/m^3
Initial concentration µg/m^3	30.5± 1.24	0.933± 0.312
Peak concentration µg/m^3	2328± 1853	76.7± 28.6
Average Concentration (8hr) µg/m^3	319 ± 173	78.5 ± 24.0
Emission rate µg/min	1.29± 1.25	0.049± 0.035

Table 2: Concentrations recorded for an open fire compared to wood stove. [Adapted from Vicente, 2020]

An earlier study was undertaken by Ward and Noonan in 2008, who conducted a $PM_{2.5}$ sampling program before and after a wood stove upgrade programme in Rocky Valley USA [Ward and Noonan, 2008]. The program involved replacing old stoves with improved EPA certified wood stoves. The study looked into particulate $PM_{2.5}$ mass concentration using a 'Dustrack' analyser, ratio of EC/OC and various chemical markers associated with woodsmoke. As with other studies, there was a substantial amount of variability seen in the concentrations between different households. Figure 5 shows the average $PM_{2.5}$ across the 20 locations investigated and it can be seen that some households had more than double the concentrations of others.

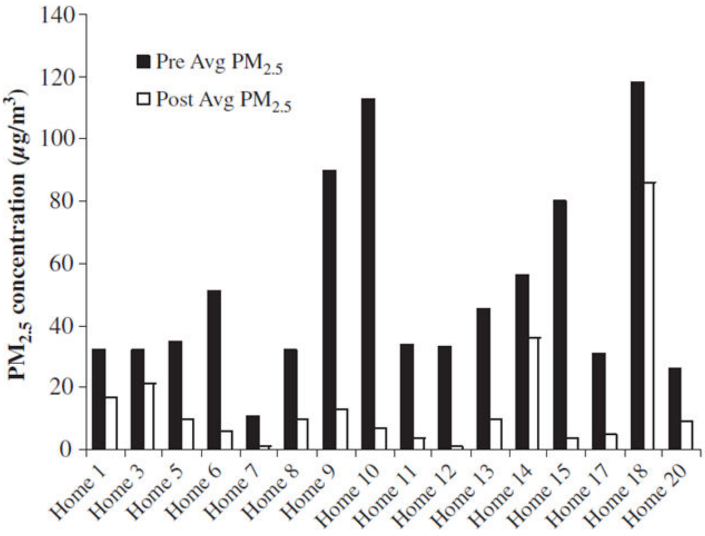


Figure 5: $PM_{2.5}$ mass concentrations before and after improved woodstove changeout [Ward and Noonan 2008]

The Ward and Noonan results demonstrated an average reduction in indoor $PM_{2.5}$ of 71% once the improved woodstoves were installed [Ward and Noonan, 2008]. The study recorded a 24-hr average of up to 118µg/m^3 before the change out, compared with most homes being below 20µg/m^3 after the changeout, which is below the WHO 24hr recommended exposure limit. The reduction demonstrates that the age and quality of stove is an important factor when considering potential risk so householders should be encouraged to ensure their appliances are well sealed and maintained. Only 2 homes exceeded 35µg/m^3 after the changeout, but the influence of influx of outdoor air, such as one resident known to be smoking on the patio, was not quantified. The study also measured a reduction by 45% of levoglucosan, which is a commonly used marker for wood combustion.

Another study compared the $PM_{2.5}$ concentration associated with stove use in 101 homes in rural USA locations [Walker 2020]. The paper gave a median indoor $PM_{2.5}$ concentration of 19µg/m^3, noting that there was high variability in the data as had been seen in other studies. Households that had not had their chimney cleaned in the previous 6 months had 65% higher mean $PM_{2.5}$, however the 'grade' of the stove use also had a substantial impact on the indoor PM in this work also, where the stove grading was based on the stove quality, operation and wood quality. The different between the highest grade of stove use compared to the lowest accounted for a 186% increase in PM. This correlates with the finding by Ward and Noonan and suggests that householders with older appliances should consider upgrading them to newer technology stoves.

A comparison of air quality using two Italian residences was conducted by Frasca et al [Frasca, 2018] One household had a 15.4 kW pellet stove, and the other had a 25kW thermo-fireplace fuelled with hardwood logs. This study found that infiltration from outdoors was main source of the fine particulates whereas dust resuspension by human movement was the main source of course particles. With regards to the PM associated with stove use, the study found that the most significant peak PM values were due to ash removal during cleaning of the stoves rather than during their operation. The ash was removed by a vacuum cleaning system for the pellet stove and by simple shovel for the thermo-fireplace. The ash removal could be a health risk as it contained significant amounts of copper and manganese which can have health impacts via oxidative stress induction [Charrier and Antasio, Crobedden]. Householders should avoid inhalation of ash-dust by good ventilation during stove cleaning, use of an ash-vacuum appliance and use of a room vacuum shortly after cleaning, allowing for deposition time of the ash onto floors.

A study by Chakraborty et al measured $PM_{2.5}$ and PM_1 using low cost sensors in 20 UK residences that had woodburning stoves [Chakraborty, 2021]. Their study identified an increase in daily average $PM_{2.5}$ by 196% and PM_1 by 227% compared to a non-stove control group, i.e. approximately a twofold increase compared to background similarly to the study by Vicente [Vicente, 2020]. It can be noted however that the actual concentration values given were fairly low, at 12.2 ±10.36 μg/m^3 $PM_{2.5}$ for instance compared to 4.12±3.6 μg/m^3 when a stove was not in use. The hourly peak $PM_{2.5}$ during stove use was 27.34 μg/m^{3}compared to 12.21 μg/m^3 without stove, whereas the PM_1 was a maximum of 19.44 μg/m^3 compared to 8.34 μg/m^3. These values are below the WHO 24hr recommended exposure limit. Their analysis of the data identified that opening the stove door for reloading of wood as the main source of indoor PM, which has also been identified as an issue by Vicente. The 'flooding' of combustion emissions into the room can be avoided if sufficient care is taken during the door opening such that the door catch should be opened very slightly initially, allowing the air pressure to settle, before fully opening the door for refuelling.

A general PM exposure study was conducted by Buonanno et al in 2018. They investigated the exposure of ~100 children to UFP and black carbon using handheld particle counters and aethalometers. The analysis showed that cooking and using transportation were recognised as the main activities contributing to exposure [Buonanno, 2018]. The study covered both indoor and outdoor exposure, and all the children had gas cooking in the home. Most of the children also had a fireplace for heating with in the homes: 48% solely a fireplace, 35% had a fireplace combined with gas heating, but the research did not specify the types of fireplaces or how often they were used. The fireplaces were not identified as a significant source of UFP or BC in this study, nor were they included in the results discussion. The study concluded that cooking activities presented the highest dose intensity for UFP, whereas transportation presented the highest exposure of black carbon due to vehicular emissions.

Research Study	**$PM_{2.5}$ Concentration μg/m^3**
Chakraborty, 2021, hourly mean	12.2 ±10.36
Salthammer, 2014. 24hr average	22
McNamara, 2013. Winter mean values	32.3±32.6
Ward and Noonan, 2008 (post upgrade program). 24hr average	<20
Walker, 2020. Median indoor value	19

Table 3: Comparison of reported $PM_{2.5}$ Concentrations

Table 3 summarises $PM_{2.5}$ concentrations reported by some of the literature studies, with variation in the values reflecting the high levels on uncertainty in the results. The values given as 24 hour averages are generally below the WHO recommended limits.

2.3 Risk of exposure evidence

Whilst some researchers have quantified the concentration of PM in households, there are relatively few literature sources that attempt to correlate the health risks associated and this is an area where more research is required.

The issues of whether adapting heating behaviours could lead to improved air quality and hence lower risk of exposure was recently considered by a team led by VITO [Cops, 2021]. The study looked at how specific procedures of stacking the wood in the stove, lighting the wood, the air settings and wood moisture could impact the resultant exposure and health of participants. The test phase of the study involved a comparison of the user's traditional stove use behaviour vs an improved stove use intervention following some stricter operational guidance. The intervention gave rules for loading of the wood according to the Swiss method, whereby largest logs are stacked at the bottom and progressively smaller towards the top, with ignition from the top of the stove. The study acknowledges that this might not be appropriate for all stove types, for instance those with air inlet from the bottom. Indoor and outdoor air quality was measured and a reduction in BC was measured in the homes with the improved behaviour intervention. Participants also had biological samples taken to measure exposure to combustion products, however the trends in the results of these were not clear-cut because of complications due to diet, exposure to vehicle emissions and underlying infections (e.g. having a cold). Due to this, only a limited influence of improved health impacts could be inferred. Another limitation of the study was that only 6 households took part in the full study rather than the 8 expected due to Covid-19 impacts, although a questionnaire on a larger group was also included. In conclusion, the researchers stated that householders should be encouraged to use alternatives to wood burning for biggest improvements to air quality, however those using wood burners could reduce their emissions by following improved firing and fuel practices. Recommendations for firing included the use of kindling or natural cubes rather than paper, cardboard or newspapers; stacking according to the Swiss method with largest logs at the bottom; wood moisture to be between 10-20% and use of a hard wood fuel (e.g. beech, oak) rather than softwoods or prunings. This led to improved combustion and hence lower emissions so reduced the risk of exposure.

The metric of lung deposited surface area can be used to evaluate the potential adverse health effects related to UFP exposure. A study by Geiss et al. 2016 used LSDA to investigate risk from a variety of environments including a house with a wood burning stove, travel by car and a factory setting. Measurements were taken from 20 minutes before the stove was lit and for three hours during combustion. Unfortunately, the authors had issues with another PM source in an adjacent room (gas cooker). The cooker was used during the sampling period and the report concluded that the gas cooker was in-fact a stronger contributor to the UFP concentrations than the woodburning stove [Geiss, 2016].

Endotoxins are a biological component of particulate matter associated with adverse human health effects such as respiratory illness. The levels of endotoxin and PM in 50 homes with woodstoves was investigated by McNamara et al [McNamara 2013]. Their results showed Winter mean values of $PM_{2.5}$ of 32.3±32.6, indicating wide uncertainty in the values. These figures are also higher than some of the other studies including Vicente, Ward and Noonan and Walker [Vicente, 2020; Ward and Noonan,2008, Walker, 2020] Significantly, although the endotoxin concentration measurements showed a correlation with the number of residents in the household, there was no correlation with $PM_{2.5}$ or the $PM_{10-2.5}$ fractions. This suggests that the particle concentration by itself does not give a good indication of risk.

The quality of the stove appliance has been seen as an important factor in PM exposure, however the human behaviour and stove location are also significant. Abbatt et al. 2019 considered the reactive multiphase chemistry involved in indoor air quality. They noted that the structure of a building is a barrier that inhibits the flow of air both indoors to outdoors and vice versa. The typical residence time for indoor air highly variable but is ~1-2 hours, and air exchange is through leaky windows and walls, driven by pressure gradients due to heating and weather [Abbatt, 2019]. Salthammer et al. 2014 also demonstrated that room volume and air exchange rate was important. It is noted that with increasing concern over the impacts of climate change, residences are driven to improve their insulation and efficiency resulting in a reduction in the air exchange rate. Decreasing the amount of air changes can cause a cumulative increase in indoor PM, regardless of the source.

Buildings can have a substantial impact on human health and wellbeing, as discussed in a report from the American Association for the Advancement of Science symposium [Ham, 2019]. A symposium participant from Harvard T H Chan School of Public Health showed that cognitive function and decision making can be dramatically improved by improving residential occupants air quality. The importance of human behaviour was highlighted, such as use of extractor fans for cooking, frequency of vacuuming and lifestyle choices to burn incense for instance [Ham, 2019]. Correct operation of wood stoves creates a natural draft that pulls air from the room into the appliance hence potentially drawing cleaner outside air into a room. Householders with woodstoves should be educated regarding the importance of ventilation in maintaining a good influx of clean air and low level of indoor PM.

The routes to exposure from stove emissions include inhalation, ingestion and permeation of skin [Kristensen 2019]. Figure 6 shows a summary of possible health implications that have been identified from various combustion emissions including PM [Ali 2021], noting that all the species identified can be reduced by increasing the efficiency of the combustion appliance. There is an ongoing drive to improve the performance of new stoves via initiatives such as *clearskiesmark* and introduction of Ecodesign 2022 regulations in Europe. The quality of the fuel is also vitally important as high moisture fuels cannot burn efficiently, hence householders in the UK should be encouraged to only used 'Ready to burn' labelled wood.

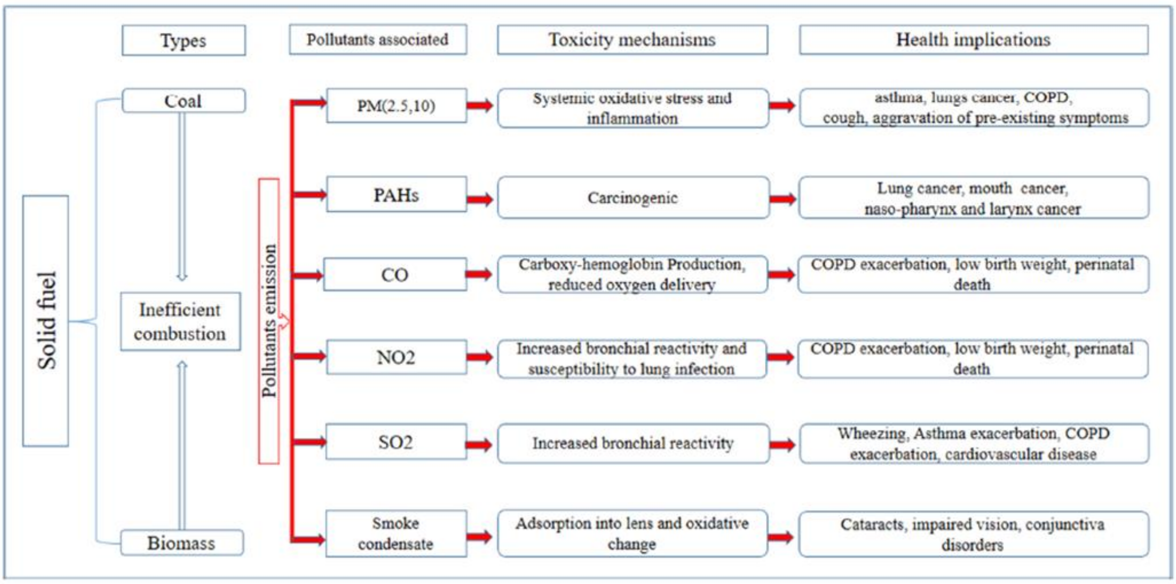


Figure 6. Pollutants associated with inefficient solid fuel combustion and possible mechanisms of toxicity. [Ali 2021]

Public Health England have conducted an extensive review of epidemiological evidence from studies across Europe, North America, Australia and New Zealand, in order to assess any associations between respiratory outcomes in children and exposure to solid fuel combustion [Guercio 2020]. Despite a broad review of available literature, they found that results were inconsistent and limited, for instance details were missing regarding types of fireplaces and stoves and often didn't specify the fuels that were used. They used statistical analysis of the data available, they found that there was no association shown between exposure to indoor wood burning and risk of asthma in developed countries. They found a slight but 'non-significant' association to risk of respiratory infections (e.g. such as rhinitis, hay fever and influenza). A study by Petry calculated estimated exposures for different room scenarios using candle combustion emissions, which were between 5.48μg/m^3 to 90.24μg/m^3 for $PM_{2.5}$ [Petry 2014]. Petry concluded that under normal conditions, these PM concentrations from scented candles do not pose known health risks to consumers. Vicente also concluded that the carcinogenic risk due to particulate bound PAH from their woodburning stove scenario was negligible, but could be at harmful levels for an open fireplace [Vicente 2020]. The PHE review concluded that they could not say that exposure to indoor solid fuel emissions doesn't affect respiratory heath, but there is currently no strong scientific evidence to say that it does. The study recommended that further, improved research is conducted in the area [Guercio 2020].

3. Other domestic sources of particulate matter

There are a wide range of common sources of PM in a typical household which include combustion and heating sources (e.g. cooking, wood stove, smoking, candles, incense), semi-volatile chemicals (cleaning products, personal care, cooking), particulates from humans themselves (skin, skin oils), plastics (microfibres and microplastics) and minerals (personal care such as cosmetics and talcum powder, potentially hazardous such as asbestos). A limitation in comparing literature concentration is that studies do not use a consistent basis of measurement. Some common sources of PM in comparison to wood stoves are discussed briefly below.

Kristensen et al, 2019 Conducted a study of semi-volatile organic compounds (SVOC) in a single family residence in California [Kristensen 2019]. Figure 7 shows a comparison of some of these in terms of the indoor gas- plus particle-phase SVOC in a Californian household.

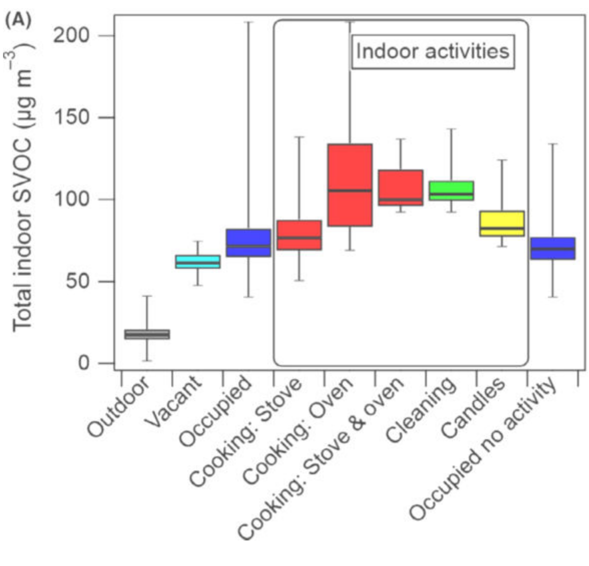


Figure 7; Box plot showing the outdoor and indoor SVOC concentrations (μg/m^3) in a Californian study. This compares a vacant period, and period of normal occupancy along with the total concentrations associated with indoor activities (stovetop and oven cooking, cleaning, and candle light burning) [Adapted from Kristensen 2019]

Kristensen observed substantial increases in SVOC associated with both cooking and cleaning. It was noticed that although thorough ventilation by opening windows could effectively reduce the indoor air concentration of VOC, the effect was only temporary and levels returned to the previous concentrations within hours. This could be explained by partitioning of species on to indoor surfaces, and household materials absorbing VOC and then re-releasing them as the air concentrations decreased to equilibrium concentrations. They found that the SVOC consisted of a complex mixture of species including gaseous compounds, dust and surface films.

The study showed that emissions exceeding 200µg/m^3 were measured with cooking activities such as oven cooking and stove top frying, but there was no SVOC associated with boiling, microwaving or toasting bread [Kristensen]. Analysis has shown that aerosols for cooking are mainly in the ultrafine particle range so extremely respirable [Abdullah 2013]

Abbatt et al. 2019 compared the combustion related sources of emissions to include wood stoves, gas stoves, candles, incense burning and cigarette smoking. Significant non combustion sources included food and cooking, cleaning products and personal care products. Abbatt discussed that shedding of skin and release of skin oils from humans themselves made a substantial contribution to the household dust. It has been shown by Downing and Milstone [Downing, 1982; Milstone, 2004] that between 10's to 100's of mg of matter/ per hour/ per human can be shed.

Another study looked at how human activities would influence the indoor concentration of particles [Tian 2020]. This study also found that cooking was a major source, but high movement activities such as mopping would also displace settled particles into the air. The study found that the dominant source of particles was associated with oil-based cooking such as frying, whereas water-based cooking, such as stewing and boiling, did not emit measurable particle increases. This correlates with the findings from Kristensen. Abdullah et al identified a number of possible chemical markers that could be used to identify PM from cooking such as carboxylic acids and levoglucosan [Abdullah, 2013]. Further research is required in this respect as the latter could be also used as marker for wood smoke.

Values of mass concentration due to cooking were measured in a manufactured test house, as part of the HomeCHEM tests [Patel, 2020]. The mass concentration in for cooking breakfast was 35±20 µg/m^3, stir fry 30± 10 µg/m^3, toast 12± 2 µg/m^3 compared to unoccupied building 2.3± 0.4 µg/m^3. The cooking activities involving frying produced higher levels of PM compared to the stove use studies reviewed in the earlier sections.

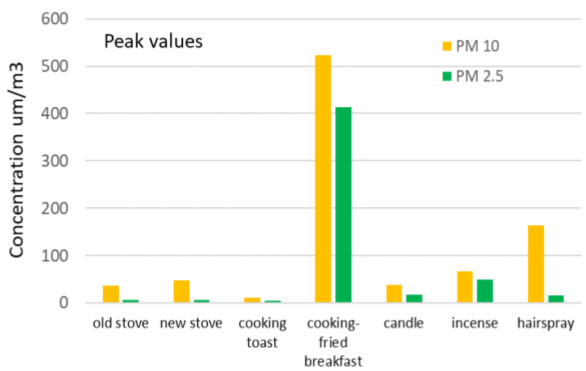
An exposure study by Beko et al involved 60 non-smoking residents in Copenhagen. They used portable devices to continuously log their exposure to UFP [Beko, 2015]. Participants were equipped with a portable monitor that continuously logged particle number concentrations, along with a GPS logger to track their locations, and they were also asked to keep a diary of their locations and activities. This study covered both indoor and outdoor environments within the participants daily exposure. The home environment was shown to account for an average of 50% of the daily exposure to UFP, however significant variability was shown between the participants. There was also a discrepancy between the GPS tracking logs and the diary entries. The results showed that homes where cooking frequently occur have significantly higher UFP daily exposures comparted to homes that did not have cooking activities. 90% of the participants daily exposure occurred within buildings as people were in buildings for ~90% of the time, although the highest average particle number concentrations were measured during passive transportation (cars, public transport). Lower particle number concentrations were associated with active transport such as walking, running and cycling.

Researchers in Korea investigated personal exposures to PM2.5 relative to various microenvironmental concentrations [Lim, 2012]. These included various indoor locations (e.g. residential, office, restaurant), transportation and outdoor locations. The average exposure per person was 19.8±15.3µg/m^3 of $PM_{2.5,}$ which is similar to the indoor concentration for stove users as discussed in the previous section. They found that different types of population group had different average exposures, ranging from 9.8µg/m3 for office workers that went home after work, to 43.1µg/m3 for office workers that went to restaurants and bars after work. These highest concentrations were due to permitted indoor smoking and use of 'at table' cooking with charcoal grills.

Burning of incense can be a significant source of PM with emission factors of PM2.5 shown to vary between different types of incense from 0.4 ('smokeless' incense stick) to 44.5 mg/g [See, 2011]. Depending on the stick composition, metals are present in the smoke, for example aluminium and iron. See et al concluded that with reference to indoor air quality guidelines, inhalation of incense smoke can cause adverse health impacts. This could be of particular concern to those burning multiple sticks per day, for example as part of religious practices.

Petry 2014 investigated the health risk from scented candles due to PM, VOC and SVOC. The tests were conducted in small (2.2m^2) and larger (26m^2) experimental chambers with control of the air exchange rate, temperature and humidity. Specific VOC were investigated such as aldehydes (formaldehyde, acetaldehyde), aromatics (e.g. benzene, toluene, styrenes), PAH, and PCDD/PCDF. The PAH and PCDD/PCDF were below the detection limits of the analysis methods. The most abundant VOC from combustion was formaldehyde with estimated exposures of up to 63.85µg/m^3 TWA.

A study at Manchester University compared indoor air associated with a 10-year-old stove, a new Ecodesign compliant stove and various typical domestic PM sources, including cooking, candles and incense [Lea-Langton, 2021]. Results from this study are shown in Figure 8, showing peak and average values of indoor air for the 10-year-old stove, Ecodesign compliant new stove, 1 piece toast, cooked breakfast, 1 scented candle, 1 incense stick and 3 puffs of hairspray. In this case, the average values were taken over the test period only, which was typically 40 minutes, rather than as a 24-hr average. The cooking activities including frying or grilling meat were by far the highest sources of PM and typically had PM concentrations over ~500µg/m^3, whereas the stove indoor air quality averages during operation was below the WHO recommended limits 24-hr average of below 25 µg/m^3. However higher values of PM_{10} of ~500µg/m^3 were seen for a short time during the ash emptying and it is recommended that the room is ventilated during this activity. These results are consistent with the other literature sources discussed in section 2.



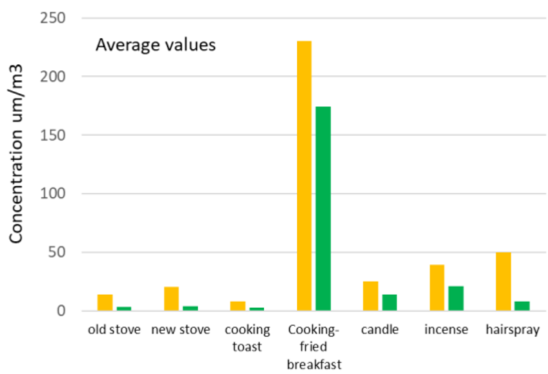


Figure 8: Comparison of PM sources of PM_{10} and $PM_{2.5}$ associated with typical domestic sources, peak values and averages over test duration [Lea-Langton, 2021].

A study by Sain et al demonstrated that using typical tap water in an ultrasonic dehumidifier would result in emission of inhalable mineral particles, especially if high hardness water is used. The study recommends the use of deionised or distilled water in these devices [Sain, 2018]. Cleaning activities can also create higher levels of airborne PM due to the unsettling of deposited material. Vicente et al investigated the amount of PM10 associated with vacuuming and measured between 75.4 ±7.89 µg/min to 200± 99 of PM_{10} emitted, depending on vacuum type [Vicente, 2020b]. The particulate collected contained a wide range of organic species as well as copper suggesting motor-related emissions were also a contributor. Hence the increase in emission during vacuuming is partly due to the motor and partly due to re-suspension of dust.

The chemistry associated with emission of various VOC species is complex and results in reactions forming secondary organic aerosols (SOA) and particulates. For instance, the rapid photolysis of chlorine from chlorine bleach followed by reaction with limonene (commonly found in foods, cleaning products and skincare products) has been shown to produce a high yield of UFP [Abbatt, 2019].

The summary of these findings is that normal domestic behaviours such as cooking, use of personal care products and cleaning are responsible for generating PM at levels that can exceed those from careful use of an enclosed woodburning stove. However, to further reduce the indoor PM from stove use; reloading of wood should be undertaken carefully to minimise any ‘flooding’ of emissions into the room, and it’s recommended that the ash removal should be done with a specialist ash-cleaning vacuum appliance and ventilation.

4. Limitations and research gaps

Analysis of literature shows that there are serious limitations regarding the quantity of research studies and consistency of the research methods used. A wide variety of analysers have been used from high specification research analysers to low-cost sensors. There is variability in the type of PM investigated, such as PM_{10}, $PM_{2.5}$ or various VOC. The stove specifications are not typically given, nor are details of the fuels or user behaviour. Factors such as metrological conditions and temperature are also known to impact emissions behaviour [Ward and Noonan 2008] but are not recorded and cannot be easily controlled. There are also inconsistencies in the exposure time to various sources- for instance high PM activities such as ash emptying or cooking activity might only last for 10-15 mins, whereas wood stoves would be lit for several hours at a time. The natural draft from a lit stove would promote ingress of air from outside however there is a drive towards increasingly well sealed buildings to improve energy efficiency. The studies reviewed had limited information on the rate of change in the air and ventilation and this should be studied further in relation to stove indoor air quality.

Manigrasso et al. 2013, highlight some of the issues in measurement of exposure to combustion source emissions. Most indoor sampling methods are unable to capture the transient behaviour associated with particle formation and growth, and high short time exposures to the smallest particles might be missed. This work demonstrated how advanced sampling methods such as a fast mobility particle sizer (FMPS) was needed to understand dosimetry in a more detailed manner.

The quality of the measurement system will impact the results obtained. Singer 2018 compared a selection of seven low-cost particle sensors against 2 research grade analysers to assess their performance in assessing $PM_{2.5}$ [Singer 2018]. The low-cost analysers were the AirBeam 1, Air Quality Egg, AirVisual Node, Awair, Foobot, Purple Air PA-II and Speck. The research grade monitors were the Thermo pDR-1500 and the MetOne BT-645. Particles from typical residential sources such as combustion and cooking were generated under laboratory conditions. The study showed a wide variation in response between the monitors. Only four of the low-cost monitors were within a factor of 2 of the estimated true concentrations (AirBeam, AirVisual, Foobot, and Purple Air), 2 others reported concentrations much lower than the true values (Air Quality Egg and Awair). One monitor did not consistently respond to the source emissions (Speck). It is noted in their conclusions that the IAQ market is dynamic in terms of new products and improvements to existing products- for example by improving the algorithm used for the concentration calculations. It recommends the introduction of an industry standard test method for IAQ.

The performance of low-cost environmental monitors and sensors for measuring air quality was also assessed by Demeanega et al [Demanega 2021]. Activities included candle burning, essential oils vacuuming and popcorn cooking. The majority of tested devices had generally good performance for gases, but under-reported PM by up to 50% and had poor quantitative agreement for VOC. Figure 8 shows a comparison of the PM 2.5 results for the different analysers compared to the research grade analyser (in black). The study found that whilst the monitors could detect source events happening, they could not accurately quantify the levels and concludes that standards and guidelines for testing are required.

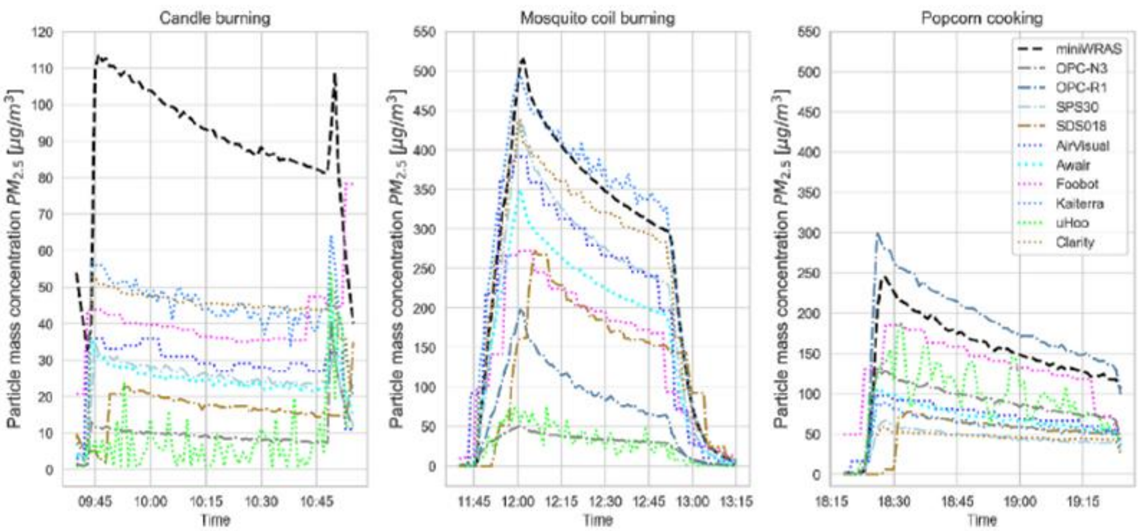


Figure 8; Low cost PM sensors compared to a research grade calibrated monitor (black dashes) [Demanega 2021]

An issue is that different types of analysers respond differently to different types of PM. [McNamara 2011] found a factor of 1.65 difference between gravimetric analysis and a handheld Dustrack analyser, whereas [Kingham 2006] found dustrack over recorded PM_{10} by a factor of 2.73. Ward and Noonan 2008, Yanosky 2002 found a reasonable correlation between dustrack measurements and a FRM sampler (R2= 0.859).

Ott et al looked at a range of PM sources using two different continuous particle monitors [Ott 2006]. The types of monitors were (a) a photo-charging ionisation technique (PC) that responds to the particle PAH, and (b) a diffusion charging technique (DC) that measures the active surface area of fine particles. A comparison of the readings as a ratio of PC/DC gives a mass of PAH to active surface area. Sources include tobacco smoke (cigarettes, pipes and cigars), incense, candles, cooking, fireplaces/ woodsmoke and in vehicle exposures (California). The ratio of readings from the two detectors varied substantially between different sources. The results gave similar values for incense and cigarette, low readings for cooking and high readings for burning of cedar wood (indoors, but not within fireplace- so no extract via chimney. A fireplace test was conducted which appeared to give a low value of PC/DC close to zero. It should be noted that the test was not performed under normal real- world conditions however as the chimney damper was closed for a short period (30s) to obtain a strong response on the analysers. The paper suggests that development of this ratio technique might be used as a signature to identify different sources.

These inconsistencies in measurement, sampling and operation of stoves should be addressed by development of a standard test protocol. There should also be development of instrumentation to assess leakage from the stove (either from fuel re-loading or poor seals), perhaps using laser or optical methods. The test protocol should take into account factors such as metrological and temperature factors, the exposure time to various sources, rate of air change, stove quality, fuel quality and user behaviour.

5. Conclusions

The most significant findings of this review are as follows:

1. No scientific evidence was found for adverse health impacts from exposure to the indoor air typically associated with modern enclosed wood burning stoves. It should also be noted however that data in the context of developed world studies is extremely limited and therefore this doesn't mean there is no risk. The World Health Organisation have stated that there is no safe level of particulate matter exposure and further research into risk is required.
2. Other sources of particulate matter in the home such as emissions from cooking can release much higher levels of PM compared to enclosed wood stoves and could therefore have a greater health risk potential.
3. Factors including stove quality, wood quality, location factors (e.g. ventilation, temperature, weather) as well as user behaviour can impact indoor air quality but these are rarely reported in the studies reviewed.
4. Standard test protocols and measurement methods for domestic indoor PM should be devised for further research in this area. These should take into account that the length of exposure may be different for the different cases, for instance a short cooking or ash removal activity compared to longer stove operation activity. The rate of air changes and ventilation needs to also be defined in a quantitative way.

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Nomenclature

BC	Black carbon, measured using
COPD	Chronic Obstructive Pulmonary Disease
CV	Cardio- vascular
DC	Diffusion Charging technique (DC)
EC	Elemental carbon
FP	Fine particle also known as $PM_{2.5}$, diameters that are < 2.5 μm.
IAQ	Indoor Air Quality
OC	Organic Carbon, condensable fraction of PM that contains complex mix of SVOC, VOC
PAH	Polycyclic Aromatic Hydrocarbons
PC	Photo-Charging ionisation technique (PC)
PCDD	Polychlorinated dibenzodioxin
PCDF	Polychlorinated Dibenzofuran
$PM_{2.5}$	Fine particles that are generally <2.5 μm diameter
PM_{10}	Inhalable particles that are generally <10μm diameters
SOA	Secondary Organic Aerosol
SVOC	Semi-volatile Organic Compounds
TWA	Time weighted average
UFP	Ultra Fine Particulates
VOC	Volatile Organic Compounds

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