REVIEW ON WOOD BURNING STOVES AND INDOOR AIR POLLUTION

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1. INTRODUCTION

In 2020, it was estimated that 3.2 million worldwide deaths per year were a result of household air pollution (WHO, 2022). With many people spending up to 90% of their time indoors, indoor air pollution is a significant risk to human health (Parliamentary Office of Science and Technology, 2023). Indoor air pollution has been linked to a variety of health impacts including respiratory diseases, heart disease, cognitive deficits, and cancer. A recent survey of people using indoor burning practices in the UK found that 46% of respondents agreed that indoor burning is a significant source of air pollution, however only 27% expressed concern over the associated health impacts of indoor burning to themselves and others (DEFRA, 2020).

Wood burning stoves are amongst a variety of sources contributing to indoor air pollution, including building materials, other combustion appliances, and solvent-containing products (AQEG, 2022). In Wales, it is estimated that 11.2% of households participate in indoor burning practices compared to about 7% in UK (DEFRA, 2020). It is further estimated that over 9% of households in Wales have use of a wood stove, (BEIS, 2016). A survey carried out by Wong & Walmsley (2012), indicated that 75% of firewood is burnt in a wood stove, of which 70% is used in rural areas. However, a more recent survey has indicated that 59% of domestic wood burning using a wood stove occurs in urban areas, compared to 41% in rural areas (DEFRA, 2020). This indicates a significant increase in the use of wood burning stoves in urban areas since 2012. It is also documented that following the increases in costs of natural gas and electricity since 2021, solid fuel burning for space heating (including wood stove use) has increased (AQEG, 2022).This review aims to collate literature on wood burning stove use and indoor air pollution in developed countries and the associated health impacts whilst describing any limitations or gaps in the research.

2. INDOOR AIR POLLUTION

2.1 LEGISLATION AND GUIDANCE

There are currently no regulations to determine limit values for indoor air pollution. However, there are currently legislation that control outdoor emissions from indoor burning practices which can also reduce indoor pollutant emissions. Building and construction regulations also provide requirements on materials used in construction which include stoves which indirectly control indoor air pollution. There is also guidance available to limit concentrations of certain pollutants in indoor environments such as NO2, CO, VOCs and PAHs.

2.1.1 Legislation

In the UK, air quality policy, objectives and targets are set at a national level. The UK government has introduced several legislative efforts in recent years to reduce pollutant emissions and improve air quality, as a result of a growing focus on and understanding of the effects of air pollution. The most recent action from the UK Government for air quality is outlined in the Environmental Plan 2023 (HM Government, 2023), where one of the goals outlined focuses solely on improving air quality in the UK. Within this goal, reducing emissions within the home is a key aim, which includes improving regulation for burning high emission materials in the home, including air quality as a key consideration in planning processes and developing widescale and targeted communications campaigns to mitigate exposure.

The Clean Air Plan for Wales (2020) sets long term ambitions and the necessary steps for improving air quality in Wales. It also highlights the importance of indoor air quality and the aim of raising awareness of indoor air pollution and reducing emissions from indoor domestic burning of solid fuels such as wet wood and traditional house coal.

A number of initiatives have been introduced to explicitly address the pollution that is produced when solid fuel is burned. The primary legislation that controls solid fuel burning is The Clean Air Act (1993) which was first introduced in 1956 as a response to London smog events. This legislation established requirements for the creation and regulation of smoke control areas where the use of appliances which emit smoke are prohibited and only authorised fuels or exempted appliances are permitted to be used. Wood is not an authorised fuel and hence can only be used in specific appliances that are exempt, such as approved stoves, boilers, and cookers. However, this legislation is primarily related to outdoor emissions and not indoor emissions.

In England, the Air Quality (Domestic Solid Fuels Standards) (England) Regulations 2020 were introduced to further limit the use of the most polluting solid fuels in houses. These regulations were made under section

87 of the Environment Act 1995 to restrict the sale of certain solid fuels (in particular bituminous coal and wet wood) and came into effect on 1st May 2021. These restrictions outline that small amounts of wood and manufactured solid fuels must be certified as 'Ready to Burn', which denotes a moisture content of less than 20%, for wood and low sulphur and smoke emissions for manufactured solid fuels. Furthermore, larger volume sales of wood are contingent upon the buyer receiving information on correct usage (such as storage and moisture level checks). Although the primary aim of these regulations is to improve outdoor air quality, indoor emissions are also controlled as a result of these regulations.

The Construction Products Regulations outlined in 'European Council Regulations 305/2011' (2011), describe that construction works must be designed and built so that, during their lifecycle, they will not be a threat to the health, hygiene or safety of workers, occupants or neighbour, nor will they have an undue influence on the environment or climate while they are being built, used, and demolished. The regulations within this directive that pertain directly to wood stoves include the regulation of emissions of dangerous substances, volatile organic compounds (VOC), greenhouse gases or dangerous particles into indoor or outdoor air and regulation of faulty discharge of wastewater, emission of flue gases or faulty disposal of solid or liquid waste.

2.1.2 Guidance

In 2010, the WHO released guidelines for indoor air quality for a selection of pollutants including Benzene, Carbon Monoxide, Formaldehyde and Nitrogen Dioxide as well as other pollutants (WHO, 2010). The WHO also released guidelines on household fuel combustion in 2014, which build upon the indoor air quality guidelines. They bring together the most recent data on fuel use, emissions and human exposure levels, health risks, intervention impacts, and policy considerations to provide actionable recommendations to lessen this health burden of poor indoor air quality. Further to these, in 2021 the WHO released guidelines that should be applied to indoor and outdoor air quality. Within these guidelines, targets are set for gaseous pollutants of O_3, NO_2, SO_2 and CO as well as particle pollutants of PM_{10} and $PM_{2.5}$ (WHO, 2021).

A summary of these guidelines is shown in Table 1 for pollutants relevant to this study. A selection of these pollutants have specified indoor pollution limit values. Other pollutants have no specific indoor limit value prescribed to them and therefore the WHO ambient limit value is outlined, as ambient limit values are used to control both outdoor and indoor pollutant concentrations.

Table 1 – WHO guidelines on Indoor Limit Values (2010) and Global Air Quality Guidelines (2021) for pollutants included within this study (WHO 2010, WHO 2021).

Pollutant	WHO Guidelines on Indoor Limit Values (2010)	WHO Global Air quality Guidelines (2021)
PM_{10}	No limit value described	45µg m^3 – 24 hour average 15 µg m^3 – Annual average
$PM_{2.5}$	No limit value described	15 µg m^3 – 24 hour average 5 µg m^3 – Annual average
NO_2	200 µg m^3 – 1 hour average 40 µg m^3 – Annual average	25 µg m^3 – 24 hour average 10 µg m^3 – Annual average
CO	100 mg m^3 – 15 minute average 35 mg m^3 – 1 hour average 10 mg m^3 – 8 hour average 7 mg m^3 – 24 hour average	4 mg m^3 – 24 hour average
PAH	No threshold determined and all indoor exposures are considered relevant to health	No limit value described
Benzene (VOC)	No safe level of exposure can be recommended	No limit value described
Naphthalene (VOC and PAH)	0.01 mg m^3 – Annual average	No limit value described
Formaldehyde (VOC)	0.1 mg m^3 – 30 minute average	No limit value described

3. STUDIED POLLUTANT EMISSIONS

3.1 PARTICULATE MATTER

3.1.1 Formation and Sources

Particulate matter (PM) are a mixture of solid particles and liquid droplets ranging in size, sources, and formation. PM is commonly categorised by size, with coarse particulate matter (PM_{10}) measuring less than 10 µm in diameter and fine particulate matter ($PM_{2.5}$) with a diameter of 2.5 µm or less. Particulate matter may be emitted directly from a source as primary particles or form secondary particles from chemical reactions in the atmosphere. Secondary particles are formed within the atmosphere through chemical reactions to produce low volatility substances which condense into solid or liquid phases and as a result form particulate matter.

Significant sources of ambient particulate matter in the UK are wood burning, and tyre and break wear from vehicles. Other sources include emissions from industrial, commercial, and domestic sectors. However, a third of particulate matter concentrations are transported to the UK from other European countries (DEFRA, 2023). PM_{10} only persists in the atmosphere for hours or days due to gravitational settling. Comparatively, $PM_{2.5}$ persists for days or weeks as it is only removed by dry deposition or scavenging by rain (Duhanyan & Roustan, 2011). Long residence times allow particulate matter to be suspended for extended periods and hence can result in long range transport by wind over vast distances up to thousands of kilometres.

3.1.2 Studies on impact of wood stoves on indoor PM

3.1.2.1 North America

Between 2005 and 2007, a community wide wood stove changeout programmed was enacted in Libby, Montana, USA. During this programme, nearly 1200 stoves were changed out with cleaner burning models. The effectiveness of this study was then assessed in four different studies. Ward, et al., (2010) identified that there was a decrease in ambient $PM_{2.5}$ concentrations of 20% following this programme. This study assessed changes in concentrations of $PM_{2.5}$ in ambient air and not indoor air quality. However, two studies also assessed the effectiveness of the changeout scheme with a focus on indoor air quality. Average indoor $PM_{2.5}$ concentrations were shown to decrease by more than 70% in the winter following the change out to cleaner burning stoves in the 16 homes sampled (Ward & Noonan, 2008). However, a small number of homes were shown to have no change in indoor $PM_{2.5}$ concentrations as a result of this scheme. As this study only monitored the changes in the first winter following the change out scheme, the long-term outcomes of this scheme were not quantified within this study. The follow-up study, continued to monitor these changes in the years following the programme and found a large variability in the average $PM_{2.5}$ levels across the homes surveyed (Noonan, et al., 2012). This study highlighted that some homes continued to experience reduced $PM_{2.5}$ concentrations compared to those measured prior to the scheme. However, some homes were shown to experience increased $PM_{2.5}$ levels in the years following the scheme. A final study investigated these changes further but provided households with wood of a consistent quality to remove the variability of wood type and moisture content and found that $PM_{2.5}$ concentrations reduced by 20% following the changeout programme. (Ward, et al., 2009). Within the studies detailed above there is high variability between findings due to the number of differences between each study. Overall, the results of these studies highlight that changing out older stoves for cleaner burning stoves can reduce indoor $PM_{2.5}$ concentrations.

A study by Fleisch, et al., (2020), investigated indoor $PM_{2.5}$ concentrations in 137 homes of pregnant women in Northern New England, with and without wood stove use. The findings of this study indicate that homes with the use of a wood stove, had $PM_{2.5}$ concentrations 20.6% greater than homes without a wood stove. These findings are consistent with a breadth of other studies that indicate PM concentrations are higher (4-36%) in homes with a wood stove compared to those without (Wyss, et al., 2016; Leaderer, et al., 1994). Further analysis was made into the age of the stoves, Environmental Protection Agency (EPA) certifications and wood moisture. Findings indicated that when stoves were older and non-EPA certified, $PM_{2.5}$ concentrations were generally higher.

In contrast to the findings of the above studies, two studies carried out in New Mexico, USA and British Columbia, Canada found no association between wood stove age and household air pollution indices (Rahman, et al., 2022; Allen, et al., 2009, Ward, et al., 2017). Indicating that instead PM emissions were associated with stove types, stove maintenance, and burning practices. Rahman, et al., (2022) found that a correlation between increased flue cleaning and reduced indoor $PM_{2.5}$ concentrations and highlighted that cleaning the flue may be more effective at reducing emissions than changing out wood stoves to newer models. Another study undertaken across three states in the USA, sampled $PM_{2.5}$ concentrations across 6 days in 101 homes shows consistent findings regarding cleaning practices (Walker, et al., 2021). Mean $PM_{2.5}$ concentrations were 65% higher in homes that had not cleaned their chimney within the past 6 months. There is shown to be a correlation between wood moisture content and PM emissions from wood stoves, where higher moisture contents can significantly increase PM_{10} and $PM_{2.5}$ concentrations due to incomplete combustion (Magnone, et al., 2016; Price-Allison, et al., 2019; Yuntenwi, et al., 2008). This may also indicate that high wood moisture content could lead to elevated indoor PM concentrations however further investigation would be required.

Another variable investigated by a number of studies is the influence of leaking or non-airtight wood stoves on indoor $PM_{2.5}$ concentrations. An early study by Traynor, et al., (1987) compared indoor PM concentrations when operating three airtight woodstoves and one non-airtight wood stove. An airtight stove is one with no visible leaks or cracks within the body of the stove or its vent system. Results from this study indicated that when airtight stoves were operated, total suspended particle concentrations were between 24 µg m^3 and 71 µg m^3. When the non-airtight stove was operated, total suspended particle concentrations were measured to be between 30 µg m^3 to 650 µg m^3. These findings are further supported by other studies with consistent findings (Carvalho, et al., 2016; Kaarakka, et al., 1989; Vincente, et al., 2020). Therefore, wood stove age may or may not be a variable affecting indoor PM concentrations. However, stoves that are leaking or that are not airtight may lead to increased concentrations due to increased circulation on PM in households.

3.1.2.2 United Kingdom

A study undertaken by Chakraborty, et al., (2020) assessed variations in $PM_{2.5}$ and PM_1 concentrations as a result of using DEFRA certified wood stoves in 20 households in Sheffield. This study also found that daily average $PM_{2.5}$ and PM_1 concentrations increased by 196.23% and 227.8% respectively. Furthermore, hourly average concentrations showed that $PM_{2.5}$ concentrations increased up to 47.60 µg m^3 during wood stove use and PM_1 increased up to 36.15 µg m^3. Analysis of these concentration changes over time indicated that concentrations significantly increased during wood stove refuelling where the stove door was opened causing a ‘flooding event’. This therefore indicated that opening the stove door was the primary source of elevated indoor PM concentrations. Further analysis highlighted that elevated PM concentrations were also associated with the number of fuel pieces burnt and the wood stove usage time. Prolonged use of a wood stove resulted in more refuelling events and therefore an increased number of ‘flooding’ events. This is consistent with findings from two other studies, both of which indicate that indoor PM concentrations are highest during ignition and refuelling phases of wood stove use, when the door is open and gaseous and particulate combustion products can circulate into the room (Salthammer, et al., 2014; Vincente, et al., 2020).

In response to the study by Chakraborty, et al., (2020), the UK Stove Industry Alliance (SIA) commissioned a report to investigate the association between indoor air quality and woodburning (Stove Industry Alliance, 2022). The literature review undertaken comprised of 35 studies, including the study completed by Chakraborty, et al., (2020). This report compares the results of the studies to the 24-hour average PM_{10} and $PM_{2.5}$ WHO air quality guidelines published in 2005, however these 24-hour recommended exposure limits have since been updated in 2021, from 50 µg m^3 to 45 µg m^3 for PM_{10} and from 25 µg m^3 to 15 µg m^3 for $PM_{2.5}$. The report endorses the findings that PM emissions are elevated over short timescales due to refuelling and ash removal causing ‘flooding’ events but suggests that these can be mitigated following maintenance and best practice guidelines (HETAS, 2015). Similar to the findings of this current study, the report commissioned by the SIA found variable results between studies and highlighted gaps in research pertaining to the variety of factors that can influence PM concentrations which are not well reported. This report further recommended standardised protocols and methods to assess variations in PM emissions whilst controlling variables. A number of other studies were highlighted within the SIA commissioned report, which indicated that other common indoor sources of PM may also cause elevated PM emissions such as cooking, cleaning, smoking and burning incense (Stove Industry Alliance, 2022). Several studies have indicated that cooking is a significant source of indoor PM emissions, especially when using oil, and can cause elevated PM concentrations of up to 1000 µg m^3 (Abdullahi, et al., 2013; Lachowicz, et al., 2021).

3.2 OXIDES OF NITROGEN

3.2.1 Formation and Sources

Nitrogen Oxides (NOx) are mainly formed during the combustion of fuels and are comprised of NO and NO_2. Although NOx is primarily released into the atmosphere through the combustion of fuels, it can also be produced naturally as a result of volcanic activity or lightning strikes. Of all anthropogenic sources of NOx, in the UK, motor vehicles produce over half of the emissions, followed by power stations and other industrial, commercial, and domestic combustion processes (AQEG, 2004). The total emissions of NOx were estimated to be 42kt in 2021 in Wales, which is 6% of the UK total (DEFRA, 2023).

3.2.2 Studies on impact of wood stoves on indoor NOx

A review of current literature suggests that NOx concentrations in indoor air as a result of wood stove burning are minimal, however there is a limited amount of literature on the associations between wood burning stoves and indoor NOx emissions. Therefore, further research should be carried out to investigate the association between NOx emissions and indoor wood burning stoves. Research carried out by Levesque, et al., (2001) sampled pollutant concentrations in 89 homes from between 1995 and 1996. When comparing NOx emissions from homes with use of a wood burning stove to those without, there was shown to be no significant difference in NOx concentrations. These results are consistent with findings by Salthammer, et al., (2014), where there were also no changes in indoor concentrations when testing seven ovens in different households. One study found that NO_2 concentrations were statistically higher when the wood stoves were in use, however this was likely a result of increased outdoor NOx pollution and not a direct result of emissions form the woodstove (Kaarakka, et al., 1989).

A study into the effect of fuel moisture content on outdoor emissions form wood stoves highlighted that NOx emissions are likely solely a result of fuel-nitrogen content of the wood used which is likely to be minimal in most cases and therefore NOx emissions are unlikely to increase significantly during wood burning (Price-Allison, et al., 2019). Furthermore, NOx emissions are thought to vary dependent on the combustion phase of burning wood, although it is unlikely that the effects of this are significant (Mitchell, et al., 2016). Although these studies are relating to the effects on outdoor emissions, it is possible that fuel moisture content and combustion phase may also have an effect on indoor NOx concentrations although further investigation would be required.

3.3 CARBON MONOXIDE

3.3.1 Formation and Sources

Carbon Monoxide (CO) is formed during incomplete combustion of carbonaceous fuels when there is insufficient oxygen present. Industrial processes, wood combustion devices, and fossil fuel-burning equipment are significant sources of carbon monoxide emissions.

3.3.2 Studies on impact of wood stoves on indoor CO

CO concentrations are directly linked to combustion efficiency, where incomplete combustion and therefore reduced efficiency leads to increased CO concentrations in exhaust gases. Salthammer, et al., (2014) documented increased CO concentrations when two of the six closed wood stoves were in use within the study. One open wood stove was also measured during this study. The maximum room CO concentrations prior to stove use were measured as 1.21 $mg\ m^{-3}$ and increased to 5.11 $mg\ m^{-3}$ when the stove was in use. As the stove door was left open during use, this is likely a contributor to the high concentrations measured. Another study found few CO concentrations above the detection limit of 1ppm during stove use (Lévesque, et al., 2001). In contrary to these findings, one study found significant increases in CO concentrations of 3.5-fold when comparing emissions in a control home to one with a wood burning stove in use (Vicente, et al., 2020).

Similar to indoor NOx concentrations, CO concentrations indoors are thought to vary dependant on the combustion phase of the wood stove, with highest concentrations measured during the smouldering phase due to the wood char readily burning with incoming oxygen (Mitchell, et al., 2016). Other variables affecting CO emissions include wood moisture content. CO concentrations are shown to be highest when moisture content of wood used is high (30% or above) due to the inefficiency of combustion under these circumstances (Bignal, et al., 2008; Yuntenwi, et al., 2008).

3.4 POLYCYCLIC AROMATIC HYDROCARBONS

3.4.1 Formation and Sources

Polycyclic aromatic hydrocarbons (PAHs) area group of organic pollutant compounds that contain two or more benzene rings in a condensed benzene core. PAHs are emitted from natural and anthropogenic sources through incomplete combustion or pyrolysis. Natural PAH emission sources include volcanic eruptions and forest fires. Anthropogenic emission sources are the main contributor to PAH emissions, of which combustion of biofuels and fossil fuels are the primary contributor.

3.4.2 Studies on impact of wood stoves on indoor PAHs

The study carried out by Salthammer, et al., (2014) also investigated indoor concentrations of PAHs in association with use of wood burning stoves. Only one PAH was measured in this study, benzo[a]pyrene (BaP), a key component of PAHs and a common product of wood burning (Piazzalunga, et al., 2013). During this study, background concentrations of BaP were measured at 0.6 ng m^3 and elevated BaP concentrations were detected from two of the wood stoves in use, of 1.1 ng m^3 and 2.8 ng m^3. This is directly associated with stove use as outdoor concentrations remained at <0.6 ng m^3 during the sampling period. There are few studies on indoor PAH concentrations as a result of wood burning stoves. However, there is evidence to suggest a good correlation between PAH and PM_{10} concentrations (Vicente, et al., 2020).

There is also evidence to suggest that ambient PAH emissions from wood burning are significantly affected by wood type, temperature and burning conditions. Despite no studies quantifying the effect of these factors on indoor air quality, studies have been undertaken for ambient emissions. It is likely that the effect of these factors is also seen in indoor PAH emissions. A lower temperature of burning is also thought to increase the ambient concentrations of PAH emissions (Price-Allison, et al., 2019). Furthermore, a study by Avagyan, et al., (2016) indicated that elevated PAHs are seen when high burn rates occur, where the stove is overloaded with more and smaller logs.

3.5 VOLATILE ORGANIC COMPOUNDS

3.5.1 Formation and Sources

Volatile Organic Compounds (VOCs) are a large group of chemicals that may be emitted in solid, liquid or gas forms. There are over 10,000 VOCs but this report will focus on benzene, toluene, ethylbenzene and xylene (BTEX) as well as formaldehyde as these are the VOCs most commonly reported in the literature studied. VOCs are widely used in construction and building products such as paints and solvents as well as household consumer products such as cleaning products, air fresheners and personal care products.

3.5.2 Studies on impact of wood stoves on indoor VOCs

A study was carried out on 9 households with wood stoves in Italy which compared indoor BTEX concentrations when wood burning stoves were not in use and when in use, following the repair of the wood stoves and education of home-dwellers (Piccardo, et al., 2014). The findings of this study suggested an increase in all BTEX pollutants of up to 70% when comparing pollution levels prior to use and during use of the wood stoves. During the sampling period where stoves were in use, this study found that benzene measurements were above 5.0 µg m^3 which is the European limit (Directive 2008/50/EC) for ambient benzene. This study also found elevated toluene concentrations, especially in three homes. Further assessment of this data identified that newspaper was used to light the stoves in all three houses. Caselli, et al., (2009) highlighted that newspapers are an important source of toluene and therefore the elevated toluene concentrations within these homes is tentatively explained as a result of the storage and use of newspapers within these homes. There are currently no studies which assess the relationship between newspaper use in wood burning stoves and toluene concentrations, therefore further research would need to be carried out.

A further study found significant increases in benzene concentrations during wood stove use, with concentrations reaching a maximum of 72 µg m^3 (Salthammer, et al., 2014). However, detailed investigation identified that the firelighters used to light the wood stove contained benzene. The stove was ignited again without the firelighters and indoor benzene concentrations were shown to be significantly lower at 8 µg m^3. Therefore, it is suggested that the use of some firelighters can contribute to elevated indoor benzene concentrations. Gustafson, et al., (2007) also noted significant increases in benzene concentrations during the use of wood stoves, with concentrations doubling when the stoves were in use. This study also found however that there was not statistical difference between formaldehyde concentrations in homes with or without wood stoves. These results are consistent with those from other studies, that identify that the use of a wood stove has no effect on formaldehyde concentrations (Lévesque, et al., 2001).

4. ASSOCIATED IMPACTS

4.1.1 Health Effects

This section aims to review epidemiological studies investigating the associated health effects of indoor air pollution as a result of wood burning and wood burning stove use in developed countries. Whilst there is a breadth of research on the health impacts of each pollutant in ambient air and also the associated health impacts of indoor air pollution, there are significantly fewer studies directly investigating the health impacts associated with wood burning.

Guerico, et al., (2021) performed a review of epidemiological evidence of pollution and health effects and found no association between exposure to wood burning and risk of asthma, wheeze, and cough. However, this study did find a small increase in respiratory infections when wood burning was carried out. A further study carried out on 20 participants, also showed no effect of wood smoke from wood burning stoves on lung function or nasal patency but did highlight mild inflammatory responses in central airways (Riddervold, et al., 2012).

Another review of epidemiological evidence by Rokoff, et al., (2017) highlighted there may be an association between wood smoke from wood burning stoves and childhood respiratory health, but more consistent associations were found between childhood respiratory health and outdoor air pollution from wood smoke. This indicates that outdoor air pollution has a greater effect on childhood respiratory health, but it may also be due to the lack of literature available, or that households with children with asthma are less likely to own or use a wood stove frequently. Further evidence suggests that vulnerable groups such as children are at a higher risk of developing respiratory illness or asthma symptoms when a wood stove is in use (Honicky, et al., 1985; Jones, 1999). McNamara, et al., (2017) also highlighted that during wood burning indoor concentrations of airborne endotoxin increased, which is associated with proinflammatory effects, to which vulnerable groups are most at risk[1].

A study carried out by Lévesque, et al., (2001) surveyed 89 households with children and adults present to assess respiratory symptoms associated with indoor wood stove use. This study indicated no association between respiratory symptoms in children and indoor wood stoves and a possible association between upper respiratory tract illnesses, coughing, wheezing and respiratory difficulty with wood stove use in adults. It is suggested that this disparity in results between adults and children may be a result of the greater number of hours adults spend in the home or other confounding factors making identifying relationships between variables difficult. Evidence from this study also suggested that opening windows reduced the number of respiratory symptoms and the number of days with respiratory symptoms, therefore indicating that good ventilation reduces negative health effects.

It is well documented that elevated CO concentrations from indoor combustion, including wood stove use, limits oxygen transportation through the body. Short term exposure to elevated CO can therefore result in headaches, nausea, dizziness or unconsciousness. Prolonged exposure can lead to carbon monoxide poisoning which may result in neurological effects, cardiological damage or fatality (Raub, et al., 2000). Due to the known risk of carbon monoxide poisoning from indoor combustion, the Welsh Government’s Building Regulations state that all dwellings with a new or replaced fixed solid fuel appliance must be provided with a carbon monoxide alarm in the room where the appliance is located (Welsh Government, 2010).

Several studies have also been carried out to assess the associated between indoor air pollution from wood smoke to cancer risk. Carcinogenic potential was found to be greater when comparing indoor and outdoor pollution during wood stove use especially when PAH concentrations were elevated (Jones, 1999; Vicente, et al., 2020). Two studies also found that use of a wood stove may be associated with a higher risk of breast cancer in women with a family history of breast cancer (White, et al., 2014; White & Sandler, 2017).

[1] Airborne endotoxins are a major component of the outer membrane of Gram-negative bacteria which are also as component of particulate matter. Endotoxins are shown to initiate inflammatory responses in the lungs and, trigger and exacerbate asthma symptoms.

4.1.2 Wellbeing Impacts

A survey of wood stove users, carried out in 2021, indicated that 93% of wood burning stove users recognise the positive impact of stove on their wellbeing. Of the 1277 respondents, 1024 indicated it aided with relaxation. Further studies have indicated that wood fires (including wood stoves) can be a preferred option for complementary heating and 'cosiness' (Karlsson, et al., 2020). Furthermore, watching a fire can have a relaxing effect in the brain and lower blood pressure (Lynn, 2014; Karlsson, et al., 2020).

5. LIMITATIONS AND GAPS

Analysis of the above literature has indicated that there are limitations in the consistency of research methods due to the breadth of variables changing between each study such as differences in stove design and operation, fuel properties, and room features such as ventilation. In many cases, the stove type or design is not described within the studies therefore making comparison between results difficult. Furthermore, a majority of studies were undertaken within households using a wood stove and stove operation was not described as being standardised, therefore variability in findings may be a result of differences in user operation. The characteristics of the fuel used also varies between studies, in some cases the type of wood or wood moisture content is not described, both of which have been shown to affect wood stove indoor emissions. Another variable that is not well described amongst these studies is the weather conditions during the monitoring periods. Weather conditions can impact room ventilation and stove draught which can have a significant impact on indoor pollutant concentrations and pollution dispersal. In addition, many studies varied in their sample sizes, sampling periods and measurement intervals. Further investigations would be needed to assess the impacts of each of these variables.

There is a breadth of information available that shows the association between wood stove use and indoor PM pollution. However, there are fewer studies investigating the effects on other pollutants, especially VOCs and PAHs. Wood stove use was also shown to have limited effects on indoor NOx concentrations. However, this may be due to the lower NOx concentrations overall and therefore sampling methods may have not detected changes in concentrations as effectively due to the detection limits of the analysers used. Some studies highlighted the effect of user stove operation such as ignition and refuelling practices and woodstove cleaning and maintenance. However, no studies proposed comprehensive good stove use practices to minimise indoor pollution associated with wood stove use. There is also limited research on the health impacts directly associated to indoor air pollution as a result of wood stove use. Most studies target the effects of indoor pollution, with few studies describing the associated impacts of wood stove use.

6. CONCLUSIONS

The aim of this review was to assess the relationship between wood burning stoves and indoor air pollution. Indoor particulate matter concentrations are generally evidenced to increase during wood stove use. Indoor concentrations of other pollutants such as nitrogen oxides and carbon monoxide are shown to be variable, generally dependant on other variables such as fuel moisture content, fuel nitrogen content and combustion efficiency. The effects of wood burning stove use on PAH and VOC concentrations are also shown to have a high amount of variability dependent on the compounds studied within these groups.

Evidence from this review highlights the significant impact of factors such as combustion efficiency and fuel characteristics. When wood moisture content is high and combustion efficiency is low, pollutant concentrations are generally shown to increase. Studies also highlight the positive effect of good wood stove maintenance such as regular cleaning and fixing leaks and drafts, both of which can reduce indoor pollutant concentrations.

There is limited research on the direct health effects associated with wood stove use. However, current evidence suggests that there may be an increased risk of respiratory symptoms such as asthma and respiratory tract infections, especially in vulnerable groups such as children. Further studies suggest carcinogenic potential was greater during wood stove use due to the carcinogenic properties of some pollutants, especially when PAH concentrations were elevated. Research has also suggested that the use of wood burning stoves has positive impacts on user wellbeing, such as aiding relaxation, providing 'cosiness' and reducing blood pressure.

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