The Overlooked Contribution of Cooking Methods' Release of Particulate Matter to Respiratory Risk Exposure: A Systematic Review and Meta-analysis

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ABSTRACT

Objective: Many governmental regulations exist around ambient (outdoor) air quality. However, most of these policies only persist until a civilian's doorstep. Indoor air quality (IAQ) is often unregulated, which is a concern because people spend a daily average of 21.6 hours indoors versus the 2.4 hours they spend outdoors. The World Health Organization (WHO) states that "Nearly 3.2 million people die prematurely each year from diseases caused by household air pollution." However, there is a significant lack of research regarding household and indoor air pollution compared to ambient air pollution. This Systemic Review and Meta-analysis investigates commonly used cooking methods, their impact on respiratory health, and the gaps in current literature.
Methods: After a total of 1912 duplicate records were excluded, 416 studies were screened. 354 of them were excluded based on title and abstract. 62 reports were sought for retrieval and screened. 13 studies were used, excluding studies from external sources.
Results: The mean PM1 emission concentrations were calculated to be 139.55μg/m³ and 58.8μg/m³ for pan-frying and toasting, respectively. As for PM2.5 emissions, all 8 selected cooking methods had enough data to be considered for statistical analysis. Deep-frying had the greatest mean PM2.5 emission concentration of 841μg/m³, followed by stewing with a mean concentration of 573μg/m³, stir-frying with a mean concentration of 558.615μg/m³, roasting with a mean concentration of 461.375μg/m³, pan-frying with a mean concentration of 234.26μg/m³, boiling with a mean concentration of 132μg/m³, toasting with a mean concentration of 72.1μg/m³, and steaming with a mean concentration of 40.4μg/m³. Finally, for PM10, the mean emission concentrations from greatest to least were as follows: deep frying with a mean concentration of 1192μg/m³, roasting with a mean concentration of 736.99μg/m³, pan-frying with a mean concentration of 198.45μg/m³, and toasting with a mean concentration of 105.1μg/m³.
Conclusion: A preliminary understanding of the types and concentrations of PM from these cooking methods was reached. Their effect on respiratory health was assessed by gathering data from studies that reported associations with cardiovascular disease, lung function, and prevalence of carcinogenic compounds. The need for further research regarding emissions from specific cooking methods and appliances, especially air fryers, was identified.

INTRODUCTION

Ambient (outdoor) air pollution was first identified as a global health concern decades ago and governments have been implementing successful measures to mitigate these effects since then. In the next few years, outdoor air pollution is predicted to decrease substantially. But what about indoor air pollution? The Global Burden of Disease study concluded that in 2021, outdoor and indoor air pollution contributed to 8 million deaths worldwide (1). Poor indoor air quality (IAQ) is a significant factor in deaths from air pollution and its contribution is often overlooked. An article in the journal *Nature* stated, “Researchers and policymakers are only now waking up to the effects of dirty indoor air. As ever, low-income and marginalized communities are most exposed” (2).

According to a survey conducted by the United States Environmental Protection Agency (EPA), humans spend 90% of their time indoors and only 10% outdoors (3). Furthermore, elderly people, a demographic that tends to be more vulnerable to respiratory complications, spend an average of 92% of their day indoors (4). Yet, significantly less research has been undertaken regarding IAQ compared to ambient air quality. Previous research has investigated the effects of a culmination of various indoor air pollutants, such as incense burning, vacuuming, and candles. However, cooking emissions are rarely ever the sole focus of a study even though people spend, on average, a greater amount of their day cooking than all these other activities. According to the US Bureau of Labor Statistics, Americans spend an average of an hour preparing food every day through the use of cooking appliances that are known to release harmful chemicals (5).

Significant research has demonstrated the effects of Volatile Organic Compounds (VOC) without a strong focus on particulate matter (PM) even though PM is typically more harmful. Outdoor PM is considered a Group 1 Carcinogen by the International Agency for Research on Cancer (IARC) (6). On the other hand, indoor PM isn’t considered a carcinogen. This is a concern because even though outdoor air pollution contains harmful chemicals and drives climate change, poor IAQ exposes humans to greater concentrations of PM which may lead to health complications.

There is significant understanding regarding types of PM prevalent in the outdoor environment, however, the gaps in understanding the cooking methods that contribute most to PM emissions in an indoor environment shouldn’t be ignored. It’s important to understand and solve these gaps because confined spaces, such as kitchens, can cause PM to accumulate in great concentrations and cause respiratory and cardiovascular disease. This systematic review and meta-analysis will investigate the overlooked role of cooking emissions on respiratory risk exposure and can serve as a guideline for future research on the subject matter.

METHODS

Database and Search Strategy

Online searches were completed using the PubMed database. This systematic review and meta-analysis followed guidelines set by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (7). Published items relevant to the research question, “How do Cooking Methods’ Release of Particulate Matter Contribute to Respiratory Risk Exposure?”, were assessed. A boolean search algorithm was implemented using the terms “carcinogen,” “air quality,” “particulate matter,” and “respiratory exposure,” in conjunction with the names of specific common cooking methods. Boolean expressions "AND" and "OR" were used alongside these search terms whenever necessary. A total of 16 searches were conducted. Finally, the "10 years" filter was applied to all searches to retrieve up-to-date studies. The search was performed from February 2024 to June 2024.

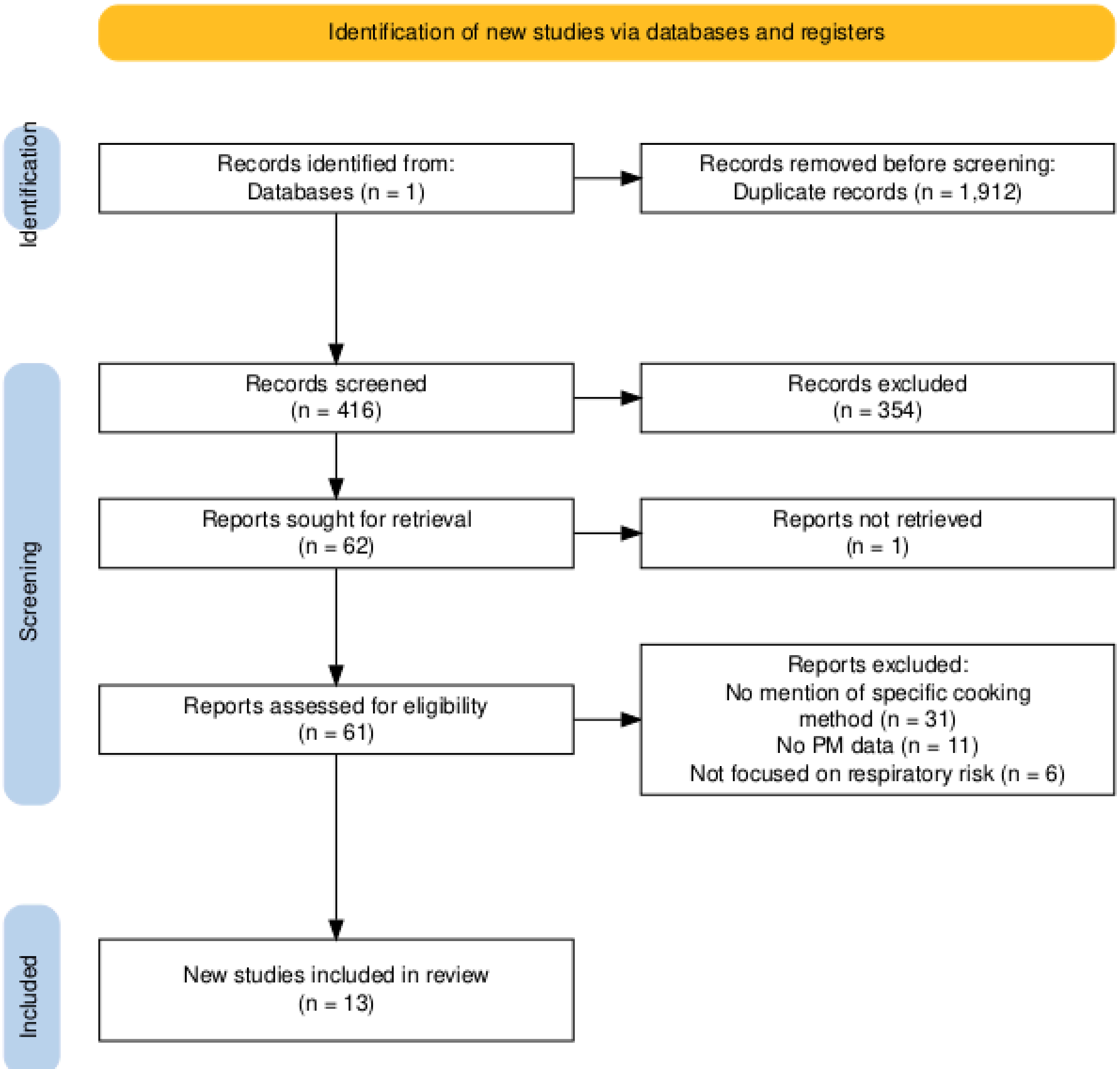

Figure 1. Flow chart of the literature search

Inclusion Criteria

The "10 years" filter was applied to all PubMed searches to retrieve studies that have been published within the last 10 years. The reason for this is that studies from over 10 years ago often lacked access to air filtration and ventilation that are common today. This in turn would cause the PM emission concentrations from those studies to be abnormally high. Published items such as review articles, abstracts, and articles not written in English were excluded.

Selection of Studies

Initial records were screened for eligibility. Then, duplicate articles were removed, and further screening removed articles based on title and abstract. Finally, the remaining articles were full-text assessed for the relevancy of data points. Reports containing data points such as PM emission concentrations from specific cooking methods were then extracted and compiled.

Statistical Analysis

The mean emission concentrations of three sizes of PM(PM1, PM2.5, PM10) were extracted from all eligible studies. Eligible studies must have recorded PM emission concentrations from specific cooking methods. Furthermore, the reported emissions must have been specific concentrations instead of emission rates or emission factors. The final cooking methods selected for statistical analysis were deep-frying, stir-frying, boiling, pan-frying, toasting, roasting, stewing, and steaming. All the PM emission data from eligible studies were organized into groups based on the cooking method and were further separated based on the size of PM reported. The majority of the reported concentrations were in units of $\mu g/m^3$(micrograms per cubic meter) but some studies reported emission concentrations in units of mg/m^3(milligrams per cubic meter). The data from these studies was converted to units of $\mu g/m^3$. Then, the mean emission concentrations for PM1, PM2.5, and PM10 were calculated for each cooking method. After finalizing the mean emission concentrations of the three sizes of PM for each cooking method, an independent(unpaired), two-tailed Student's t-test was conducted between two groups for PM2.5 and PM10. The two groups were cooking methods that involve frying (deep-frying, stir-frying, pan-frying) and cooking methods that don't involve frying (boiling, stewing, steaming, roasting, toasting). This test was conducted to see if there was a statistically significant difference (SSD) in the emission concentrations of PM2.5 and PM10 between the two groups.

RESULTS

Mean PM Emission Concentrations

Only one included study reported PM1 emission concentrations for specific cooking methods. Data was extracted from Soppa et al. 2014, which is the only available study that reported the PM1 emissions from pan-frying sausages and toasting (8). This study reported emission concentrations for two different exposure levels for both cooking methods. The mean PM1 emission concentrations were calculated to be 139.55$\mu g/m^3$ and 58.8$\mu g/m^3$ for pan-frying and toasting, respectively (Figure 2).

All eight selected cooking methods had enough data to be considered for statistical analysis of PM2.5 emissions. Deep-frying had the greatest mean PM2.5 emission concentration of 841$\mu g/m^3$, followed by stewing with a mean concentration of 573$\mu g/m^3$, stir-frying with a mean concentration of 558.615$\mu g/m^3$, roasting with a mean concentration of 461.375$\mu g/m^3$, pan-frying with a mean concentration of 234.26$\mu g/m^3$, boiling with a mean concentration of 132$\mu g/m^3$, toasting with a mean concentration of 72.1$\mu g/m^3$, and steaming with a mean concentration of 40.4$\mu g/m^3$ (Figure 2). Finally, for PM10, the mean emission concentrations from greatest to least were as follows: deep frying with a mean concentration of 1192$\mu g/m^3$, roasting with a mean concentration of 736.99$\mu g/m^3$, pan-frying with a mean concentration of 198.45$\mu g/m^3$, and least was toasting with a mean concentration of 105.1$\mu g/m^3$ (Figure 2).

Reference and year	Location/Setting	Number of subjects	Mean PM1 emission concentrations	Mean PM2.5 emission concentrations	Mean PM10 emission concentrations	Cooking method(s)	Health Complications/Respiratory Symptoms
Siponen et al, 2019	Suburb in Kuopio, Finland	37 elderly residents	Not stated	pan frying: 4.4 μg/m³	Not stated	Pan Frying	Not stated
Soppa et al, 2014	Not stated	55 healthy individuals(28 men + 27 women)	Toasting Bread Level 1*: 37.7 ± 7.0 μg/m³; Level 2*: 79.9 ± 16.1 μg/m³ Pan Frying Level 1: 71.3 ± 28.2 μg/m³; Level 2: 207.8 ± 62.4 μg/m³	toasting bread Level 1: 62.6 ± 27.7 μg/m³; Level 2: 81.6 ± 16.6 μg/m³ pan frying Level 1: 84.4 ± 37.3 μg/m³; Level 2: 235.2 ± 81.4 μg/m³	Toasting Bread Level 1: 125.6 ± 87.1 μg/m³; Level 2: 84.6 ± 18.6 μg/m³ Pan Frying Level 1: 100.0 ± 51.9 μg/m³; Level 2: 296.9 ± 133.9 μg/m³	Toasting Pan Frying	"Our study indicates a possible association of short-term exposure to fine and ultrafine particles emitted from common indoor sources with small decreases in lung function in healthy adults."
See et al, 2006	National University of Singapore (NUS) Kent Ridge campus	NA	Not stated	Chinese stall: 201.8 ± 140.5 μg/m³ Malay stall: 245.3 ± 77.1 μg/m³ Indian stall: 186.9 ± 43.6 μg/m³	Not stated	Deep Frying Stir Frying Simmering	PM2.5 levels measured at the 3 food stalls far exceeded the National Ambient Air Quality Standard (NAAQS) at 65 μg/m³ for the 24hr standard.
Sjaastad et al, 2010	Model kitchen in conditions similar to those in a Western European restaurant kitchen	NA	Not stated	Not stated	Not stated	Pan Frying on electric stove Pan Frying on gas stove	Not stated
Sofuoglu et al, 2015	A Turkish university canteen that serves the school of architecture	NA	Not stated	deep frying: 108 ± 44 μg/m³	1192 μg/m³	Deep Frying	"PM10 concentrations associated with frying are much higher than the indoor air standard level of 8-h average 180 μg/m3 in Hong Kong but lower than the occupational standard of 8-h average 10,000 μg/m3 set by ACGIH. but lower than the occupational standard of 8-h average 10,000 μg/m3 set by ACGIH."
Lu et al, 2019	Nankai District in Tianjin, China	NA	Not stated	deep-frying: 1720 μg/m³ stir-frying: 629.33 μg/m³ stewing: 573 μg/m³ quick-frying: 201 μg/m³ boiling: 125.5 μg/m³ steaming: 49.5 μg/m³	Not stated	Deep Frying Stir Frying Stewing Quick Frying Boiling Steaming	Not stated

Table 1. Summary of included studies [first six studies of the thirteen studies included in the review]

Reference and year	Location/Setting	Number of subjects	Mean PM1 emission concentrations	Mean PM2.5 emission concentrations	Mean PM10 emission concentrations	Cooking method(s)	Health Complications/Respiratory Symptoms
Lee et al, 2020	Republic of Korea(South Korea)	NA	Not stated	grilling: 754 mg-PM-kg-meat	Not stated	Grilling	Not stated
Sharma et al, 2020	Residential apartment in the western region of Singapore	NA	Not stated	deep-frying: 695.0 µg/m^3 pan-frying: 646.3 µg/m^3 stir-frying: 487.9 µg/m^3 boiling: 138.5 µg/m^3 steaming: 31.3 µg/m^3	Not stated	Deep Frying Pan Frying Stir Frying Boiling Steaming	Not stated
Kong et al, 2020	Namdong District, South Korea	NA	Not stated	roasting: 96.21 ± 65.72 µg/m^3	127.01 ± 119.26 µg/m^3	Roasting	Not stated
Lee et al, 2022	Schools in Republic of Korea(South Korea)	NA	oily cooking: 13.30 µg/m^3 little oily cooking: 9.80 µg/m^3	oily cooking: 15.30 µg/m^3 little oily cooking: 11.20 µg/m^3	oily cooking: 17.0 µg/m^3 little oily cooking: 12.90 µg/m^3	Oily Cooking(deep frying, stir frying, roasting) Little Oily Cooking(boiling, steaming)	Not stated
Le et al, 2022	Kitchen of commercial Chinese restaurant	NA	Not stated	deep frying: 0.68 ± 0.11 mg/min grilling: 1.58 ± 0.25 mg/min	Not stated	Deep Frying Grilling	"These compounds included known carcinogens such as benzene, formaldehyde, acrolein, and acetaldehyde at concentrations exceeding the RfC limits set by the US EPA and ATSDR."
Padhi et al, 2022	Indo-Gangetic Plain(Uttar Pradesh)	NA	Not stated	boiling: 7.0 ± 2.7 gkg	Not stated	Boiling	Not stated
Lyu et al, 2022	6 types of commercial kitchens in Shanghai		Not stated	teppanyaki kitchen: 850.4 ± 533.4 µg/m^3 barbecue kitchen: 146.6 ± 59.8 µg/m^3 chinese kitchen: 679.1 ± 1922.5 µg/m^3 western kitchen: 272.2 ± 250.1 µg/m^3 fried chicken kitchen: 257.2 ± 44.5 µg/m^3 hotpot cooking area: 110.8 ± 59.8 µg/m^3	Not stated	Teppanyaki Kitchen Barbecue Kitchen Chinese Kitchen Western Kitchen Fried Chicken Kitchen Hotpot Cooking Area	Chinese kitchens (CK) have the highest deposition rates across all regions of the respiratory system including the upper airways, tracheobronchial, and alveolar regions. Furthermore, the alveolar region generally has the highest deposition rates compared to all other regions, indicating that PM2.5 penetrates deep into the lungs.

Table 2. Summary of included studies [the remaining 7 studies included in the review]

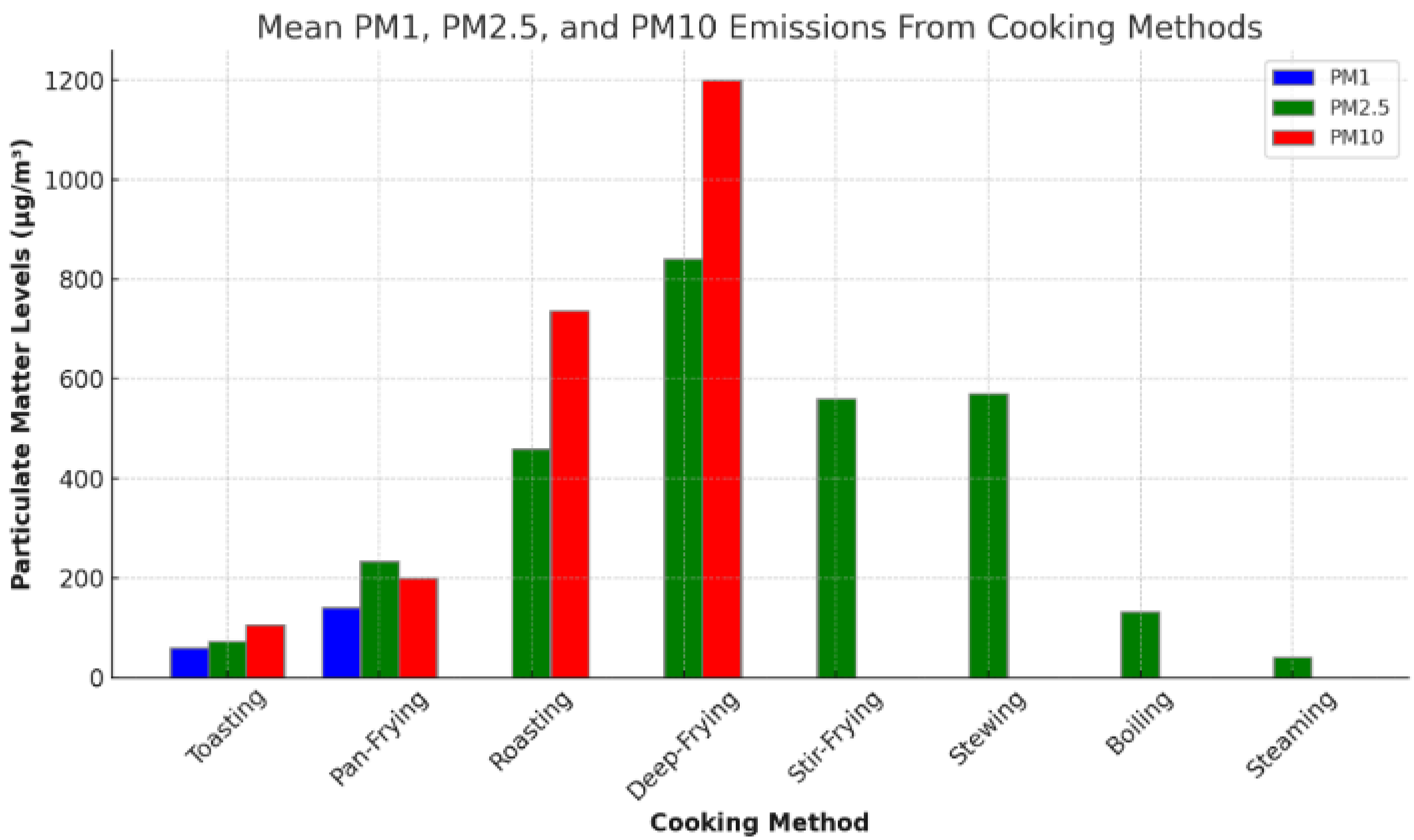

Figure 2. Mean PM1, PM2.5, and PM10 emissions from different cooking methods as retrieved from included studies

Comparison of PM2.5 and PM10 Emissions From Frying Versus Non-frying Cooking Methods

The null hypothesis for the t-test analysis of PM2.5 and PM10 emissions between frying cooking methods (deep-frying, stir-frying, pan-frying) and non-frying cooking methods (boiling, stewing, steaming, roasting, toasting) was as follows: "There is no statistically significant difference between mean emissions of cooking methods that involve frying and cooking methods that don't involve frying." For PM2.5 emissions between the two study groups, $p > 0.05$, indicating a lack of a statistically significant difference between the amount of PM2.5 emissions from frying and non-frying methods. Only four cooking methods were involved in the t-test for PM10 emissions. Two methods involved frying (deep-frying and pan-frying) and two methods didn't involve frying (roasting and toasting). The difference in mean PM10 emissions between the two study groups had a $p > 0.05$, indicating the absence of a statistically significant difference between the amount of PM10 emissions from frying and non-frying methods. A t-test analysis was not conducted for PM1 emissions between frying and non-frying methods due to a lack of data from eligible studies.

DISCUSSION

The U.S. Environmental Protection Agency (EPA) has two primary standards for fine particulate matter (PM2.5): an annual average of 9.0 micrograms per cubic meter and a 24-hour average of 35 micrograms per cubic meter (9). The EPA strengthened the primary annual PM2.5 standard from 12.0 to 9.0 micrograms per cubic meter on February 7, 2024. These standards state that, on average, the concentration of PM2.5 should not exceed 9.0 µg/m³ when measured across the span of a year. In addition, on any given day, the concentration of PM2.5 shouldn't exceed 35 µg/m³. However, the data from this meta-analysis shows that PM2.5 emissions from every selected cooking method significantly exceeded these standards (Figure 2). The EPA has a similar 24-hour standard for PM10: an area meets the standard if it does not exceed a concentration of 150 µg/m³ more than once per year on average over three years (10). Once again, the PM10 emissions from every selected study in this meta-analysis exceeded this standard significantly (Figure 2). This raises concern given that there are no current regulations of IAQ in households that use these cooking methods daily.

Unlike PM2.5 and PM10, PM1 is unregulated, and monitoring technology for PM1 is lacking (11). The specific harm that PM1 causes in contrast to other particulate pollutants and ultrafine particles is still under investigation (11). When calculating the increased risk of cardiovascular disease from three types of PM, Yin and colleagues found a 0.29% increase for every 10 µg/m³ increase in PM1, which was significantly greater than the increases in cardiovascular disease from PM2.5 and PM10 exposure (12). This study supports the idea that PM1 may be a higher risk factor for disease due to its small size, allowing it to penetrate deeper into vessels than other types of PM. This warrants more research to better understand the relationship between PM1 emissions and respiratory and cardiovascular health.

Some studies found that PM exposure from specific cooking methods was associated with detrimental health effects. For example, Soppa et al. measured forced expiratory volume (FEV), which is the amount of air a person can forcefully exhale after a deep breath, to determine the lung function of healthy adults before and after exposure to PM from toasting bread and pan-frying (8). They concluded that a 10 µg/m³ increase in PM10, PM2.5, and PM1 emitted from pan-frying sausages was associated with decreases in FEV. On the other hand, they didn't identify any associations between toasting bread and changes in lung function. Le et al. found that Benzene, Formaldehyde, Acrolein, and Acetaldehyde were among the compounds found within emissions from deep-frying and grilling (13). Furthermore, concentrations of Benzene, Acrolein, and Formaldehyde significantly exceeded the Reference Concentrations (RfCs) limits set by the U.S. EPA, and concentrations of Formaldehyde exceeded Minimal Risk Levels (MRLs) set by the Agency for Toxic Substances and Disease Registry (ATSDR). Benzene, Formaldehyde, and Acetaldehyde are all classified as Group 1 Carcinogens by the International Agency for Research on Cancer, while Acrolein is classified as a Group 2 Carcinogen (14). This supported the notion that deep-frying is perhaps the most polluting cooking method because not only does it release the greatest concentrations of PM, but it also contains significant amounts of carcinogenic compounds.

There is an urgent need for further research regarding PM emissions from air fryers and their effect on respiratory health. Air fryers are relatively new and quickly becoming one of the most popular cooking appliances. However, there is a significant lack of research on the pollution of air fryers compared to other cooking methods. An experiment by Wang et al. 2023 found that PM10 emissions from the air frying of chicken wings and breast were higher than pan cooking by a factor of 2.1 and 5.4, respectively (15). This is a serious health concern because statistical analysis among selected cooking methods for this review found that pan-frying was the most polluting method in terms of PM1 emissions, the fifth most polluting for PM2.5 emissions, and the third most polluting for PM10 emissions. The conclusions from Wang et al. show that there is a possibility that air frying is one of the most polluting cooking methods.

Given the high variations in PM concentrations reported from various studies, further research must be undertaken regarding the quality of assays and methods used to measure these emissions. For example, different studies used different equipment and methods to measure emission concentrations which could result in drastically different data. Another important gap is that the type of oil and frying fat tested was inconsistent between selected studies. So, study methods that involve the use of a specific oil or frying fat may have different emission data from studies that used other oils and frying fats. For instance, Sjaastad et al. found that pan-frying on an electric stove with margarine as the frying fat had a total particle emission of 1.8mg/m³ while cooking with soybean oil as the frying fat had a total particle emission of 1.6mg/m³ (16). In the same experiment, they reported a total particle emission of 5.5mg/m³ for pan-frying on a gas stove with margarine as the frying fat whereas cooking with soybean oil had an emission report of 7.2mg/m³.

CONCLUSION

Data compiled from several important studies found that PM emissions from common cooking methods often exceeded the standards set by the EPA. Furthermore, associations between cardiovascular disease, detriments to lung function, and the presence of significant amounts of carcinogenic compounds were identified from the emissions of several cooking methods. The impact of such emissions from common cooking methods is often overshadowed by the types of cooking fuel used. Future research must investigate the health impacts of specific cooking methods as opposed to solely the type of fuel. Furthermore, in future research, it's important to keep specific variables constant, such as the measuring methods and equipment as well as the types of oil and frying fat tested when measuring emissions.

ACKNOWLEDGEMENTS

There are no relevant disclosures by the author.

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