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Charcoal-based products combustion: Emission profiles, health exposure, and mitigation strategies

Alessio Mencarelli[a,*], Rosa Greco[a], Stefania Balzan[b], Stefano Grigolato[a], Raffaele Cavalli[a]

[a] Department of Land, Environment, Agriculture and Forestry, University of Padova, Viale dell'Università 16, Legnaro, PD 35020, Italy
[b] Department of Comparative Biomedicine and Food Science, University of Padova, Viale dell'Università 16, Legnaro, PD 35020, Italy

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ABSTRACT

Charcoal-based products are widely spread and appreciated as fuel for grilling food. However, during their use, they release high emissions that pose significant environmental issues and health risks. Charcoal grilling emissions contain a wide range of pollutants including CO, CO_2, NOx, PM, PAHs, VOCs, and trace metals. The emission of these pollutants contributes to both indoor and outdoor air pollution. Factors such as charcoal type and qualitative characteristics, combustion temperature, and the presence of food influence the emission released. Compared to domestic emissions, charcoal grilling restaurants can be a major source of air pollutants affecting both indoor and outdoor air quality. The deterioration of air quality determines health repercussions. This study aimed to review the existing scientific literature on the environmental and health implications of charcoal-based products used in domestic and restaurant settings. The association between charcoal grilling emissions, respiratory illnesses, cardiovascular diseases, and the increased risk of developing carcinogenic conditions was evaluated. Workers in restaurant settings, exposed to cooking fumes for several hours, are particularly vulnerable to these health risks, but even short exposure can lead to health problems. Mitigation strategies involve different approaches, including the use of high-quality charcoal, implementing a certification system to ensure high-quality tested products, using grilling equipment designed to reduce emissions, ensuring proper ventilation, using abatement systems, and promoting responsible and sustainable grilling practices. Implementing these strategies guarantees more eco-friendly and safer grilling conditions while effectively reducing the adverse impacts of charcoal combustion on the environment and human health.

1. Introduction

In the last years, charcoal grilling, whether in the form of domestic barbecues or at charcoal restaurants, has gained widespread popularity due to the unique smoky flavor and smell it imparts to food (Allais, 2021; HPBA, 2023; Vicente et al., 2018; Yu et al., 2020). Despite the availability of various alternative grilling fuels such as gas, electricity, wood, and pellets, charcoal-based products continue to dominate as the most widely used option for barbecue activities (Allais, 2021; Jelonek et al., 2020).

Charcoal derives from the pyrolysis process of various types of biomasses, primarily wood, conducted at relatively low temperatures and reduced oxygen concentration (Seboka, 2009). It offers several advantages compared to wood, including higher calorific value, faster ignition times, and ease of transport and storage (Johnson, 2009; Sharp and Turner, 2013). In addition to lump charcoal, charcoal briquettes have gained popularity as an alternative grilling fuel, particularly for barbecues (Seboka, 2009; Sotannde et al., 2010). Briquettes consist of charcoal dust compacted with binding agents like starch, resulting in a uniform and compressed fuel with a regular shape. Charcoal briquettes are appreciated for grilling food because of their high density, extended burning duration, steady ember temperature, effortless ignition, and more affordable cost in comparison to lump charcoal (Badyda et al., 2017; Jelonek et al., 2020; Ju et al., 2020; Seboka, 2009).

Despite the great popularity of charcoal grilling, it is essential to recognize and address the potential environmental issues associated with this cooking method. Charcoal grilling is known to release significant quantities of various pollutants, including particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VOCs), trace metals, and other minor pollutants (Jelonek et al., 2020; Jeoung et al., 2020; Ju et al., 2020; Kabir et al., 2010; Vicente et al., 2018). The concentrations

* Corresponding author.
E-mail address: alessio.mencarelli@unipd.it (A. Mencarelli).

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of air pollutants are determined by the simultaneous influences of various factors, including charcoal quality, combustion conditions, and the characteristics of the food being cooked.

The presence of food during charcoal combustion leads to an additional increase in pollutant concentrations (Alves et al., 2022; Elsharkawy and Ibrahim, 2022; Lee et al., 2020; Lin et al., 2021). When food is grilled, visible fumes are produced, which are associated with the dripping of oil and fat into the embers, the evaporation of water from cooked food, and the formation of organic pollutants (Abdullahi et al., 2013). Due to large-scale operations, charcoal restaurants may produce higher emissions compared to domestic barbecues. Factors such as larger grilling surfaces, increased food preparation volume, and longer grilling durations contribute to higher emissions (Arar et al., 2022; Elsharkawy and Ibrahim, 2022; Kim et al., 2020; Song et al., 2018). The emissions from domestic barbecues and charcoal grilling at restaurants contribute significantly to air pollution, posing a significant health risk to both individuals near the combustion sites and those in the vicinity of grilling areas.

Several works in the literature have demonstrated the association between emitted pollutants during charcoal grilling and various adverse health effects. These include short-term effects such as eye irritation, coughing, and headaches (Orozco-Levi et al., 2006; UNEP, 2019), as well as more serious long-term health problems such as respiratory illnesses, cardiovascular diseases, and the heightened risk of developing carcinogenic conditions (Lachowicz et al., 2022; Lenssen et al., 2022; Orozco-Levi et al., 2006; Ortiz-Quintero et al., 2023). The health risks associated with charcoal grilling are not limited to outdoor settings but are magnified in indoor grilling scenarios. The confined environment indoors can lead to higher concentrations of harmful pollutants, significantly increasing the health risks, particularly for restaurant employees who are exposed to cooking fumes for extended periods (Arı et al., 2020; Cheng Lee et al., 2001; EPA, 2023; Zhang et al., 2017). The existing evidence strongly emphasizes the pressing requirement for a comprehensive understanding of charcoal grilling emissions and the development of effective mitigation strategies to reduce the associated health risks.

To address these concerns, exploring and evaluating the factors influencing the emission levels and composition of pollutants during charcoal grilling in both domestic and restaurant settings is crucial. Examining the characteristics of the grilling process and the role of different fuel properties, grilling settings, and conditions, is essential for developing effective mitigation strategies. This review aims to comprehensively analyze charcoal grilling emissions and associated health risks in both domestic and restaurant scenarios. By analyzing existing literature, this paper aims to identify knowledge gaps, trends, and areas for future research on charcoal grilling emissions and health risks.

2. Charcoal combustion emissions and conditioning factors

Charcoal combustion represents an important source of different air pollutants. Research conducted by Vicente et al. (2018) examined the particulate and gaseous emissions from charcoal combustion in a brick barbecue, revealing emission factors (EFs) for different pollutants based on dry-burned charcoal. The EFs were measured at 2619 ± 110 g kg^{-1} for CO_2, 219 ± 44.8 g kg^{-1} for CO, 3.01 ± 0.70 g kg^{-1} for NOx, and 7.38 ± 0.35 g kg^{-1} for $PM_{2.5}$, In terms of VOCs emitted during the combustion of different charcoal samples, Kabir et al. (2010) detected notable concentrations of VOCs, with variations depending on the characteristics of the charcoal. The mean concentration of total VOCs (TVOC) was measured at 3367 ± 6573 ppb, with toluene (116 ppb), benzene (98.7 ppb), and ethyl benzene (22.7 ppb) being the most prominent compounds detected. Carbonyl compounds were also emitted, with formaldehyde having the highest concentration at 275 ± 477 ppb, followed by acetaldehyde at 126 ± 229 ppb. Moreover, charcoal combustion is known to emit particulate matter (PM), primarily consisting of fine particles with a diameter of less than 2.5 μm, as consistently indicated by various studies (Alves et al., 2022; Lee et al., 2011; Taner et al., 2013; Xu et al., 2023). Additionally, these fine particles can transport PAHs (Badyda et al., 2017; Badyda et al., 2019; Lao et al., 2018a) and trace metals (Sharp and Turner, 2013; Susaya et al., 2010). The previous findings highlight the substantial release of pollutants during charcoal grilling and the potential environmental and health risks associated with these emissions.

Several factors can contribute to varying levels of contaminant concentrations, including combustion conditions (Ju et al., 2020), charcoal quality (Deng et al., 2019; Jelonek et al., 2020), type of fuel used (Jelonek et al., 2020; Kuo et al. 2006), and the characteristics of the food being cooked (Alves et al., 2022; Xu et al. 2023). Understanding and effectively managing these factors is crucial to reduce the negative environmental and health impacts of charcoal emissions.

2.1. Combustion phases

The combustion process of solid biofuels can be divided into distinct phases, including: i) an initial drying phase, where the moisture present in the biofuel evaporates, ii) devolatilization (pyrolysis), during which the volatile components in the fuel are released, iii) combustion of the volatile matter, iv) char combustion, and finally v) the extinguishing phase (Demirbas, 2004; Kleinhans et al., 2018; Yang et al., 2021). The duration of these phases can vary depending on factors such as fuel characteristics, type and size, moisture content, temperature, and combustion conditions.

In comparison to other solid biofuels, charcoal combustion follows slightly different phases. Upon ignition, the fuel undergoes rapid dehydration due to its lower moisture content compared to other biofuels like wood. The charcoal combustion process is characterized by an initial intense flaming phase, with the presence of visible flames, where gaseous compounds are combusted, and a great heat quantity is generated. Following this, the smoldering phase occurs, during which combustion takes place directly on the surface of the fuel without visible flames. This phase produces less heat than the previous phase but has a longer duration (Alves et al., 2022; Huang et al., 2016; Kleinhans et al., 2018; Olsson and Petersson, 2003). During the smoldering phase, the food is typically placed over the glowing embers for cooking.

According to Deng et al. (2019), the combustion process of charcoal can be divided into two stages based on real-time changes in the fuel's carbon content. In Phase I, there is a loss of moisture and the devolatilization of volatiles, leading to a rapid increase in carbon content while phase II is characterized by a stable and high carbon content, indicating that the combustion is primarily driven by the fixed carbon present in the fuel. Furthermore, the Authors noted variations in CO emissions throughout the combustion process, with an initial peak observed in Phase I, followed by a gradual decrease. Each phase is associated with the emission of specific compounds at different concentrations.

Multiple studies in the literature have confirmed that the initial combustion phase of charcoal-based fuels is associated with higher concentrations of pollutants. In the study conducted by Alves et al. (2022), elevated emissions of various pollutants such as CH_4, ethylene (C_2H_4), carboxylic acids, TVOC, and PM_{10} were detected during the flaming phase following charcoal ignition. Similarly, Jelonek et al. (2020) observed that CO, CO_2, NOx, and $PM_{1\text{-}10}$ emissions from charcoal and briquette combustion were highest in the first 15-20 minutes, followed by a progressive decrease and stabilization. The work by Huang et al. (2016) investigated the variations in pollutant emissions (CO, CO_2, HC, NOx, C_2H_4O, HCHO, $PM_{2.5}$, and PM_{10}) during the flaming and smoldering phases. Although some variations have been observed according to the type (charcoal or briquettes) and qualitative characteristics of the fuel, it was generally found that the flaming phase resulted in higher emissions for all considered pollutants compared to the smoldering phase. Jeoung et al. (2020) assessed the emission changes over time during the combustion of three commonly used charcoal briquettes. Consistent with previous studies, the initial combustion phase led to a higher production of CO and NOx, attributed to incomplete fuel combustion. In contrast to the previously mentioned works, Ju et al. (2020) observed that real-time emissions of CO, CO_2, and NOx did not decrease as combustion progressed, but rather exhibited a slight increase in concentrations. However, even in this case, a significant rise was observed during the initial combustion phase. In a specific investigation of the glowing phase, Olsson and Petersson (2003) conducted a comparison of emissions from glowing charcoal and charcoal briquettes with firewood and pellet embers. The study revealed that during this phase, up to 0.1 % of the carbon emitted from glowing charcoal can be released as benzene, posing significant inhalation risks.

Based on previous studies, the smoldering phase of charcoal combustion results in lower pollutant emissions compared to the initial flaming phase. The flaming phase, characterized by high temperatures and the release of water and volatiles, leads to irregular combustion and higher pollutant emissions (Huang et al., 2016). Conversely, during the smoldering phase, most of the volatiles have already been released, resulting in more regular and lower concentrations of pollutant compounds. To minimize exposure to emitted pollutants, it is necessary to avoid proximity to the barbecue after charcoal ignition and ensure adequate ventilation. However, it should be noted that even during the smoldering phase, elevated pollutant concentrations can be present, especially when grilling food is involved.

2.2. Charcoal quality and characteristics

The properties of charcoal exhibit significant variability, influenced by the combination of a multitude of factors that determine the characteristics of the final product. Key factors include the wood species used, as well as the parts of the plants used (e.g., branches or stems), the temperatures and conditions employed during the pyrolytic process, and the type of kiln used (Dias Junior et al., 2020; Mencarelli et al., 2022).

Despite the widespread popularity of barbecue charcoal, there are inadequate international standards for assessing the quality of this material. In Europe, the quality of charcoal is evaluated according to the EN 1860-2:2023 standard (EN, 2023). The standard defines the criteria for analyzing the qualitative characteristics of barbecue fuels and establishes corresponding limits. Specific limits for each fuel type are provided in Table 1. The purpose of the standard is to minimize the potential hazards associated with the use of solid fuels for barbecuing. The standard covers different types of fuels, including charcoal, charcoal briquettes, and impregnated charcoal/briquettes. The latter refers to products that have been treated with a lighting agent to enhance their grilling performance.

Despite the presence of standards, consumers have limited access to information about charcoal characteristics and properties, leaving them uncertain about the quality and characteristics of the material they are purchasing (Mencarelli et al., 2022). According to Jelonek (2020), many charcoal and briquette manufacturers conduct these tests only once to obtain a single long-term certificate. This is due to the belief that charcoal production follows a standardized process, and the wood used exhibits minimal variability in its parameters. Moreover, conducting frequent tests represents an additional cost for companies, contributing to this practice. However, it is important to note that variations in the quality of charcoal can impact the emissions generated during grilling activities (Deng et al., 2019; Jelonek, 2020; Jelonek et al., 2020).

For cooking applications, the fixed carbon, representing the solid carbon of charcoal remaining after the carbonization process (Basu, 2018), should have values greater than 75% (Elyounssi et al., 2010; FAO, 1985). High values guarantee more regular and flameless combustion (Dias Júnior et al., 2020, 2017). Fixed carbon content exhibits a positive correlation with CO_2 emissions and a negative correlation with CO, $PM_{2.5}$, PM_{10}, and carbonyl compound emissions (Huang et al., 2016; Yu et al., 2020).

Ash represents the solid remnants of charcoal combustion it primarily consists of mineral compounds (Neina et al., 2020), and holds relevant importance for grilling applications. Although the standard sets the limit to 8% for lump charcoal and 18% for charcoal briquettes (Table 1), Authors in the literature have argued that, for barbecue purposes, charcoal should ideally have an ash content ranging from 0.5% to 5% (Antal and Grønli, 2003; Dias Júnior et al., 2020; FAO, 1985). Higher values of ash content not only decrease the heating value but also lead to fouling in grilling devices, as well as soot and slag issues (Dias Júnior et al., 2021, 2020).

The inorganic fraction in charcoal is affected by the raw materials used and the production process involved. In some cases, producers can deliberately include inorganic matter (e.g., sand) to support the burning temperature which increases the weight of the fuel and results in elevated ash content which might cause slag problems (Drobniak et al., 2021). In addition, charcoal-based products can include trace metals in their composition. In a study conducted by Kabir et al. (2011), the concentrations of 10 trace elements were determined in 11 charcoal-based products. The detected values showed variability

Table 1
Qualitative characteristics required by EN 1860-2:2023 and relative limits for the various charcoal-based products.

Parameters	Unit of measure	Charcoal	Charcoal briquettes	Impregnated charcoal and briquettes
Fixed carbon	% dry basis	> 75%	> 60%	No limits
Ash	% dry mass	< 8%	< 18%	No limits
Total moisture	% wet basis	< 8%	< 8%	No limits
Granulation		Particle size shall be between 0 mm to 150 mm: - Particles greater than 80 mm: < 10% - Particles greater than 20 mm: > 80% - 0 mm – 10 mm: < 7%	Granules less than 20 mm: < 10%	No limits
Volatile matter	% dry basis	No limits		
Bulk density	kg m^{-3}	> 130 kg m^{-3}	No limits	No limits
Binder	/	No limits	The binder must not pose any health risks when its combustion gases come into contact with food and must be of food-grade quality	No limits
Inadmissible additions (e.g. glass, slag, rust, splinters of metal and stone powder)	% by volume	Not exceed 1% by volume		
Chemical burning sustainers	/	Not allowed		
Impregnating content		No limits		

depending on the specific sample analyzed and the element being examined. The metals were found to be present in descending concentrations according to the following order: Fe>Zn>Co>Cr>Cu>Pb>Ni>Hg>As>Cd. The metal concentration is affected by the type of product (charcoal or briquettes), the production process, and the raw materials used (Kabir et al., 2011; Pandey et al., 2009; Sharp and Turner, 2013). In some cases, charcoal may be produced improperly using treated wood such as old furniture containing adhesives and paints increasing the concentration of certain hazardous metals such as Hg, Pb, and Zn (Kabir et al., 2011; Pandey et al., 2009; Sharp and Turner, 2013; Susaya et al., 2010). During charcoal combustion, inorganic components undergo chemical and physical transformations resulting in their release that can be inhaled or ingested with grilled food (Kleinhans et al., 2018; Sharp and Turner, 2013; Susaya et al., 2010). The release of metallic emissions is dependent on their volatility rather than their abundance in the material. In terms of the most emitted elements, the concentrations follow the following order: Zn>Pb>Cu>Cr>Co>Cd>Ni>Hg>As (Kabir et al., 2011; Pandey et al., 2009; Susaya et al., 2010).

The moisture content is one of the most important parameters during the grilling of foods (Dias Júnior et al., 2020). High values determine the difficulty of ignition and irregular combustion, also reducing the burning rate (Bhattacharya et al., 2002; Dias Júnior et al., 2021, 2017). Additionally, moisture content has a significant impact on the emissions generated during combustion (Deng et al., 2019). Studies by Jeoung et al. (2020) and Yu et al. (2020) have observed a positive correlation between higher moisture content and increased emissions of CO and hydrocarbons (HCs).

Although the standard does not specify any limits for the volatile content, different studies have indicated that high-quality cooking charcoal should ideally not have values higher than 30% (Charvet et al., 2021; Dias Júnior et al., 2021; FAO, 1985). During the pyrolysis process, which converts biomass into charcoal, a significant portion of volatile compounds should already be eliminated (Demirbas, 2004; Lachowicz et al., 2022). However, if pyrolysis is conducted at low temperatures and for short durations, it can result in higher volatile content in the charcoal (Huang et al., 2016; Yu et al., 2020). High volatile values cause irregular and smoky combustion (Dias Júnior et al., 2021) promoting the release of CO, HCs, $PM_{2.5}$, and benzene (Jeoung et al., 2020; Yu et al., 2020).

Charcoal-based products can contain a wide range of contaminants, originating from several sources. These contaminants may arise depending on the raw material used, as well as factors related to harvesting, fuel production, and transportation processes. Accidental introductions of metals, rust, and oils may also occur during the manufacturing process, often linked to the machinery used. Moreover, producers might intentionally incorporate components such as flammable substances to improve the ignition and energy performance characteristics of the fuel. Consequently, the presence of these contaminants can be linked to the emission of various polluting agents during charcoal-based combustion (Drobniak et al., 2021, 2022; Jelonek et al., 2021).

In the literature, only Jelonek (2020) and Jelonek et al. (2020) have evaluated the presence of inadmissible compounds in lump charcoal and charcoal briquettes. Using petrographic analysis with a reflected light microscope the Authors identified the presence of several contaminants such as tar, mineral matter, metals, rust, glass, plastic, and biomass (non-pyrolyzed wood). The latter refers to raw wood, which can also be added by manufacturers for food flavor purposes (Drobniak et al., 2021). In charcoal-based products, charcoal represents the primary component, while the inclusion of raw biomass becomes a contamination source, leading to increased emissions of CO, CO_2, and PM (Jelonek et al., 2020). Charcoal briquettes exhibited a higher presence of contaminants than lump charcoal. Notably, the EN 1860-2:2023 standard does not classify biomass among the inadmissible pollutants. Furthermore, wood may be intentionally included by manufacturers to enhance the released aroma during combustion (Jelonek et al., 2020). Although total impurity content has a significant positive effect only on PM_{1-10}, a weak relationship has also been observed with CO_2, CO, and NOx emissions. Increasing biomass content was associated with higher concentrations of CO, CO_2, and PM_{1-10}.

2.3. Type of fuel used for grilling

Several types of barbecues are now available on the market. They can utilize various types of fuels from charcoal lumps and briquettes to Liquefied Petroleum Gas (LPG), electricity, wood, or various biomass pellets. The type of fuel used not only affects the organoleptic characteristics of the food but also impacts the concentration and composition of polluting emissions released into the atmosphere.

2.3.1. Comparison of charcoal-based products

Despite being charcoal-based products, lump charcoal, charcoal briquettes, and impregnated charcoal with flammable substances exhibit variations in pollutant emissions due to their different compositions and characteristics. Table 2 presents a comparison of EFs for nine pollutants resulting from the combustion of charcoal-based products.

In their study, Kuo et al. (2006) compared the emissions resulting from the combustion of lump charcoal (Taiwanese and Indonesian charcoal) and fast-lighting charcoal (impregnated charcoal). Based on the findings, the use of fast-lighting charcoal resulted in higher PAH emissions compared to lump charcoal. Specifically, fast-lighting charcoal emitted up to 14 times more Benzo(a)pyrene and 40 times lead (Pb) than lump charcoal. The use of impregnating agents, such as alcohol, paraffin, or firelighters, enhances the energy performance of the product and facilitates its ease and speed of use. However, since impregnating agents consist of highly volatile components, impregnated charcoals release high concentrations of VOCs, PAHs, carbonyl compounds, and NOx (Campbell and Stockton, 1990; Huang et al., 2016; Jelonek et al., 2020; Kuo et al., 2006).

Among the non-impregnated products, charcoal briquettes tend to have higher emissions compared to lump charcoal. Jelonek et al. (2020) analyzed combustion emissions from both charcoal briquettes and lump charcoal. Charcoal briquettes release higher CO, CO_2, and PM_{1-10} than lump charcoal. These findings partially contradict a previous study by the same Author (Jelonek, 2020), highlighting higher CO_2 and CO emissions from lump charcoal combustion. However, consistent with previous findings, higher PM emissions were observed when charcoal briquettes were burned. A comparison of lump charcoal and charcoal briquette emissions was also conducted by Huang et al. (2016). In contrast to previous studies, no significant difference was found between emissions from briquettes and lump charcoal. However, the highest emission values for HC, CH_2O, C_2H_4O, $PM_{2.5}$, and PM_{10} were detected in a sample of charcoal briquettes. Similarly, Ju et al. (2020) did not observe a significant difference in CO_2 and NOx emissions between charcoal and charcoal briquettes but charcoal briquettes emitted more CO than lump charcoal. Factors contributing to the higher emissions of briquettes compared to lump charcoal include differences in composition and contaminant concentrations between the two products (Jelonek, 2020; Jelonek et al., 2020; Sharp and Turner, 2013). In the research conducted by Jelonek et al. (2020) that analyzed 74 charcoal-based grilling fuels sourced from various countries, the findings revealed that lump charcoal primarily consists of charcoal, with a mean value of 98.7%. On the other hand, charcoal briquettes exhibit a broader range of contaminants (e.g., mineral matter), which means that charcoal accounts for approximately 90% of the total volume. Within this product, the contamination values exhibited a range spanning from 0.6 to 26.6% of its volume.

2.3.2. Comparing emissions from charcoal-based products with electricity and LPG

Barbecues using charcoal-based products generate higher levels of pollutants compared to gas or electric barbecues, resulting in increased

Table 2
Comparison of EFs of gaseous pollutants from the combustion of various charcoal-based products from literature values.

BBQ device	Fuel type	Sample ID	CO_2 (g kg^{-1})	CO (g kg^{-1})	NOx (mg kg^{-1})	HC (mg kg^{-1})	HCHO (mg kg^{-1})	C_2H_4O (mg kg^{-1})	$PM_{2.5}$ (mg kg^{-1})	PM_{10} (mg kg^{-1})	Σ PAHs (mg kg^{-1})	Reference
Portuguese brick barbecue	Charcoal	Charcoal (Portuguese)	2619 ± 110	219 ± 44.8	3006 ± 698	/	383 ± 90.3	/	/	/	/	(Vicente et al., 2018)
Tube furnace	Charcoal	Eco-friendly charcoal (C1S)	776.0 ± 45.8	128.2 ± 22.1	834.1 ± 491.0	3048.0 ± 768.4	8.0 ± 6.1	45.0 ± 12.7	235.3 ± 27.5	286.8 ± 43.7	/	(Huang et al., 2016)
		Mangrove charcoal (I2)	855.1 ± 92.1	108.5 ± 19.3	277.0 ± 44.2	9313.5 ± 2997.9	26.7 ± 11.4	135.9 ± 52.1	955.7 ± 112.6	1189.8 ± 138.3	/	
		Eco-friendly charcoal (T1S)	644.4 ± 53.1	179.5 ± 25.1	158.5 ± 22.9	3989.9 ± 1176.7	38.6 ± 14.8	93.5 ± 41.5	707.2 ± 46.7	854.5 ± 71.9	/	
		Acacia charcoal (T2)	1113.6 ± 83.9	84.3 ± 1.0	823.9 ± 357.3	8062.8 ± 753.6	19.8 ± 2.9	36.9 ± 5.2	325.1 ± 67.7	440.7 ± 96.4	/	
		Longan charcoal (T3)	1096.6 ± 42.4	107.6 ± 9.8	621.1 ± 209.4	4013.4 ± 75.7	15.1 ± 3.5	10.6 ± 3.1	67.1 ± 15.0	87.4 ± 15.0	/	
		Binchōtan (B1)	1225.2 ± 39.0	76.6 ± 14.4	831.9 ± 295.9	3923.9 ± 1191.0	16.2 ± 4.6	4.3 ± 0.8	12.0 ± 2.4	21.6 ± 1.2	/	
	Charcoal briquettes	Charcoal briquettes (C2S)	835.8 ± 21.4	168.8 ± 20.5	674.6 ± 93.6	11209.3 ± 1275.8	519.9 ± 200.8	769.5 ± 31.6	9905.4 ± 1221.6	12041.3 ± 1377.8	/	
		Charcoal briquettes (C3S)	986.8 ± 60.0	300.3 ± 31.3	161.1 ± 98.6	5276.8 ± 394.4	9.8 ± 2.5	43.0 ± 5.1	368.9 ± 47.3	471.8 ± 78.4	/	
		Charcoal briquettes (I1S)	878.7 ± 96.3	214.7 ± 16.6	462.1 ± 68.4	1965.3 ± 216.1	6.1 ± 0.4	1.3 ± 0.3	153.9 ± 11.4	201.2 ± 19.8	/	
		Charcoal briquettes (I3S)	723.7 ± 43.2	67.7 ± 56.4	413.6 ± 149.3	4057.5 ± 560.0	57.8 ± 10.4	102.6 ± 4.8	282.6 ± 91.6	329.9 ± 101.8	/	
Commercial barbecue	Charcoal	Taiwanese charcoal	/	/	/	/	/	/	/	/	6.45 ± 0.37	(Kuo et al., 2006)
		Indonesian charcoal	/	/	/	/	/	/	/	/	9.29 ± 0.47	
	Impregnated charcoal	Fast-lighting charcoal	/	/	/	/	/	/	/	/	29.77 ± 1.61	
Tube furnace	Charcoal	Longan charcoal (LC)*	1851 ± 41	303.3 ± 34.8	243.2 ± 42.8	10300 ± 1184	/	/	/	/	/	(Yu et al., 2020)
		Longan charcoal (LC) **	1747 ± 40	222.9 ± 34.4	223.8 ± 75.0	5273 ± 2929	/	/	/	/	/	
		Binchōtan (BC)**	1875 ± 147	135.2 ± 22.0	189.0 ± 31.6	1085 ± 64	/	/	/	/	/	
	Charcoal briquettes	Charcoal briquettes (CB) *	2656 ± 151	319.6 ± 27.2	330.4 ± 28.4	1590 ± 351	/	/	/	/	/	
		Charcoal briquettes (CB) *	1813 ± 327	244.3 ± 40.2	380.9 ± 53.1	1237 ± 95	/	/	/	/	/	

* Burning temperature = 425 °C.
** Burning temperature = 500 °C.

pollutant concentrations. In a study conducted by Badyda et al. (2017), emissions from three types of barbecues fueled by lump charcoal, briquettes, and LPG were compared. $PM_{2.5}$ and $PM_{2.5–100}$ emissions were collected during grilling, and subsequently, 16 PAH congeners were extracted from the collected PM samples. The results revealed that briquettes and lump charcoal emitted significantly higher levels of PM compared to gas barbecue. Additionally, briquettes exhibited the highest concentrations of PM-bound PAHs, including chrysene, benz[a]anthracene, and benzo[b]fluorathene. The Authors noted that LPG resulted in fewer emissions due to its more complete combustion. In a subsequent study by the same Authors in 2019, the concentrations of PAHs emitted by the same devices were compared, including an electric barbecue (Badyda et al., 2019). The findings demonstrated that both electric and gas grills emitted lower concentrations of PM-bound PAHs compared to charcoal-based barbecues, particularly briquettes. In 2020, Badyda et al. (2020) compared the concentrations of various pollutants, including CO, CO_2, CH_4, NH_3, N_2O, NO, NO_2, SO_2, and $PM_{2.5}$, released by charcoal briquette barbecues and LPG barbecues. Except for N_2O and NO_2, the emissions from charcoal briquettes were found to be higher than those from LPG barbecues.

Aside from their elevated emissions during combustion, charcoal-based products used for grilling also have a considerably larger carbon footprint when compared to other fuel types. Johnson (2009) conducted a comprehensive analysis of the carbon emissions associated with charcoal and gas (LPG) barbecues. The study revealed that charcoal grilling resulted in an almost threefold higher carbon footprint (998 kg CO_2e) than LPG grilling (349 kg CO_2e). This substantial disparity can be attributed to several factors, including the environmentally intensive production process of charcoal and the combustion-related aspects such as lower efficiency (e.g., prolonged heating and cooling phases), the absence of power settings, and the need for firelighters to initiate the combustion. A subsequent study by Johnson and Gafford (2022) further examined the carbon footprint of various barbecue types used in the United States, including gas, wood pellet, charcoal briquette, and electric barbecues. Although charcoal briquettes are derived from wood, which is generally considered carbon-neutral, numerous studies in the literature have emphasized that the combustion of wood fuels leads to an increase in greenhouse gas emissions, primarily CO_2 (Flammini et al., 2022; Leturcq, 2014; Sterman et al., 2022). The findings of the work of Johnson and Gafford (2022) indicated that charcoal briquettes exhibited a higher carbon footprint compared to other barbecue fuels. In line with the previous study, the Authors claimed that the heightened carbon footprint of charcoal briquettes can be ascribed to multiple factors, including emissions from the production process, the presence of contaminants (e.g., fossil coal) in the product, and combustion inefficiency.

2.4. Combustion temperature

The emissions resulting from the combustion of charcoal-based products are also influenced by the combustion temperature inside the barbecue device, which can have both positive and negative effects depending on the type of pollutant (Torkmahalleh et al., 2017). Yu et al. (2020) compared emissions from burning charcoal at 425 °C and 500 °C. The increase in temperature resulted in a significant reduction in emissions of HC, formaldehyde, and CO. However, higher temperatures may also promote the release of metals contained in charcoal (e.g. Fe and Zn) (Kabir et al., 2011; Yu et al., 2020). Huang et al. (2016) assessed the variation in emission by altering the combustion temperature from 450 to 550 °C. Although the emission rate between different temperatures did not show statistically significant differences ($p > 0.05$), increasing the temperature slightly reduces the emissions of C_2H_4O, NOx, and HC. Conversely, as the temperature increased, CO, PM2.5, PM10, and HCHO emissions rose. According to Badyda et al. (2017), increasing the temperature also favors the release of higher PM-bound PAHs deriving from charcoal combustion.

Therefore, the higher emissions observed in the previous paragraph from charcoal briquettes could be also due to the higher temperatures achieved during their combustion (Badyda et al., 2017). The elevated temperatures promote a greater release of certain pollutants. In contrast, gas and electric barbecues, which reach lower and more stable temperatures, are associated with lower emissions (Badyda et al., 2017).

2.5. Type and characteristics of the grilled food

The grilling process involves several chemical reactions leading to the transformation of food components, such as thermal oxidation and decomposition of food and oil, the Maillard reaction primarily involves proteins, amino acids, and carbohydrates, as well as secondary reactions between intermediate and final products (Abdullahi et al., 2013; Lachowicz et al., 2022; Wang et al., 2018). These chemical changes in food play a crucial role in thermal decomposition and the generation of new volatile compounds that are released into the surrounding air (Kim and Lee, 2012; Wang et al., 2018). The type of cooking, the fat content of the food, the thickness of the food, and the addition or not of marinades can affect the concentration and composition of emissions (Abdullahi et al., 2013; Alves et al., 2022; Lee, 1999; McDonald et al., 2003; Torkmahalleh et al., 2017; Wu et al., 2015; Yu et al., 2020).

Compared with the emissions deriving only from charcoal combustion, in a work published by the U.S. Environmental Protection Agency (Lee, 1999), it was observed that the addition of meat (chicken and beef) determines an increase in PM, THC, VOCs, and SVOCs. Badyda et al. (2017) examined the impact of adding pork meat to three barbecues fueled by gas, charcoal, and charcoal briquettes, respectively. Across all types of fuel considered, the addition of pork meat resulted in higher concentrations of $PM_{2.5}$ and PAHs compared to values observed during charcoal combustion without food. Specifically, PM concentration dramatically rose by 2 to 18 times for briquettes and charcoal, respectively, whereas a smaller increase was observed for gas barbecues due to the presence of an indirect heat source and lower temperatures. In the study conducted by Badyda et al. (2020), the emissions deriving from a charcoal briquette barbecue and a gas barbecue grilling meat or vegetables were compared. For both types of fuels, cooking meat resulted in a greater release of $PM_{2.5}$, SO_2, CH_4, and CO while cooking vegetables was associated with higher concentrations of NO_2 and CO_2. The type of foods cooked and their fat content determined different emission profiles.

Based on the literature, several Authors highlighted how food fat content is the main element that determines the variation of concentrations and composition of pollutants. McDonald et al. (2003) grilled hamburgers with different fat contents and evaluated changes in PM emissions. The highest values observed corresponded to the grilling of hamburgers richer in fat with $PM_{2.5}$ emission rates ranging from 4.4 to 15.0 g of cooked meat. Xu et al. (2023) evaluated the emissions from grilling chicken wings, beef steak, and streaky pork in a charcoal barbecue. Having a higher fat content, pork determines the highest emissions of different PM fractions ($PM_{1.0}$, $PM_{2.5}$, $PM_{4.0,}$ and PM_{10}), PAHs, benzo[a]pyrene (BaP), VOCs, and carbonyl compounds. Similar results were found by Alves et al. (2022). The highest concentrations of pollutants were measured during fish grilling (salmon and sardines) since they had the highest fat content among the grilled foods considered. According to the work of Kuo et al. (2006), higher fat content leads to higher PAH emissions. Comparing emissions resulting from grilling pork, vegetables, and seafood (non-fish), pork meat having higher fat content is related to higher emissions in terms of total PAHs and BaP.

The emission increase associated with the grilling of fat-rich foods is attributed to the drippings of meat juices into charcoal embers. Although the composition of meat juices may vary depending on the grilled food type (e.g., meat or fish), they are mainly composed of water and fat. When subjected to high temperatures, the fat and oil present in the drippings undergo incomplete combustion or pyrolysis (Abdullahi et al., 2013; Duedahl-Olesen and Ionas, 2020; Lee et al., 2016), leading to the formation of flames and higher smoke emissions rich in PM and PM-bound PAHs, including carcinogenic compounds such as BaP, that have the potential to contaminate the grilled food or be inhaled by barbecue users (Alves et al., 2022; Chung et al., 2011; Kuo et al., 2006; Lao et al., 2018a; Lee, 1999; Lenssen et al., 2022; Rose et al., 2015; Saito et al., 2014; Viegas et al., 2012; Xu et al., 2023).

In addition to the fat dripping resulting from food, the addition of marinades, particularly those rich in oils, can affect the level of emissions by contributing to an increase in VOCs and PM emissions (Lee, 1999). A study by Yu et al. (2020) examined the impact of lard oil drippings, BBQ sauce drippings, and a combination of both on emission levels when falling into charcoal embers. In comparison with emissions deriving from the charcoal combustion, all three combinations exhibited an increase in emission factors for HC, $PM_{2.5}$, aromatic hydrocarbons (benzene and toluene), and aldehydes (formaldehyde and acetaldehyde).

In summary, when grilling food using charcoal, it is crucial to avoid the use of food with high-fat content and marinades rich in oil. Several studies in the literature have demonstrated that preventing fat dripping leads to reduced concentrations of PAHs in grilled food (Duedahl-Olesen and Ionas, 2020; Lee et al., 2016; Oz and Yuzer, 2016; Saint-Aubert et al., 1992), to minimize emissions, it is advisable to prevent fat from dripping into the charcoal embers.

3. Emissions from charcoal grill restaurants

The emissions deriving from the use of charcoal for grilling food do not involve only amateur grillers but extend to restaurants, fast food establishments, and steak houses, presenting a broader issue. Especially in urban areas, the release of fumes deriving from cooking food on charcoal can contribute to the deterioration of outdoor air quality (Yu et al., 2020).

Multiple factors can simultaneously affect the concentrations of emissions released into the atmosphere. Key factors include the cooking method and technique, choice of fuel (such as charcoal, gas, or electricity), cooking temperatures reached, the amount of oil used, the fat content of the cooked food, ingredients used (such as marinades), the size and quantity of food being cooked, ventilation conditions and cleaning conditions of the device used (Alves et al., 2022, 2015; Arar et al., 2022; Elsharkawy and Ibrahim, 2022; Li et al., 2015; Song et al., 2018; Whynot et al., 1999).

3.1. Outdoor emissions of charcoal grill restaurants

In terms of outdoor emissions, charcoal restaurants play a significant role, particularly concerning the release of PM and organic pollutants.

Kim et al. (2020) conducted a study measuring PM emissions resulting from five urban charbroiling restaurants in Seoul. $PM_{2.5}$ and PM_{10} mean concentrations were detected in the range of 4300-41100 μg m^{-3} and 4500-41400 μg m^{-3}, respectively. The Authors attributed the wide range of values among different restaurants to variations in charcoal consumption, types of grilled meat, and characteristics of the food, including fat content and marinades used. The average $PM_{2.5}$ to PM_{10} ratio of 0.98 indicated that the majority of particulate matter emitted from charcoal restaurants was smaller than 2.5 μm. Similarly, Lee et al. (2011) investigated the same pollutants in four restaurants that used charcoal for grilling different meats. Average $PM_{2.5}$ values were found between 5168-22409 μg m^{-3} while for PM_{10} between 7084-22412 μg m^{-3}. Consistent with the previous study, most of the particulate matter emitted by restaurants using charcoal is mainly composed of $PM_{2.5}$. The Authors also estimated that emissions from charcoal restaurants could contribute up to 2.4% of the atmospheric concentration of PM_{10} in Seoul. In a study conducted by Song et al. (2018), fine particulate emissions from seven outdoor barbecue restaurants in urban Jinan in eastern China were examined. The measurements conducted revealed that barbecues are a significant contributor to $PM_{2.5}$ emissions, resulting in increased concentrations in urban air. The mean levels of $PM_{2.5}$ detected ranged from 71 to 1083 μg m^{-3}.

To investigate the release of organic pollutants, Arar et al. (2022) measured the concentration of PAHs in the outdoor air of meat charcoal-grill restaurants. The mean total PAH concentration detected ranged from 0.72 to 16.8 μg m^{-3}. As for the other pollutants, the variability found between different restaurants was explained by the variability in terms of the type and quantity of charcoal used, food cooked, fat released from the meat, and marinades used during cooking and the sampling season. Kim and Lee (2012) measured the level of VOCs (BTEX and n-alkanes) in outdoor air in 10 urban areas containing at least 3 charcoal grill restaurants within a 30 m radius and 10 areas with no charcoal restaurants within the same distance. At non-charcoal-grill sites, the mean concentrations of benzene and total BTEX were 1.82 and 5.79 μg m^{-3}, respectively. At charcoal grill sites, these concentrations were higher, measuring 2.93 and 10.5 μg m^{-3}, respectively. This determines a possible greater occurrence of diseases in people who usually live and frequent these areas.

3.1.1. Comparison of charcoal grill restaurant outdoor emissions to other cuisine types

Numerous studies in the literature have investigated the emissions of different pollutants resulting from the utilization of charcoal compared to alternative cooking methods employing different fuels, primarily gas, and electricity (Cheng et al., 2016; Lin et al., 2021). The type of cuisine and the fuel used play a crucial role in determining the emissions released into the atmosphere during cooking (Cheng et al., 2016; Lin et al., 2021). Elsharkawy and Ibrahim (2022) conducted a study involving twenty restaurants, including grilling, frying, cooking, and bakery establishments. The aim was to compare the emissions of pollutants, namely CO, CO_2, VOCs, NO_2, and SO_2, both in the restaurant chimneys and in the outdoor air surrounding the restaurants. Grill restaurants exhibited higher levels of air pollutants compared to other types of restaurants in both the chimney emissions and the surrounding outdoor air. High VOC emissions resulting from grilling restaurants were also detected by Cheng et al. (2016). The Authors compared emissions resulting from four different Chinese cooking styles, namely home cooking, Shandong cuisine, Hunan cuisine, and barbecue. Barbecue fumes exhibited higher concentrations of total VOCs (TVOCs) with a mean value of 3494 ± 1042 μg m^{-3}, which was more than 13.6 times greater than the lowest concentration observed in Shandong cuisine. These findings are consistent with those of Alves et al. (2015). In their study, the Authors compared VOCs and carbonyl compound emissions from a charcoal-grilled chicken restaurant and a university canteen using electric or gas cooking devices, as well as a restaurant specializing in wood-oven roasted piglets. Charcoal and wood-burning restaurants exhibited the highest concentrations of VOCs and carbonyl compounds. According to the study conducted by Lin et al. (2021), the increased emissions of barbecue fumes were attributed to the combined effects of cooking emissions and charcoal combustion. This combination led to higher temperatures, resulting in elevated emission rates in the exhaust fumes. Their research further included a comparison of 18 restaurants in Beijing, China, considering both barbecue and non-barbecue establishments. The findings revealed higher emissions of non-methane hydrocarbons and oxygenated volatile organic compounds (OVOCs) from barbecue restaurants. Moreover, barbecue restaurants were associated with higher $PM_{2.5}$ emissions.

Charcoal-grilling restaurants emit the highest PM levels, especially fine PM, which can carry significant quantities of PAHs (Wang et al., 2015, 2020). Wang et al. (2015) conducted a study assessing $PM_{2.5}$ emissions in five restaurants employing four prevalent cooking styles in China, namely Shandong cuisine (2), Hunan cuisine (1), home cooking (1), and barbecue (1). Charcoal-fired barbecue cooking produced $PM_{2.5}$ concentrations 3.7 to 5.6 times higher than other cooking methods. This observation is consistent with the work of Li et al. (2015), who examined emissions from cafeteria boiling, cafeteria frying, meat roasting, fish roasting, and snack-street boiling. Once again, it was observed that the use of charcoal for grilling meat resulted in the highest concentrations of pollutants, exceeding background levels by more than 9.6 times. Furthermore, the emitted PM can contain notable concentrations of organic pollutants, specifically PAHs. Although charcoal cooking fumes contain mostly low-medium weight PAHs (LMW) (Hou et al., 2008; Xu et al., 2023), they can also contain high concentrations of carcinogenic compounds such as benzo[a]pyrene (Wang et al., 2015, 2020).

Overall, all the examined types of cuisine contribute to the emission of various pollutants into the atmosphere. Nevertheless, previously mentioned studies indicate that restaurants employing charcoal as a fuel for cooking are linked to higher levels of pollutants. While several factors influence the composition and quantity of emitted pollutants, the type of fuel used plays a crucial role.

3.1.2. Efficiency of abatement system for reducing emissions in charcoal grilling restaurants

Despite the high emissions released during the use of charcoal to grill food, many restaurants are not equipped with efficient pollutant abatement systems, contributing to the deterioration of the air quality surrounding the restaurant (Alves et al., 2015; Cheng et al., 2016; Gysel et al., 2018b; Kim and Lee, 2012; Li et al., 2015). Depending on the specific pollutants that need to be addressed, various solutions can be employed. Advanced and larger-scale systems can simultaneously reduce multiple pollutant emissions (Singh and Shukla, 2014). However, these systems are often impractical for restaurant settings due to their size and high cost. The process of flue gas cleaning involves the removal of PM, harmful substances (e.g. heavy metals), and water-soluble pollutants using different abatement systems.

Abatement systems can be classified into dry or wet removal techniques, depending on whether or not a liquid is used to eliminate pollutants from exhaust emissions (Singh and Shukla, 2014). In dry systems, the most common solutions mainly include the use of fabric filters, cyclones, and electrostatic precipitators (ESP). Wet systems include scrubbers, wet scrubbers with condensation, electrified wet scrubbers, and wet electrostatic precipitators as the main approaches for pollutant removal (Singh and Shukla, 2014).

Filtration systems are among the most common technique which has proven to be effective in the removal of some pollutant (Alves et al., 2015; Arar et al., 2022; Still et al., 2018). These systems use filters that can be employed several times, provided they are regularly cleaned or replaced when they become saturated. Because of their cost-effectiveness, this system can also be easily installed in residential homes or small restaurant kitchens (Still et al., 2018). However, in large kitchen restaurants that operate for long hours, employ cooking methods involving high grease content, and produce intense odors, relying solely on filters may not be sufficient (Gysel et al., 2018a). In large kitchens, electrostatic precipitators (ESPs) are widely used for reducing air pollution. These systems employ an induced electrostatic charge to effectively eliminate pollutants from the airflow while maintaining minimal impedance to the gas flow. By utilizing high voltage to ionize air molecules and incorporating negatively or positively charged collector plates, ESPs efficiently capture and remove charged particles, ensuring improved air quality (Lin et al., 2021).

Various studies in the literature have examined the efficacy of different solutions in removing PM from cooking fumes. Kim et al. (2020) evaluated the effectiveness of various abatement systems in reducing $PM_{2.5}$, PM_{10}, and total particulate matter (TPM) in five restaurants. Four of these restaurants used emission control systems based on ESPs, while the remaining restaurants employed a porous ceramic filter (PCF) unit. The findings demonstrated an average reduction efficiency of over 85% for both $PM_{2.5}$ and PM_{10}. Lee et al. (2011) evaluated the removal efficiency of $PM_{2.5}$, PM_{10}, and total suspended particles (TSP) using three different types of precipitators: bag filter (BF), electrostatic precipitator (ESP), and a combined system of ESP with catalysis. The findings revealed that all three precipitators were effective in removing PM from cooking fumes. The bag filter (BF) demonstrated the highest removal efficiency among the three types of precipitators. Cho et al. (2020) evaluated the effectiveness of a lab-scale orifice wet scrubber abatement system on PM emitted by grilling pork belly. The results demonstrated that also this type of technology was capable of effectively removing PM from the cooking fumes. The implementation of these abatement systems not only resulted in the reduction of PM but also contributed to a decrease in PM-bound PAH emissions (Kim et al., 2020).

Aside from PM emissions, abatement systems are used also to reduce organic pollutants. Gysel et al. (2018b) studied the effectiveness of three different pollutant abatement systems for reducing meat charbroiling emissions. The first system employed a dual-stage filtration, consisting of a steel cartridge filter followed by a fabric filter, installed within a hood. The second system was a prototype for aerosol grease removal, utilizing patented technology based on the boundary layer momentum transfer theory (BLMT) to separate particles (liquid or solid) from the exhaust flow. The third system was an electrostatic precipitator (ESP), which employed high voltage to ionize air molecules and remove charged particles from the flow using collector plates with negative and positive charges. VOCs were then adsorbed into an activated carbon bed. Based on the results obtained, the latter system appears to be the most effective for the removal of PM, inorganic ions, carbonyl compounds, and VOCs. In another research conducted by the same Authors (Gysel et al., 2018a), the same three abatement systems were evaluated for their effectiveness in removing other classes of compounds derived from cooking meat. Consistent with the previous findings, the ESP system exhibited the highest efficiency in removing organic acids, PAHs, nitro-PAHs, metals, and heterocyclic aromatic amines (HAAs).

Table 3 presents a comparison of the PM removal efficiency of the previously described systems. ESP and bag filter systems have the potential for high particulate removal efficiencies, theoretically exceeding 99 % for PM_{10} and 95 % for $PM_{2.5}$ (Miller, 2010; Still et al., 2018). However, achieving these values depends on operating under optimal

Table 3
Comparison of the particulate abatement efficiency of the different abatement systems described.

Abatement systems	Particulate matter fractions	Removal efficiency (%)	Reference
ESP with post-filter with	$PM_{2.5}$	99.1-98.0 [a]	(Kim et al., 2020)
packed beds of activated	PM_{10}	92.9-24.4 [a]	
carbon granules (A-E)	TMP	98.2-98.0 [a]	
ESP with a cylindrical cell	$PM_{2.5}$	90.3-23.8 [a]	
precipitator (B-C)	PM_{10}	97.3-97.9 [a]	
Porous ceramic filter (D)	TMP	88.3-23.8 [a]	
	$PM_{2.5}$	31.5-90.2 [a]	
	PM_{10}	92.5-88.3 [a]	
	TMP	26.7-89.8 [a]	
		91.9-88.1 [a]	
		23.2-89.4 [a]	
		91.3-87.9 [a]	
		39.6-94.4 [a]	
		31.1-94.5 [a]	
		34.1-94.6 [a]	
Electrostatic precipitator	$PM_{2.5}$	50.0	(Lin et al., 2021)
Electrostatic precipitator	$PM_{2.5}$	54.6–97.4	(Lee et al., 2011)
Electrostatic precipitator + catalyst	PM_{10}	54.8–97.4	
Bag filter	TSP	89.6–98.3	
	$PM_{2.5}$	92.9	
	PM_{10}	93.0	
	TSP	93.0	
	$PM_{2.5}$	99.0	
	PM_{10}	99.0	
	TSP	100.0	
Dual stage filtration	$PM_{2.5}$	86.0-90.0 [b]	(Gysel et al., 2018b)
Aerosol grease removal prototype	$PM_{2.5}$	58.0-57.0 [b]	
Electrostatic precipitator	$PM_{2.5}$	25.0-21.0 [b]	
Orifice wet scrubber	$PM_{>2.5}$	99.7	(Cho et al., 2020)
	$PM_{1.0\text{-}2.5}$	89.4	
	$PM_{0.5\text{-}1.0}$	62.1	
	$PM_{<0.5}$	36.5	
Flameless catalytic oxidizer	PM_{10}	83.0	(Whynot et al., 1999)

[a] Values in the same line represent the efficiency observed in consecutive samplings within the same abatement system. Values listed in successive lines denote measurements conducted on different restaurants utilizing the same device.

[b] Values in the same line indicate the efficiency observed using two different dilution methods.

conditions. Factors such as system operation and maintenance, characteristics of cooked meat (e.g., fat content), and test conditions can affect removal efficiency (Lee et al., 2011). The high presence of grease in cooking fumes can accumulate up to coating the walls of the precipitator making parts of it inoperable (Francis and Lipinski, 1977; Lee et al., 2011; Lin et al., 2021). Kim et al. (2020) observed varying efficiencies for the same electrostatic systems in consecutive measurements, attributing the variations to different cleaning conditions of the devices. The removal efficiency can also be affected by variations in incoming flow rates and PM size. In the study conducted by Cho et al. (2020), an orifice wet scrubber was employed, which demonstrated a removal efficiency of over 89% for PM larger than 1.0 μm. However, for PM with a size of 1.0 μm and below ($PM_{1.0}$), the removal efficiency ranged from 37% to 62%. Moreover, it is necessary to carefully select the location of the flue gas exhaust chimney, positioning it at the highest feasible point to facilitate the upward dispersion of pollutants and minimize their concentration in the surrounding areas (Elsharkawy and Ibrahim, 2022).

It is worth noting that abatement systems primarily targeting PM emissions may not effectively address other gaseous pollutants, such as VOCs, PAHs, NOx, SOx, and odors (Kim et al., 2020). In the study conducted by Lin et al. (2021), the ESP system demonstrated a significant reduction in $PM_{2.5}$ emissions by almost 50%. However, the system was found to be ineffective in removing non-methane hydrocarbon

(NMHC) and oxygenated volatile organic compounds (OVOCs). These findings highlight the limited capability of ESP systems in reducing gaseous emissions. Therefore, it is necessary to combine different systems to ensure a more effective reduction of emissions.

In addition to the installation of abatement systems, the development of appropriate legislation plays a crucial role in mitigating the impact of cooking fumes. This involves setting limits for air emissions, facilitating control, monitoring emissions, and setting emission limits. Recognizing that the installation and maintenance of abatement systems represent additional costs for restaurants (Cho et al., 2020; Whynot et al., 1999), economic incentives and supportive legislation are essential in promoting the widespread adoption of pollutant abatement systems.

3.2. Indoor air pollution in charcoal restaurants

Grilling food not only contributes to outdoor air pollution but also results in higher concentrations within enclosed restaurant spaces (Arı et al., 2020; Cheng Lee et al., 2001). Indoor air pollution in restaurants can derive from a variety of sources, including construction materials, interior equipment, human activities such as cooking and heating, the infiltration of outdoor air pollutants, the use of cleaning products, the ventilation system, and environmental conditions such as humidity and temperature (Arı et al., 2020; EPA, 2023; Lachowicz et al., 2022; Saito et al., 2014; Zhang et al., 2017). Among the most prevalent pollutants present are CO, CO_2 (Cheng Lee et al., 2001; Ojima, 2011; Zhang et al., 2017), PM (Cheng Lee et al., 2001; Lachowicz et al., 2022), VOCs (Arı et al., 2020; Cheng Lee et al., 2001; Kim and Lee, 2012), PAHs (Oliveira et al., 2019), and trace metals (Taner et al., 2013).

Zhang et al. (2017) conducted a monitoring study on the indoor air quality of Chinese barbecue restaurants, collecting samples from both the kitchen area and the dining hall. During cooking activities, elevated concentrations of CO and CO_2 were detected in both areas. Arı et al. (2020) conducted a study investigating the indoor concentrations of VOCs in different restaurant styles, including barbecue, deep-frying, and stir-frying. The total VOC concentrations ranged from 200.4 to 426 μg m^{-3}. The volatile compounds detected mainly consisted of aromatic compounds such as benzene, toluene, and terpenes. Among the carcinogenic VOCs, median concentration values of 6.11 μg m^{-3} for benzene, 3.51 μg m^{-3} for chloroform, 1.58 μg m^{-3} for styrene, and 1.12 μg m^{-3} for ethylbenzene were observed.

The presence of PM emissions indoors can lead to elevated concentrations of trace metals and PAHs. In a study conducted by Taner et al. (2013), the concentrations of metals in different PM fractions from 14 Turkish charcoal restaurants were investigated. The metallic element concentrations varied across different PM fractions, with a higher concentration in $PM_{2.5}$ fraction than $PM_{>2.5}$. In all PM fractions, researchers found that Ca, Fe, Al, and Mg were the most prevalent elements. $PM_{>2.5}$ mainly consisted of crustal metals including Al, Ag, Ca, Ce, Co, Fe, Mg, Mn, and Mo. While hazardous metals such as As, Cr, Cu, Ni, Pb, Se, V, and Zn were predominantly found in $PM_{2.5}$.

Using portable samplers, Oliveira et al. (2019) collected PM samples from the breathing air zone of grill workers in a barbecue restaurant, determining the concentration of 18 PM-bound PAHs. During the working period, the total PAH values ranged from 0.06 to 0.26 μg m^{-3}, with a median concentration of 0.08 μg m^{-3}. The median concentration of carcinogenic PAHs in the breathing zone of workers was 0.01 μg m^{-3}, with values ranging from 0.002 to 0.039 μg m^{-3}. Compared to other cooking styles, grilling is linked with higher PAH emissions. Wu et al. (2019) compared the concentrations of PAHs in various types of kitchens and restaurants using personal samplers. Their findings revealed that grilling food on barbecues led to the highest personal concentrations of PAHs, accompanied by moderate levels of aldehydes. These results highlight the inhalation risks faced by operators in such settings.

3.2.1. Indoor air pollution mitigation strategies

To ensure lower concentrations of indoor pollutants, it is recommended to properly ventilate the rooms using air recirculation systems. Song et al. (2018) conducted a study to assess the concentration of $PM_{2.5}$ in a closed kitchen before and after activating the range hood. The Authors found that operating the hood resulted in a significant reduction in indoor pollution, with an efficiency of 86% for $PM_{2.5}$, 80% for sub-micron particles, and over 90% for super-micron particles. Ju et al. (2020) observed that the use of a ventilation fan helped decrease the levels of CO, CO_2, and NOx emitted from a charcoal roaster. Adequate fresh air supply promotes more complete combustion, leading to reduced emissions.

However, the presence of ventilation systems could not guarantee the complete elimination of indoor pollutants (Oliveira et al., 2021; Zhang et al., 2017). To effectively remove pollutants, it is crucial to tailor the sizing of ventilation systems to meet operational requirements considering factors such as the amount of charcoal used and the types of food being cooked (Ojima, 2011). Various solutions can be employed to mitigate indoor pollution (Arı et al., 2020; Oliveira et al., 2019; Still et al., 2018; Wu et al., 2019):

i) Replace charcoal with more efficient and less polluting fuels (e.g., gas or electricity);
ii) Use devices that promote efficient combustion and prevent the fat from dripping onto the fuel;
iii) Implement a properly sized ventilation system that effectively expels pollutants according to the operational requirements;
iv) Encourage regular air changes within the indoor environment to improve air quality;
v) Regularly clean and change the clothes used during work to avoid pollutant accumulation.

4. Health risks associated with charcoal grilling

The previous paragraphs have illustrated how the use of charcoal to grill foods causes the release of high concentrations of pollutants, primarily PM, PAHs, and VOCs. In addition to contributing to the deterioration of air quality, emissions can seriously affect human health. Inhalation of charcoal and wood combustion fumes can lead to short-term effects determining cardiovascular issues, altering blood pressure, and promoting heart rhythm disturbances (Orozco-Levi et al., 2006). Prolonged exposure to biomass combustion fumes can cause the insurgence of respiratory inflammation, reduced lung function, and the insurgence of Chronic Obstructive Pulmonary Disease (COPD), resulting in cough, wheezing, hyperproduction of mucus, dyspnea, and chronic bronchitis (Orozco-Levi et al., 2006; Ortiz-Quintero et al., 2023).

As described in Section 2.5, cooking fumes can contain higher concentrations of pollutants compared to charcoal combustion fumes (Ortiz-Quintero et al., 2023). The composition and potential hazards of cooking fumes are affected by several factors mainly regarding food characteristics (e.g., fat content, use of marinates or additives), grilling conditions (e.g., temperature and duration), types of cooking tools used (e.g., pans), grill cleaning conditions, and cooking fuel used (Lachowicz et al., 2022). Prolonged exposure to cooking fumes can increase the risks for serious health problems like asthma, cardiovascular issues, lung cancer, and acute pulmonary illness (Lachowicz et al., 2022).

4.1. PM inhalation risks

Grilling determines high PM concentrations that can be easily inhaled and penetrate the lungs. Based on the size, particles can deposit differently into the human respiratory system. Particles with a diameter less than 10 μm (PM_{10}) can deposit into the extrathoracic zone, consisting of the zone between the oral cavity and pharynx, while particles with a diameter less than 2.5 μm ($PM_{2.5}$) can easily penetrate the tracheobronchial region that includes trachea and bronchi. Particles with a diameter of less than 1.0 μm ($PM_{1.0}$) can reach the alveolar region into the lungs (Lao et al., 2018b; Nicolaou et al., 2021; Saito et al., 2014; Wu et al., 2015). Therefore, as the diameter decreases, the potential hazard to human health increases. PM can also act as a carrier for other hazardous pollutants, both organic (e.g. PAHs) and inorganic (e.g., trace metals)(Badyda et al., 2017; Iqbal and Kim, 2016; Lachowicz et al., 2022; Susaya et al., 2010; Taner et al., 2013).

4.1.1. Risks of PAHs from charcoal cooking fumes

PAHs from charcoal-cooked food can be absorbed by humans through ingestion, inhalation, and dermal contact (Badyda et al., 2022; Wu et al., 2015). Although food ingestion is the primary source of PAHs (Alomirah et al., 2011; Duedahl-Olesen and Ionas, 2020), significant amounts can also be inhaled or come into contact with the skin (Badyda et al., 2022; Lao et al., 2020; Oliveira et al., 2021; Wu et al., 2015). Wu et al. (2015) emphasized the substantial health risks posed by fumes from grilling meat, especially through skin contact, which aligns with the findings of Lao et al. (2018b, 2020). These studies observed comparable or higher levels of PAHs resulting from dermal contact compared to inhalation exposure. Fine particles carrying medium molecular weight (MMW) and high molecular weight (HMW) PAHs can adhere to and penetrate the skin. The number of rings and molecular weight determine the carcinogenicity of PAHs. Low molecular weight PAHs (LMW-PAHs) with 3-4 rings are less dangerous than heavy PAHs having 4-6 rings (Badyda et al., 2022; Lao et al., 2020). In addition, the size of particles plays a critical role in determining the risks associated with inhalation and dermal contact, thereby having a significant impact on the levels of exposure.

Particle size influences the inhalation exposure to PM-bound PAHs by affecting their entry and deposition in the respiratory tract (Lao et al., 2018a). According to Saito et al. (2014), more than 90% of the PAHs emitted from cooking can penetrate and deposit into the alveolar region. In the study conducted by Lao et al. (2018a), the PM-bound PAHs, particularly the carcinogenic ones with 4-6 rings, collected from barbecue fumes at a distance of 2 meters from the stove, were mainly associated with fine particles in the size range of 0.18 to 1.8 μm. In their study, Badyda et al. (2017) found that $PM_{2.5}$-bound PAHs resulted in higher exposure compared to PAHs bound to $PM_{2.5\text{-}100}$. Inhalation of $PM_{2.5}$-bound PAHs was associated with greater cancer risks since a significant portion of these particles could pass through the respiratory system and be deposited in the lungs. In contrast, the smaller amounts of $PM_{2.5\text{-}100}$-bound PAHs were less likely to efficiently penetrate the respiratory system and be deposited. The overall risk associated with PAHs varies based on the duration of exposure, food consumption, and particle size. It is advisable to minimize prolonged exposure to cooking fumes and limit the consumption of grilled and smoked food to mitigate potential health risks.

4.1.2. Exposure and health implications of trace metals

Charcoal grilling can significantly contribute to the presence of trace metals, frequently exceeding safety limits (Susaya et al., 2010). Table 4 provides a comparison of trace metal concentrations detected in both indoor and outdoor environments. The exposure to trace metals can vary depending on the PM fraction considered. Sharp and Turner (2013) conducted a risk assessment on the inhalation of inorganic elements in five different PM fractions. The findings revealed higher concentrations of trace metals in $PM_{2.5}$ compared to $PM_{>2.5}$, resulting in increased cancer risk.

Pandey et al. (2009) investigated the emissions of mercury from 11 barbecue charcoal commonly available in Korea. Mercury emissions had a mean value of 0.24 μg m^{-3} and a range of observation from 0.11 to 0.50 μg m^{-3} depending on the sample considered. Mercury poses a potential risk to human health as it can easily accumulate in closed environments, such as restaurants, and gradually increase inhalation exposure for workers. In addition to inhalation, trace metals can accumulate in food and subsequently be ingested. Sharp and Turner (2013) estimated that during a meal, people could potentially ingest up to 1 g of ashes resulting from charcoal combustion. The ashes may contain varying amounts of bioaccessible trace metals, with charcoal-briquettes grilled food ranging from 1 μg (Cd and Pb) to over 2000 μg (Al) while lump charcoal exhibited concentrations ranging from 0.001 μg (Pb) to over 500 μg (Al). To assess the significance of these values, a comparison

Table 4
Mean concentration and standard deviation values of trace metals resulting from charcoal combustion.

Reference	(Kuo et al., 2006)	(Taner et al., 2013)						(Pandey et al., 2009)	(Susaya et al., 2010)
Fuel	Charcoal and fast-lighting charcoal	Charcoal	Charcoal	Charcoal	Charcoal	Charcoal	Charcoal	Charcoal	Charcoal
PM Fraction	PM_{10}	$PM_{>2.5}$	$PM_{2.5}$	$PM_{2.5\text{-}1.0}$	$PM_{1.0\text{-}0.5}$	$PM_{0.5\text{-}0.25}$	$PM_{0.25}$	/	PM_{10}
Number of observations	2	14	14	14	14	14	14	11	11
Unit of measure	ng m^{-3}	ng m^{-3}	ng m^{-3}	ng m^{-3}	ng m^{-3}	ng m^{-3}	ng m^{-3}	ng m^{-3}	ng m^{-3}
Source	Outdoor air	Restaurant air	Restaurant air	Restaurant air	Restaurant air	Restaurant air	Restaurant air	Combustion Emission	Combustion Emission
Al	/	1073 ± 942	1911 ± 1010	722 ± 523	606 ± 324	517 ± 316	215 ± 262	/	/
As	/	15.3 ± 10.4	111 ± 76.1	22.3 ± 11.6	44.7 ± 24.6	38.7 ± 21.2	28.3 ± 21.2	/	29 ± 24.1
Ba	/	/	/	/	/	/	/	/	522 ± 399
Ca	/	3072 ± 2246	5320 ± 3487	1729 ± 1060	1540 ± 952	882 ± 935	2228 ± 2044	/	/
Cd	/	0.06 ± 0.04	4.59 ± 6.39	0.07 ± 0.08	0.14 ± 0.16	0.17 ± 0.11	4.30 ± 6.38	/	297 ± 828
Co	/	0.62 ± 0.44	0.96 ± 0.45	0.28 ± 0.17	0.27 ± 0.23	0.16 ± 0.12	0.30 ± 0.23	/	393 ± 1020
Cr	/	28.9 ± 21.6	118 ± 45.5	32.5 ± 14.3	35.7 ± 28.6	25.9 ± 12.0	25.2 ± 18.5	/	444 ± 1162
Cs	/	0.19 ± 0.15	0.41 ± 0.38	0.21 ± 0.05	0.18 ± 0.02	0.20 ± 0.09	0.31 ± 0.30	/	/
Cu	/	20.3 ± 10.4	55.3 ± 33.4	17.0 ± 11.9	19.8 ± 30.5	12.4 ± 11.3	28.5 ± 25.0	/	477 ± 895
Fe	/	1383 ± 609	4430 ± 1493	1266 ± 428	1211 ± 389	1118 ± 457	888 ± 388	/	/
Hg	/	/	/	/	/	/	/	242 ± 115	/
Mg	/	678 ± 434	1246 ± 566	446 ± 192	364 ± 173	328 ± 149	200 ± 174	/	722 ± 461
Mn	/	76.4 ± 130	69.1 ± 107	22.2 ± 35.5	12.7 ± 17.5	16.2 ± 25.2	18.1 ± 39.4	/	134 ± 121
Ni	/	7.90 ± 7.85	46.2 ± 37.5	9.80 ± 9.65	17.9 ± 34.5	7.37 ± 7.24	17.4 ± 11.9	/	199 ± 147
Se	/	57.1 ± 51.7	336 ± 242	139 ± 110	145 ± 92.4	67.2 ± 49.2	59.2 ± 48.2	/	46.5 ± 44.1
Pb	77.5 ± 41.9	5.65 ± 4.24	42.8 ± 29.5	4.30 ± 2.70	7.84 ± 9.55	9.53 ± 6.18	21.1 ± 22.9	/	14720 ± 20540
V	/	84.0 ± 52.2	477 ± 211	142 ± 63.4	139 ± 60.2	124 ± 46.8	90.5 ± 39.7	/	447 ± 1064
Zn	/	56.0 ± 91.8	187 ± 158	62.6 ± 106	57.1 ± 79.7	26.9 ± 20.9	26.9 ± 20.9	/	18360 ± 16540

was made with the daily dietary intake values for the UK adult population. The findings revealed that briquette barbecuing could contribute to 23 % and 65 % of the daily intake of As and Al, respectively. Therefore, the consumption of food prepared on charcoal grills, particularly those using briquettes, can significantly impact the intake of these trace metals.

Overall, charcoal grilling poses risks of trace metal exposure, particularly in indoor environments such as restaurants, and the type of charcoal used can significantly influence the levels of trace metals emitted and subsequently ingested.

4.2. Impact of grilling fuel choice on health risks

In accordance with the earlier discussion in paragraph 2.3, the choice of grilling fuel has a significant impact on emission levels and, consequently, potential health risks. Badyda et al. (2017) compared griller exposure resulting from the use of charcoal briquettes, lump charcoal, and gas barbecues. It was found that the daily exposure of operators to PM-bound PAHs resulting from grilling fumes, adjusted to the toxicity equivalent of benzo[a]pyrene (BaP_{eq}), was measured at 401.6 ng day^{-1} (briquettes), 326.9 ng day^{-1} (charcoal), and 0.04 ng day^{-1} (gas). Furthermore, exposure to fumes resulting from charcoal briquette combustion (10^{-1}) led to significantly higher values of Incremental Lifetime Cancer Risk (ILCR) compared to gas usage (10^{-5}). ILCR is a metric used to assess the potential risk of developing cancer in humans due to chemical exposure. It quantifies the increased probability of cancer occurrence during the lifetime of individuals. A value of 10^{-6} indicates that out of one million people exposed to a carcinogen, one person can develop cancer. This value is considered the threshold of *de minimis* risk, indicating a negligible risk for values below this threshold (EPA, 1991). In a subsequent study, the same researchers examined the exposure of grillers to inhalation of PAHs and VOCs, specifically benzene, toluene, and xylenes (BTX) using various types of barbecues fueled using lump charcoal, charcoal briquettes, LPG, and electricity (Badyda et al., 2019). The daily exposure dose of $PM_{4.0}$-bound BaPeq, a measure of the carcinogenic potential of PAHs, during food preparation, ranged from 92-118 ng day^{-1} (electricity), 121-142 ng day^{-1} (LPG), 124-204 ng day^{-1} (lump charcoal), and 1022-1121 ng day^{-1} (charcoal briquettes). Consequently, the ILCR associated with inhalation exposure was higher when using briquettes compared to gas grilling. In 2022, the same Authors (Badyda et al., 2022) conducted a study to evaluate the impact of using the same fuels used previously on cancer risks associated with exposure to PAHs and benzene, toluene, ethylbenzene, and xylenes (BTEX). Based on the findings, the use of charcoal and charcoal briquettes increased cancer risks for users compared to gas and electricity. Emissions of BTEX compounds were found to be significantly higher, approximately 130 times, during charcoal grilling compared to gas grilling, indicating the substantial impact of charcoal and charcoal briquette usage on elevated levels of BTEX compounds in contrast to gas and electric grilling methods. Using charcoal briquettes increased the risk of developing cancer three times compared to using a gas grill.

Overall, the use of charcoal-based products leads to higher exposure to air pollutants. This elevated exposure can be attributed to lower combustion efficiency, resulting in a greater release of harmful compounds compared to gas and electric cooking methods (Badyda et al., 2022). Based on the findings of the previously mentioned studies, it can be inferred that the use of gas and electricity significantly reduces the occurrence of health risks for users. When charcoal products are used, it is recommended to minimize exposure to cooking fumes to less than 1 hour (Badyda et al., 2017).

4.5. Indoor vs outdoor exposure risks

4.5.1. Indoor air pollution

The health risks associated with charcoal combustion can vary depending on whether it occurs indoors or outdoors. Indoor environments can have pollutant concentrations significantly higher than outdoor environments. This is particularly relevant for charcoal grill restaurants, where a variety of air pollutants emitted during charcoal barbecues can accumulate indoors. Direct exposure to emitted air pollutants from charcoal-fired appliances, especially combustion pollutants including carcinogenic compounds, can have adverse health effects on barbecue customers and workers if proper ventilation is lacking (Huang et al., 2016). Several studies have shown that people, including restaurant employees, are exposed to pollutant concentrations exceeding safety limits established by organizations like the WHO and the U.S. EPA (Ortiz-Quintero et al., 2023; Susaya et al., 2010). Restaurant workers, especially those working in kitchens, are the most susceptible to prolonged exposure. In addition, both customers and waiters can be exposed to cooking fumes (Taner et al., 2013). The main pollutants of concern for health risks in these settings are VOCs, PAHs, and PM.

A study by Arı et al. (2020) assessed the ILCR for restaurant workers resulting from inhalation of VOCs, estimating a probable risk for lung cancer within the range of 3.4×10^{-8} to 1.1×10^{-5}, with the highest risks associated with chloroform and benzene. Regarding PM and trace metal emissions, the findings of Taner et al. (2013) showed that restaurant employees are exposed to high levels of fine particles, particularly those with a diameter between 0.5 and 1.0 μm, posing significant health risks.

Charcoal grill restaurants can contain significantly higher concentrations of indoor PAHs compared to background levels. Lao et al. (2020) found that while grilling food indoors, the total gaseous PAH concentration near doors and windows was detected to be 770-1127 ng m^{-3}, whereas background air levels were 37 ng m^{-3}. Wu et al. (2019) compared the exposure to PAHs and aldehydes in three different cooking workplaces and found that workers in street food carts, where charcoal is often used, had higher personal concentrations of pollutants, increasing their risk of developing cancer. A study conducted in the Oporto district of Portugal assessed the urinary levels of hydroxylated polycyclic aromatic hydrocarbons (OHPAHs) in restaurant workers as a means of evaluating occupational exposure to PAHs (Oliveira et al., 2021). The study found that OHPAH levels were 9 times higher during working days, indicating an accumulation of exposure from consecutive working days. The use of charcoal, combined with inadequate fume extraction systems such as fume extractors, can lead to higher exposure to pollutants.

Ventilation is a critical factor in controlling indoor air pollution in restaurants (Huang et al., 2016; Lachowicz et al., 2022; Wu et al., 2019). Properly installed and functioning ventilation systems are essential for preserving the health of workers and customers.

4.5.2. Outdoor health risks

Despite indoor pollution poses a greater risk of exposure to air pollutants, outdoor charcoal grilling also represents a potential risk to users and individuals close to the stove. Distance from the barbecue is one of the most important parameters to reduce exposure to harmful compounds. As observed in the study of Lenssen et al. (2022), increasing the distance reduced the concentrations of $PM_{2.5}$, particle number concentrations (PNC), and black carbon (BC). Based on the research conducted by Lao et al. (2018a), it was observed that increasing the distance from 2 to 10 m resulted in decreased exposure to PM-bound PAHs. Furthermore, this increase in distance led to a reduction in both the molecular weight and mean size of the PM-bound PAHs. The detected samples at 2 m and 10 m ranged between 0.43-3.27 μm and 0.60-1.56 μm, respectively. The findings were in line with the study conducted by Wu et al. (2015), which observed lower concentrations of PM_{10}, $PM_{2.5}$, and PAHs in fumes collected at a distance of 10 m compared to 2 m. As the distance increases, the influence of environmental factors on the concentration of pollutants becomes more pronounced.

Environmental factors linked to wind direction, temperature, and relative humidity reduce exposure to harmful compounds (Lao et al., 2018a; Lenssen et al., 2022). Song et al. (2018) investigated the dispersion of pollutants by the wind. They repeated the concentration measurements of $PM_{2.5}$ at distances of 1.5,10,15, 25, and 35 m from the emission sources. The results showed that the highest concentrations were observed near the charcoal combustion area. However, for $PM_{2.5}$ a lower concentration was observed at 5 m, followed by an increase in concentration at 10-15 m. Therefore, wind plays a role in distributing pollutants differently in the environment, potentially contributing to localized deterioration of air quality.

During barbecue is recommended to not stay close to the barbecue and if possible, to position the stove in a well-ventilated location to increase the polluting dispersion in the air and the deposition of the heavy compounds (Lao et al., 2018a).

4.6. Health impact of seasonal periods and festive celebrations

The prolonged use of charcoal for grilling food leads to higher pollutant concentrations in the atmosphere, which can be particularly pronounced during certain periods of the year such as spring or summer, as well as during festive celebrations (Badyda et al., 2020; HPBA, 2023; Kuo et al., 2006; Wu et al., 2015). According to Badyda et al. (2020), although charcoal grilling produces lower annual pollutant concentrations compared to other sources like biomass stoves, the Authors affirmed that emissions from charcoal grilling can cause significant local air quality issues during spring and summer. During these periods, the inhalation of charcoal combustion fumes can contribute to an increased incidence of health issues such as COPD (Orozco-Levi et al., 2006). Furthermore, during summer periods there could be an elevated exposure to PAHs from grilling meat due to increased skin contact resulting from the absence of protective clothing (Lao et al., 2020; Wu et al., 2015). Lao et al. (2018b), claimed that the extent of exposed skin area affects the dermal absorption of PAHs, suggesting that increased skin area can result in higher absorption compared to inhalation alone. Notably, hair follicles and the forearm can serve as significant reservoirs for fine particles, expanding the exposure area and promoting the dermal absorption of PM-bound PAHs (Lao et al., 2020). To mitigate this exposure, Oliveira et al. (2019) suggested that the griller should avoid direct skin contact by regularly washing areas exposed to fumes and wearing long clean clothes. Morrison et al. (2016) emphasized that even in non-occupational environments, the use of clean clothes can play a significant role in protecting against the dermal uptake of pollutants. Lao et al. (2018b) confirmed that wearing clothes can reduce the dermal absorption of PAHs during short-term exposure to grilling fumes while clothes polluted with PAHs can represent an additional source of dermal intake, in particular 4-5 rings of PAHs.

Higher emissions can arise also during celebratory events when multiple grilling stoves and barbecues are used simultaneously (HPBA, 2023). Kuo et al. (2006) found that during Mid-Autumn Festival nights, the concentrations of PAHs and BaPeq in PM_{10} increased by 1.6 and 1.5 times, respectively, compared to non-festival nights, with emissions exceeding those typically generated by domestic kitchens and restaurants on regular days. Furthermore, the average concentration of Pb in the air was also 2.8 times higher on festival nights.

5. Mitigation strategies and limitations

5.1. Mitigation strategies

Based on the previous findings, to mitigate environmental and health risks several solutions could be implemented:

i) To guarantee the high quality of charcoal-based products, and to reduce the relative pollutant emissions, it is imperative to establish a more effective certification system. This system should promote frequent and rigorous controls, incorporating advanced testing methods, to guarantee charcoal-based products with well-defined characteristics.

ii) Charcoal-based producers and sellers should include in the bag a comprehensive list of tested parameters, along with their corresponding values and limits, similar to the practices already adopted in other solid biofuels (e.g., pellet). Additionally, providing guidelines for the proper use of the product can further enhance the adoption of responsible grilling practices.

iii) Barbecue users are encouraged to use lump charcoal instead of charcoal briquettes. Lump charcoal typically exhibits lower contamination levels and emissions.

iv) It is advisable to avoid the use of firelighters or impregnated charcoal, as they often contain petroleum products, leading to higher emissions and associated health risks compared to non-impregnated products. A safer and more environmentally friendly alternative for charcoal ignition is chimney starters or electric starters.

v) To effectively reduce emissions and inhalation risks during food grilling, it is highly advisable to avoid using fat-rich food and recommends using grilling equipment designed to prevent oil and fat from dripping into charcoal embers. This combination of practices can effectively reduce both smoke and polluting emissions, contributing to a safer and healthier grilling experience.

vi) Before grilling, it is essential to regularly clean the barbecue equipment by removing grease or food residues.

vii) To ensure safety, it is advisable to avoid remaining close to the barbecue, especially during the charcoal ignition phase.

viii) During outdoor barbecues, ensuring proper ventilation is crucial for reducing exposure risks. Positioning the grill in an open area allows for optimal air circulation, effectively dispersing the smoke and preventing its accumulation in a limited space. Furthermore, aligning the barbecue with the wind direction will further enhance smoke dispersion.

ix) Charcoal-grilling restaurants should install abatement systems that effectively reduce the dispersion of high concentrations of pollutants. These systems ensure controlled and minimized release of harmful substances into the outdoor air, creating a safer environment both for customers and surrounding areas.

x) During indoor barbecuing, it is crucial to ensure proper ventilation using natural airflow or dedicated ventilation equipment. This practice minimizes the accumulation of smoke and pollutants in closed environments. Adequate ventilation allows for the dispersal of harmful pollutants, creating a healthier indoor atmosphere and reducing potential health risks associated with prolonged exposure to grilling emissions.

xi) Implementing regulations for charcoal combustion is crucial in controlling emissions. Such regulations can include setting limits on air pollutant concentrations, placing temporary restrictions on charcoal use, promoting the adoption of cleaner technologies and abatement systems, and monitoring compliance with such standards.

5.2. Limitations

Although this study primarily focused on the key factors influencing pollutant emissions, other factors unexplored in this work may also play a role in influencing the release of pollutants. These include aspects such as air supply, stove geometry, barbecue equipment parameters, and the variability associated with different grilling techniques. By considering these factors, a deeper understanding of pollutant emissions and their broader implications can be achieved.

In terms of health risks, this study highlighted the potential hazards associated with charcoal emissions, specifically focusing on inhalation and dermal contact. The impact of charcoal emissions on food quality was not considered, since previous publications have already addressed this aspect (Bansal and Kim, 2015; Duedahl-Olesen and Ionas, 2020;

Onopiuk et al., 2021). Nevertheless, the present study highlights the health risks and environmental issues linked to charcoal emissions. It emphasizes the importance of conducting additional research to increase the knowledge about factors affecting polluting emissions and the necessity of developing effective mitigation strategies.

6. Conclusions

Despite charcoal grilling being appreciated worldwide for its unique flavors, this cooking method determines serious environmental and health risks. The emissions generated during charcoal grilling include mainly PM, PAHs, CO, CO_2, VOCs, and trace metals. The concentration of these pollutants is affected by different factors. Notably, the combustion phase, qualitative characteristics of charcoal-based products, and the presence of food represent the most important factors in this regard.

The combination of emissions resulting from amateur barbecue and charcoal grilling restaurants can seriously contribute to air pollution. Exposure to charcoal cooking fumes can represent a potential human health risk causing health problems that should not be underestimated. Restaurant workers are prolonged exposed to several air polluting determining the possible insurgence of severe health problems. Moreover, even the health of amateur grillers can be affected since it was demonstrated that also short exposure can impact human health.

The implications of these findings are significant for policymakers, environmental agencies, restaurant owners, and barbecue users who are interested in promoting safe and eco-friendly grilling practices.

Raising public awareness about the risks associated with charcoal combustion and the importance of adopting cleaner cooking practices is crucial in promoting responsible behavior among charcoal users. For this purpose, educational campaigns play a key role in disseminating information about the advantages of using high-quality products, understanding the qualitative and emission differences among the various charcoal-based products available in the market, grilling equipment, food, and appropriate cooking practices.

In addition to this, to achieve sustainable charcoal usage, it is imperative to improve the current standards and implement certification systems that enhance transparency regarding charcoal characteristics and ensure stringent quality controls.

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CRediT authorship contribution statement

Alessio Mencarelli: Conceptualization, Investigation, Data curation, Writing – original draft, Visualization. **Rosa Greco:** Conceptualization, Writing – review & editing. **Stefania Balzan:** Conceptualization, Writing – review & editing. **Stefano Grigolato:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Raffaele Cavalli:** Conceptualization, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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