Review

# The modern paradox of unregulated cooking activities and indoor air quality

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## ABSTRACT

Pollutant emission from domestic and commercial cooking activities is a previously neglected area of concern with respect to human health worldwide. Its health effects are relevant to people across the globe, not only those using low quality food materials in lesser-developed countries but also to more affluent people enjoying higher quality food in developed countries. Based on the available database of pollutant emissions derived from fire-based cooking, its environmental significance is explored in a number of ways, especially with respect to the exposure to hazardous vapors and particulate pollutants. Discussion is extended to describe the risk in relation to cooking methods, cooking materials, fuels, etc. The observed pollutant levels are also evaluated against the current regulations and guidelines established in national and international legislation. The limitations and future prospects for the control of cooking hazards are discussed.

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## Contents

## 1. Introduction

With the progress of healthcare science, human life expectancy has increased gradually over the years. Likewise, with the increasing pervasiveness of advanced civilization and urbanization many primitive risks that threatened human life previously have been reduced or eliminated. As such, the pattern of risks to livelihood and their relative magnitudes have also been altered dramatically. Among many risks in our normal everyday life, not many people are aware of the risks associated with cooking activities. As the use of fire became part of human culture, all populations have become prone to this cooking-related risk, regardless of their race, age, wealth, cultural food preferences, etc.

The selection of fire-based cooking approaches such as frying, roasting, and grilling can exert a significant impact not only on the quality of the food but also on pollutant emissions [1,2]. The extent of the latter can be controlled by the combined effects of different recipes, cooking procedures, food materials (and ingredients), fuel types, extraction/ventilation equipment, etc. [3]. The style of these cooking activities and their impact can also be affected by macro-scale variables like population, culture, climate, and geographical location. Thus assessment of these cooking related risks becomes a delicate issue with sociological sensitivities, if certain cooking types with deeply ingrained traditional methods are labeled as increased risk.

Humans can be subject to cooking-related risks via various intake routes either directly (overcooked foodstuffs) or indirectly (fumes). Our emphasis in this review is directed mainly

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towards indoor air pollutants (IAP) liberated from fire-based cooking activities, the ubiquitous risks of their exposure, and guidelines/regulations for maintaining indoor air quality (IAQ) from such activities.

## 2. Pollutants released from cooking fuels and their effect on indoor air pollution

As most fire-based cooking cannot be carried out without fuels, the effect of fuel combustion can add to the risks of cooking activities. In fact, cooking fuels are one of the most important causes of IAP, particularly in developing countries [4]. Nearly half of the world's population use solid fuels and biomass (e.g., coal, wood, animal dung, and crop residues) as their primary energy source [5,6]. Solid fuel is used commonly among the poor, particularly in rural areas in developing countries [7]. In urban areas comparatively clean fuels (like liquid petroleum gas (LPG), biogas, natural gas, and kerosene) are available for cooking purposes, along with electricity [7]. Biomass combustion produces a large number of harmful pollutants including respirable particulate matter ($PM_{10}$), carbon monoxide (CO), nitrogen oxides ($NO_2$), formaldehyde, benzene, poly-cyclic aromatic hydrocarbons (PAH), and many other toxic compounds [8,9]. Furthermore, because of the relatively confined nature of indoor spaces with low air turnover rates, pollutants liberated inside will not disperse quickly to sustain low IAQ.

Pollutants emitted from fuel consumption (for cooking purposes) have been studied in relation to cooking fuel type as part of IAP research (Tables 1 and 2). Traditional open-fire cooking stoves, used extensively in rural households in many developing countries, generally release high quantity of particles and harmful pollutants in smoke [10–12]. Indoor $PM_{10}$ concentrations from cooking via biomass combustion were measured as 1545 $\mu g\,m^{-3}$ in Kenya [13] and 1200 $\mu g\,m^{-3}$ in Mozambique [14]. In rural Bolivia, the 6-h mean levels of $PM_{10}$, when cooking from indoor and outdoor kitchens by cow dung, were 1830 and 250 $\mu g\,m^{-3}$, respectively [15]. Additionally, common volatile organic compounds (VOCs) such as benzene, toluene, and xylene (commonly called BTX) were significantly higher with the use of biomass fuel relative to natural gas [16]. Likewise, considerable emissions of VOCs and metals have also been detected from combustion of BBQ charcoals produced from several countries [17,18]. As cooking activities occur in the close proximity of people, they are usually exposed to high levels of these pollutants [19].

## 3. The effect of different cooking methods and ingredients on IAQ

Cooking ingredients vary widely, reflecting local environmental, geographical, economic, and cultural factors. Moreover, cooking methods are diverse enough to encompass baking, roasting, frying, grilling, barbecuing, smoking, boiling, steaming, microwaving, braising, etc. As such, the cooking of each food reflects its own combinations for the above factors. The data on air pollutant emissions as a function of different food ingredients are summarized in Table 3. Moreover, as the pollutant type and levels are also influenced by the cooking methods, the data for air pollutant emissions is also compiled in relation to cooking style in Table 4. For instance, stir-frying in a wok is the most common cooking practice in China through which many HAPs are released [20].

Schauer et al. [21] estimated emission rates of gas-phase, semi-volatile, and particle-phase organic compounds (C1 to C27) from commercial-scale food cooking operations using seed oils. In Korean-style barbecue restaurants using hot steel pan and broiling steel bars (above a charcoal burner), a list of 99 pollutants (including respirable suspended particulates (RSP), CO, and VOCs) were detected [22]. Lee et al. [20] investigated the IAP at four restaurants in metropolitan Hong Kong and found high concentrations of formaldehyde (177 $\mu g\,m^{-3}$) and benzene (18.4 $\mu g\,m^{-3}$) in the dining areas of the Korean-style barbecue restaurant. Furthermore, meat charbroiling was thus identified as one of the previously unconsidered sources of heavy aldehydes in urban air [23].

Acrolein is also released from heated oils during domestic cooking. Heated canola, extra-virgin olive, and olive oils, when heated at 180 °C, were reported to emit acrolein at 52.6, 9.3, and 9.6 $mg\,h^{-1}\,L^{-1}$ [24], respectively. Moreover, indoor acrolein levels are found to persist for a considerable time (a half-life of $14.4 \pm 2.6$ h) after cooking under poor ventilation [25].

## 4. Emission inventories of pollutants released from cooking activities

Cooking related emissions can be important sources of major airborne pollutants (e.g., PM, $SO_2$, and CO) as well as trace-level pollutants (e.g., secondary organic aerosols (SOA), organic carbon (OC), and elemental carbon (EC)). The latter also represents important constituents of the global carbon balance. Emissions inventories for cooking activities are generally lacking, and considered a "missing or unaccounted fraction of the area source category", regardless of pollutant type. Several researchers estimated emissions inventories for many cooking activities based on various statistical approaches (Table 5), and some limited national inventories exist. In the UK, the National Atmospheric Emissions Inventory (NAEI – www.naei.org.uk) estimated VOC emissions for commercial food production activities such as animal feed manufacture, biscuit, cake and cereal production, coffee roasting, sugar production, and margarine and vegetable oil production.

**Table 1**
Comparison of indoor air pollutant concentrations measured from different fuels used for cooking (concentrations in $\mu g\,m^{-3}$).

| Fuels used for cooking | CO | $SO_2$ | $NO_2$ | $PM_{10}$ | Benzene | Toluene | Xylene | Formaldehyde | Country | References |
|---|---|---|---|---|---|---|---|---|---|---|
| Natural gas | 4170 | 185 | – | 247 | | | | | China | [34] |
| | | 56.2 | | | 13.7 | 2.70 | 3.81 | 17.2 | Bangladesh | [16] |
| Coal | 6550 | 436 | – | 708 | | | | | China | [34] |
| Charcoal | | | | | 315 | 625 | | 337 | Korea | [17] |
| LPG | – | 4.24 | 30.3 | 710 | | | | | India | [11] |
| | 115 | | | 50 | | | | | Malaysia | [12] |
| | 284 | 27.3 | 70.9 | 147 | | | | | India | [35] |
| Biomass | – | 6.03 | 36.3 | 744 | | | | | India | [11] |
| | | | | 1545 | | | | | Kenya | [13] |
| | | 60.1 | | | 54.2 | 34.2 | 18.5 | 9.92 | Bangladesh | [16] |
| | 959 | 61.5 | 135 | 353 | | | | | India | [35] |
| Wood | | | | 1200 | | | | | Mozambique | [14] |
| | 3322 | | | 300 | | | | | Malaysia | [12] |
| Dung | | | | 1830 | | | | | Bolivia | [15] |

**Table 2**

Comparison of emission concentrations between different cooking activities in various indoor (and outdoor) environments.

| Country | Environment/ emission source | $CO_2$ (ppm) | CO (ppb) | $PM_{10}$ (ppb) | $PM_{2.5}$ (ppb) | HCHO (ppb) | THC (ppm) | Benzene (ppb) | Toluene (ppb) | Methyl Chloride (ppb) | Chloroform (ppb) | n-Fatty acids (ppm) | Dicarboxylic acids (ppm) | PAH (ppb) | n-Alkanes (ppb) | Total carbonyls (ppb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hongkong (Lee et al. [20]) | Korean BBQ-style restaurant (indoor) | 1648 | 15.7 | 1.44 | 1.17 | 0.18 | 11.40 | 0.02 | 0.16 | 0.001 | 0.015 | | | | | |
| | Chinese hot-pot restaurant (indoor) | 2344 | 8.11 | 0.11 | 0.08 | 0.04 | 8.50 | 0.01 | 0.09 | 0.020 | 0.010 | | | | | |
| | Chinese dim sum restaurant (indoor) | 1031 | 2.23 | 0.03 | 0.03 | 0.02 | 5.60 | 0.01 | 0.08 | 0.007 | 0.003 | | | | | |
| | Western canteen (indoor) | 636 | 0.01 | 0.04 | 0.02 | 0.02 | 4.00 | 0.00 | 0.02 | 0.001 | 0.001 | | | | | |
| | Korean BBQ-style restaurant (outdoor) | 512 | 1.92 | 0.08 | 0.06 | 0.13 | 6.78 | 0.01 | 0.21 | 0.011 | 0.004 | | | | | |
| | Chinese hot-pot restaurant (outdoor) | 780 | 1.21 | 0.08 | 0.07 | 0.06 | 6.50 | 0.00 | 0.03 | 0.002 | 0.003 | | | | | |
| | Chinese dim sum restaurant (outdoor) | 4.2 | 1.26 | 0.08 | 0.06 | 0.02 | 5.10 | 0.01 | 0.04 | 0.014 | 0.002 | | | | | |
| | Western canteen (outdoor) | 435 | 1.13 | 0.10 | 0.07 | 0.02 | 4.10 | 0.01 | 0.04 | 0.001 | 0.001 | | | | | |
| China (He et al. [49]) | Chinese restaurant (Hunan cooking style emissions) | | | | 1.41 | | | | | | | 287 | 8.15 | 25.0 | 250 | |
| | Chinese restaurant (Cantonese cooking style emissions) | | | | 0.67 | | | | | | | 97.6 | 5.14 | 41.7 | 357 | |
| | Chinese restaurant (ambient concentrations) | | | | | | | | | | | 0.31 | 0.04 | 65.9 | 129 | |
| Bangladesh (Beghum et al. [50]) | Average of different kitchen environments | | | 0.60 | | | | | | | | | | | | |
| | Average of different Living room environments | | | 0.19 | | | | | | | | | | | | |
| Honduras (Clark et al. [51]) | Indoor with traditional stoves | | 13,100 | | 1.00 | | | | | | | | | | | |
| | Outdoor | | | | 0.36 | | | | | | | | | | | |
| | Indoor with improved stoves | | 1800 | | 0.27 | | | | | | | | | | | |
| | Outdoor | | | | 0.22 | | | | | | | | | | | |
| | Personal (using traditional stoves)[a] | | | | 0.14 | | | | | | | | | | | |
| | Personal (using improved stoves)[a] | | | | 0.07 | | | | | | | | | | | |

Table 2 (*Continued*)

| Country | Environment/ emission source | CO$_2$ (ppm) | CO (ppb) | PM$_{10}$ (ppb) | PM$_{2.5}$ (ppb) | HCHO (ppb) | THC (ppm) | Benzene (ppb) | Toluene (ppb) | Methyl Chloride (ppb) | Chloroform (ppb) | n-Fatty acids (ppm) | Dicarboxylic acids (ppm) | PAH (ppb) | n-Alkanes (ppb) | Total carbonyls (ppb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hongkong (Ho et al. [52]) | General Chinese Restaurant | | | | | | | | | | | | | | | |
| | Large | | | | | | | | | | | | | | | 831 |
| | Medium 1 | | | | | | | | | | | | | | | 96.6 |
| | Medium 2 | | | | | | | | | | | | | | | 277 |
| | Small | | | | | | | | | | | | | | | 289 |
| | Sinchuan Spicy Food Restaurant | | | | | | | | | | | | | | | 715 |
| | Hongkong style Fast food | | | | | | | | | | | | | | | 152 |
| | Demonstration Kitchen | | | | | | | | | | | | | | | |
| | Single dish 1 | | | | | | | | | | | | | | | 226 |
| | Single dish 2 | | | | | | | | | | | | | | | 81.8 |
| | Chinese barbeque kitchen | | | | | | | | | | | | | | | |
| | A | | | | | | | | | | | | | | | 179 |
| | B | | | | | | | | | | | | | | | 188 |
| | C | | | | | | | | | | | | | | | 414 |
| | Korean BBQ | | | | | | | | | | | | | | | 473 |
| | Western fast-food chain stops | | | | | | | | | | | | | | | |
| | A | | | | | | | | | | | | | | | 762 |
| | B | | | | | | | | | | | | | | | 350 |
| | Western small fast-food chain stops | | | | | | | | | | | | | | | |
| | A | | | | | | | | | | | | | | | 113 |
| | B | | | | | | | | | | | | | | | 149 |
| | Western restaurant | | | | | | | | | | | | | | | 160 |

[a] Honduras. Personal PM$_{2.5}$ was assessed by attaching the sampler to the participant's clothing nearest breathing zone and placing the pump in a pack worn around waist.

**Table 3**
Differences in pollutant emissions between different oil types under varying cooking conditions (mean: mg h$^{-1}$ L$^{-1}$).

| Order[a] | Oil type/treatments | Total akanals | Total alkenals (mg h$^{-1}$ L$^{-1}$) | Total alkadienals (mg h$^{-1}$ L$^{-1}$) | Total aldehydes (mg h$^{-1}$ L$^{-1}$) | Total oleic acid derivatives (mg h$^{-1}$ L$^{-1}$) | Total linoleic acid derivatives (mg h$^{-1}$ L$^{-1}$) | Total linolic acid derivatives (mg h$^{-1}$ L$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| 1 | Canola oil (heated at 180 °C for 15 h) | 24.7 | 33 | 50.5 | 108.1 | 46.3 | 26.5 | 34.3 |
| | Extra virgin olive oil (heated at 180 °C for 15 h) | 25.1 | 46.7 | 8.6 | 80.4 | 61.4 | 13.5 | 4.1 |
| | Olive oil (heated at 180 °C for 15 h) | 30.2 | 51 | 7.41 | 88.5 | 70.7 | 13.8 | 2.48 |
| | Canola oil (heated at 240 °C for 7 h) | 38.5 | 84.7 | 51.9 | 175 | 112 | 30.7 | 31.7 |
| | Extra virgin olive oil (heated at 240 °C for 7 h) | 64.5 | 124.3 | 7.09 | 195.9 | 171.1 | 18.8 | 2.73 |
| | olive oil (heated at 240 °C for 7 h) | 69.2 | 138.1 | 7.61 | 214.9 | 156.2 | 44 | 2.81 |
| 2 | Safflower oil heated at 210 °C for different intervals (h) | | | | | | | |
| | 0 | 317 | 653 | 28.7 | 999 | | | |
| | 1 | 408 | 947 | 48.1 | 1403 | | | |
| | 2 | 349 | 949 | 43.7 | 886 | | | |
| | 3 | 365 | 489 | 45.4 | 900 | | | |
| | 4 | 400 | 447 | 45 | 892 | | | |
| | 5 | 375 | 635 | 43.3 | 1053 | | | |
| | 6 | 369 | 611 | 42.4 | 1022 | | | |
| | Safflower oil heated for 6 h at different temperatures (°C) | | | | | | | |
| | 180 | 388 | 799 | 47.5 | 1235 | | | |
| | 210 | 369.36 | 611.1 | 42.4 | 1023 | | | |
| | 240 | 1658.5 | 969.2 | 25.2 | 2653 | | | |
| | 270 | 1371.4 | 1942.4 | 80.7 | 3395 | | | |
| 3 | Coconut oil heated for 6 h at different temperatures (°C) | | | | | | | |
| | 180 | 370.1 | 198.7 | 15.61 | 584 | | | |
| | 210 | 951.3 | 255.4 | 13.88 | 1221 | | | |
| | 240 | 1853.5 | 493 | 34.6 | 2381 | | | |
| | 270 | 3429.6 | 420.7 | 18.38 | 3869 | | | |
| 4 | Canola oil heated for 6 h at different temperatures (°C) | | | | | | | |
| | 180 | 303.07 | 304 | 110.7 | 718 | | | |
| | 210 | 335.4 | 607.6 | 158.2 | 1101 | | | |
| | 240 | 339.07 | 806.1 | 195.3 | 1340 | | | |
| | 270 | 1691.1 | 1549.1 | 419 | 3659 | | | |
| 5 | Extra virgin olive oil heated for 6 h at different temperatures (°C) | | | | | | | |
| | 180 | 481.1 | 310.8 | 27.3 | 819 | | | |
| | 210 | 855.6 | 939.1 | 162.5 | 1957 | | | |
| | 240 | 1288.8 | 1562.5 | 637.2 | 3489 | | | |
| | 270 | 1392.1 | 1699.7 | 736 | 3828 | | | |

[a] Source of the data: For order 1 (Fullana et al. [53]) and orders 2 through 5 (Katragadda et al. [54]).

In 2009, these estimates ranged from 70 (for coffee roasting) to 10,400 tonnes (animal feed production). The US EPA [26] estimated emissions from cooking beef and chicken by street vending cooking devices (charcoal grilling). It revealed that marinated meat resulted in higher pollutant emissions than non-marinated meat, while no significant differences exist in emission strengths between meat types. It was also pointed that charcoal did not contribute significantly to the pollutant emissions relative to the meat stuffs.

In order to acquire a broader understanding of the emission profile of different cooking activities, Roe et al. [27] developed a national emissions inventory for commercial cooking in the USA (Table 5). Apart from these examples, there are relatively few efforts to develop emission inventories of the range of cooking activities in domestic and commercial settings. As the extent and nature of cooking activities can vary considerably, there is a pressing need to establish emission inventories across a much wider range of geographies, cultures and cooking styles. Such efforts will help us assess both short and long-term health impacts of human exposure to cooking related pollution and accelerate the implementation of regulation to govern safe levels of emission (especially in commercial settings).

## 5. The level of cooking-related emission in relation to regulations and guidelines

To protect the public from the possible health effects of cooking emissions, various regulations and guidelines have been issued by various authorities (Table 6). The pollutants measured from cooking fuels and food smoke were compared based on the literature survey (Table 1). As health criteria for IAP are generally limited, this focuses on CO, BTX, and formaldehyde. Note that CO and xylene however did not exceed any of their regulations and guidelines (Table 6).

Kabir et al. [17] reported levels of toluene (625 μg m$^{-3}$) that exceeded the chronic-duration inhalation MRL (300 μg m$^{-3}$) and the EPA reference air concentration (400 μg m$^{-3}$). Their benzene data (315 μg m$^{-3}$) likewise exceeded the chronic (10 μg m$^{-3}$), intermediate (20 μg m$^{-3}$), and acute (30 μg m$^{-3}$)-duration inhalation MRLs set by ATSDR, and the 30 μg m$^{-3}$ reference air concentration set by EPA. Similarly, formaldehyde levels greatly exceeded the chronic, intermediate, and acute-duration inhalation MRL set by ATSDR, the REL (8-h TWA), and the 15-min ceiling limit set by NIOSH.

Aside from charcoal, other cooking fuels can yield considerable emissions. Khalequzzaman et al. [16] reported 17.2 μg m$^{-3}$ of

**Table 4**
Comparison of pollutant emissions between different food/cooking methods.

[A] Microwaving popcorn (Rosati et al. [55])

| Compound name | Concentration range in chamber (ng mL$^{-1}$) |
|---|---|
| Butyric acid | 0.1–8.6 |
| Diacetyl | 0.02–5.8 |
| Acetoin | 0.01–4.2 |
| Propylene glycol | 0.005–1.3 |
| 2-Nonanone | 0.005–1.4 |
| Triacetin | 0.01–1.2 |
| Acetic acid | 0.005–0.5 |
| 2-Butoxy-1-methyl-2-oxoethyl ester butanoic acid | 0.005–0.7 |
| p-Xylene | 0.01–0.4 |
| Pentanal | 0.01–0.02 |
| Toluene | 0.01–0.04 |
| Hexanal | 0.01–0.05 |
| 2-Methyl propanoic acid | 0.01–0.27 |
| 2-Octanone | 0.01–1.28 |
| Heptanal | 0.01–0.02 |
| Benzaldehyde | 0.01–0.02 |
| 2-(2-Hydroxypropoxy) 1-propanol | 0.01–0.5 |
| Acetophenone | 0.015–0.01 |
| Siloxanes | 0.01–0.03 |
| 2-Tridecanone | 0.01–0.16 |
| 3-Methyl butanal | 0.01–0.01 |
| 2-Methyl butanal | 0.01–0.03 |
| Furfural | 0.01–0.37 |
| 4-Methyl-3-penten-2-one | 0.01–1.20 |
| 2-Pentyl furan | 0.01–0.01 |
| 2-(2-Ethoxyethoxy) ethanol | 0.01–0.3 |
| 2-Ethyl 1-hexanol | 0.01–0.06 |
| 3-Hexanone | 0.01–0.17 |
| Ethyl ester butanoic acid | 0.01–0.05 |
| Butyl ester 2-propenoic acid | 0.01–0.04 |
| 2,3-Butanedioldiacetate | 0.01–0.33 |
| Cyclotetrasiloxane | 0.01–0.09 |
| Decamethyl cyclopentasiloxane | 0.01–0.02 |
| Octanoic acid | 0.01–0.16 |
| Dodecamethyl cyclohexasiloxane | 0.01–0.05 |
| Dodecamethyl pentasiloxane | 0.01–0.03 |
| Dihydro-5-pentyl-2(3H)-furanone | 0.01–0.08 |
| Octanal | 0.015–0.01 |
| Styrene | 0.01–0.02 |
| 1-Ethoxy-2-methyl propane | 0.01–0.02 |
| Methyl ester octanoic acid | 0.01–0.01 |
| Ethyl ester octanoic acid | 0.01–0.05 |
| Tridecane | 0.01–0.05 |
| 2-(Perfluorooctyl)ethanol 8:2-telomer | 0.0005–0.009 |

[B] Emission from combination of food and cooking style (all concentration in ppb: Kabir et al. [2])

| Compound | Steamed cabbage | Boiled clam | Brewed coffee | Fried cabbage | Grilled clam | Roasted coffee |
|---|---|---|---|---|---|---|
| Hydrogen sulfide | 0.86 | 0.2 | 0.2 | 0.2 | 39.6 | 2398 |
| Methane thiol | 0.15 | 0.15 | 13.5 | 63.8 | 0.15 | 2070 |
| Dimethyl sulfide | 9.44 | 0.26 | 16.9 | 25.6 | 31.3 | 98.7 |
| Dimethyl sulfide | 1.2 | 0.06 | 4.32 | 9.34 | 35.5 | 24.5 |
| Acetaldehyde | 12 | 18.7 | 153 | 12.5 | 253 | 5233 |
| Propionaldehyde | 0.39 | 2.81 | 31.8 | 5.4 | 8.65 | 366 |
| Butyraldehyde | 0.39 | 0.39 | 77.6 | 15.3 | 12.9 | 458 |
| Isovaleraldehyde | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 600 |
| Styrene | 0.37 | 0.31 | 0.36 | 0.07 | 0.2 | 8.36 |
| Toluene | 26.3 | 19.8 | 24 | 51.2 | 51.1 | 123 |
| para-xylene | 1.62 | 1.51 | 1.95 | 1.57 | 1.99 | 0.03 |
| Methylethyl ketone | 3.21 | 5.45 | 52.6 | 3.21 | 28.2 | 964 |
| Methylisobutylketone | 0.04 | 0.48 | 0.04 | 0.04 | 0.04 | 0.04 |
| Butylacetate | 0.44 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| Isobutylalcohol | 0.09 | 0.09 | 3.08 | 0.09 | 3.91 | 0.09 |
| Propionic acid | 2.27 | 2.5 | 5.84 | 4.39 | 36.1 | 695 |
| Butyric acid | 0.06 | 0.2 | 0.06 | 0.06 | 5.11 | 67 |
| Isovaleric acid | 3.46 | 5.75 | 15.9 | 0.05 | 1.97 | 132 |
| Valeraldehyde | 0.06 | 0.06 | 0.06 | 0.14 | 0.12 | 8.39 |

**Table 5**
Emission inventory of air pollutants released from different cooking activities.

[A] Emission factors considering a mass balance approach

| Cooking activity | Emission rate ($\mu g\,kg^{-1}$) | | | Reference |
|---|---|---|---|---|
| | Air pollutant category | Gas phase | Particle phase | |
| Meat charbroiling | Alkanes | 1,470,000 | | [23] |
| | Olefins | 2,450,000 | | |
| | Carbonyls | 5,480,000 | | |
| | Aromatics and napthenes | 200,000 | | |
| | Unidentified organic compounds | 4,590,000 | | |
| | Aliphatic aldehydes | | 260,000 | |
| | Ketones | | 220,000 | |
| | Alkanoic acids | | 480,000 | |
| | Alkenoic acids | | 320,000 | |
| | Unresolved mixture | | 1,300,000 | |
| Stir frying vegetables | Alkanes | 15.8 | 0.96 | [21] |
| | Saturated n-aldehydes | 138.6 | | |
| | Ketones | 12.9 | | |
| | n-Alkanoic acids | 25.2 | 4.9 | |
| | Others | 25.6 | 0.89 | |
| | Olefinic n-aldehydes | | 0.72 | |
| | n-Alkenoic acids | | 7.98 | |
| | Non-extractable organics | | 0.34 | |

[B] Total emission rate estimated for USA (based on Roe et al. [27]).

| Air pollutant category | Emission rate (tonnes $year^{-1}$) | | | | |
|---|---|---|---|---|---|
| | Conveyorized charbroiling | Under-fired charbroiling | Deep fat frying | Flat griddle frying | Clamshell griddle frying |
| VOCs | 2113 | 7234 | 1173 | 39 | 940 |
| PAHs | 43 | 122 | | 41 | |
| CO | 7401 | 23,662 | | 1941 | |
| PM$_{10}$ | 8460 | 60,304 | | 15,679 | 1073 |
| PM$_{2.5}$ | 8201 | 58,295 | | 11,916 | 909 |

formaldehyde from Bangladeshi cooking fuels which slightly exceeded its chronic-duration inhalation MRL ($10\,\mu g\,m^{-3}$). The same research team measured $13.7\,\mu g\,m^{-3}$ of benzene from natural gas which exceeded the $10\,\mu g\,m^{-3}$ chronic-duration inhalation MRL set by ATSDR. They also measured $54.2\,\mu g\,m^{-3}$ of benzene from biomass which exceeded the chronic, intermediate, and acute-duration inhalation MRLs and the reference air concentration set by the EPA. According to Qing [34], very high levels of $SO_2$ from natural gas ($185\,\mu g\,m^{-3}$) and coal ($436\,\mu g\,m^{-3}$) exceeded not only the acute-duration inhalation MRL ($30\,\mu g\,m^{-3}$) but the air quality guidelines of the WHO ($40$–$60\,\mu g\,m^{-3}$) and NAAQS ($80\,\mu g\,m^{-3}$). The $SO_2$ emission from coal ($436\,\mu g\,m^{-3}$) further exceeded the NAAQS (24-h exposure limit: $365\,\mu g\,m^{-3}$) of the EPA and 1-h exposure limit ($350\,\mu g\,m^{-3}$) set by the WHO. Its emission from biomass fuel ($61.5\,\mu g\,m^{-3}$) [35] also exceeded the acute-duration inhalation MRL ($40$–$60\,\mu g\,m^{-3}$) of the WHO. In addition, acrolein levels reported in Section 3 commonly exceeded many exposure guidelines. Its indoor concentrations ($26.4$–$64.5\,\mu g\,m^{-3}$) during cooking exceeded not only the inhalation reference concentration (RfC: $0.02\,\mu g\,m^{-3}$) of the EPA but also the intermediate ($0.09\,\mu g\,m^{-3}$) and acute-duration inhalation MRLs ($6.88\,\mu g\,m^{-3}$) [25].

Considering the frequent exceedance of the IAP due to cooking, one could easily extrapolate its effect on human health. In this regard, it is worth assessing the carcinogenic potentials of the pollutants discussed above. It should be noted that benzene is a known human carcinogen for all routes of exposure based on convincing evidence from both human and animal studies by IARC, EPA, and NTP. Furthermore, formaldehyde has been classified as a probable human carcinogen based on limited (human) and sufficient (animal) evidence [36]. As such, formaldehyde (and toluene) are regulated as hazardous air pollutants (HAPs) by the U.S. Congress [37] and are subject to the regulations for various manufacturing processes and operations [38]. However, as to the carcinogenicity, various regulatory agencies have not yet firmly assigned cancer classifications for xylene, toluene, CO, $SO_2$, and acrolein or assessed their carcinogenic potential due to inadequacy of data or evidence.

## 6. Health and environmental impacts of cooking activities

There is a line of evidence that cooking related emissions can cause severe health problems. For instance, Yang et al. [39] demonstrated that cooking fume is a major cause of lung cancer in Chinese women. Based on an epidemiological study, Yu et al. [40] also concluded that cumulative exposure to cooking emissions by means of any form of frying could increase the risk of lung cancer for non-smoking women in Hong Kong. Despite a low smoking rate, these subjects recorded one of the highest non-smoking lung cancer rates worldwide which was ascribed to cumulative exposure to cooking fume rather than to the peak concentrations experienced during cooking [40].

Furthermore the risk of active tuberculosis increased in Indians (aged 20 years and older) cooking with biomass fuel relative to cleaner fuels [41]. This estimate is comparable to the report made by WHO [42] based on non-clinical measures [43]. In addition, chronic exposure to biomass fuel combustion products was also suspected to cause chromosomal and DNA damage and upregulation of DNA repair mechanisms in premenopausal women in rural areas [44]. Evidence also indicates an etiological link between indoor coal burning and lung cancer. For instance, high lung cancer rates in Chinese women were closely associated with the combustion of smoky coal emitting submicron particles with mutagenic organics, especially aromatic and polar compounds [45].

There have been many attempts to estimate the global burden of disease due to the use of solid fuels by applying disease specific

**Table 6**

International and national regulations, advisories, and guidelines issued by various agencies and published by the Agency for Toxic Substances and Diseases Registry (ATSDR).[a]

| Agency | Description | Formaldehyde (Ref. [28]) (mg m$^{-3}$) | Benzene (Ref. [29]) (mg m$^{-3}$) | Toluene (Ref. [30]) (mg m$^{-3}$) |
|---|---|---|---|---|
| *International guidelines (Air)* | | | | |
| ATSDR | Acute-duration MRL | 0.05 | 0.03 | 3.8 |
| | Intermediate-duration MRL | 0.04 | 0.02 | |
| | Chronic-duration MRL | 0.01 | 0.01 | 0.3 |
| IARC | Cancer classification[b] | Group 2A | Group 1 | Group 3 |
| *National regulations and guidelines (Air)* | | | | |
| ACGIH | TLV – 8 h TWA | | 1.6[f] | 188 |
| | STEL | | 7.99[f] | |
| | Ceiling Limit for Occupation Exposure (TLV-STEL) | 0.37 | | |
| | Cancer classification[c] | | | A4 |
| EPA | Hazardous Air Pollutants | Yes | Yes | Yes |
| | Cancer classification[d] | B1 | A | D |
| | Inhalation reference concentration | | 0.03 | 0.4 |
| OSHA | PEL (8-h TWA) for general, construction, and shipyard industries | 0.92 | 3.19 | 754 |
| | 15-min STEL | 2.46 | | |
| | Acceptable ceiling concentration | | | 1130 |
| | Acceptable max. peak above the acceptable ceiling conc. for an 8-h shift for a max. duration of 10 min | | | 1884 |
| NIOSH | REL (8-h TWA) | 0.02 | | 377 |
| | REL (10-h TWA) | | 0.32[g] | |
| | REL (15-min ceiling) | 0.12 | | |
| | IDLH | 24.6 | 1597[g] | |
| | STEL | | 3.19[g] | 565 |
| NTP | Cancer classification[e] | B | A | |

| Agency | Description | SO$_2$ (Ref. [31]) (mg m$^{-3}$) | CO (Ref. [32]) (mg m$^{-3}$) | Acrolein (Ref. [33]) (mg m$^{-3}$) |
|---|---|---|---|---|
| *International guidelines* | | | | |
| ATSDR | Inhalation MRL | | | |
| |   Acute-duration | 0.03 | | 0.003 |
| |   Intermediate-duration | | | 4.0E−05 |
| | STEL (occupational exposure) | 10 | | |
| IARC | Cancer classification[b] | Group 3 | No data | Group 3 |
| WHO | Air quality guidelines | | | |
| |   10-min exposure limit | 0.5 | | |
| |   1-h exposure limit | 0.35 | | |
| |   24-h exposure limit | 0.10–0.15 | | |
| |   Annual arithmetic mean | 0.04–0.06 | | |
| | TWA based on effects other than cancer or odor/annoyance: | | | |
| |   15 min-TWA | | 100 | |
| |   30 min-TWA | | 60 | |
| |   1 h-TWA | | 30 | |
| |   8 h-TWA | | 10 | |
| *National regulations and guidelines (Air)* | | | | |
| ACGIH | TLV (TWA) | 5.2 | 29 | |
| | TLV (ceiling limit) | | | 0.23[f] |
| | Carcinogenicity classification[c] | | | A4 |
| EPA | Hazardous Air Pollutants | | No | Yes |
| | Cancer classification[d] | | No | ID |
| | Inhalation reference concentration | | No | 2.00E−05 |
| | National Ambient Air Quality Standards (NAAQS) | | | |
| |   24-h exposure limit | 0.365[h] | | |
| |   Annual arithmetic mean | 0.08 | | |
| |   3-h exposure limit | 1.3[h] | | |
| |   8-h averaging time | | 10[h] | |
| |   1-h averaging time | | 40[h] | |
| OSHA | PEL (8-h TWA) for general industry | 13 | 55 | 0.23 |
| NIOSH | REL TWA | 5 | | |
| | REL (10-h TWA) | | 40 | 0.23 |
| | IDLH | | 1375 | 4.59 |
| | STEL | 13 | | 0.69 |
| | Ceiling | | 229 | |
| NTP | Cancer classification[e] | | None | |

[a] *Definitions*: ACGIH = American Conference of Governmental Industrial Hygienists; EPA = Environmental Protection Agency; IARC = International Agency for Research on Cancer; IDLH = immediately dangerous to life or health; MRL = inhalation Minimum Risk Level; NIOSH = National Institute for Occupational Safety and Health; NTP = National Toxicology Program; OSHA = Occupational Safety and Health Administration; PEL = permissible exposure limit; REL = recommended exposure limit; STEL = short-term exposure limit; TLV = threshold limit values; TWA = time-weighted average; WHO = World Health Organization.

[b] IARC cancer classification: Group 1 (carcinogenic to humans); Group 2A (probable human carcinogen), Group 3 (Not classifiable as to carcinogenicity to humans).

[c] ACGIH cancer classifications: A4 (not classifiable as a human carcinogen).

[d] EPA cancer classification: A (known human carcinogen); B1 (probable human carcinogen); D (substances are unclassifiable as to their carcinogenicity); ID (data are inadequate for an assessment of the carcinogenic potential).

[e] NTP cancer classifications: A (substance known to be carcinogenic); B (reasonably anticipated to be a human carcinogen).

[f] Refers to the potential significant contribution to the overall exposure by the cutaneous route, including mucous membranes and the eyes, either by contact with vapors or, of probable greater significance, by direct skin contact with the substance.

[g] NIOSH potential occupational carcinogen.

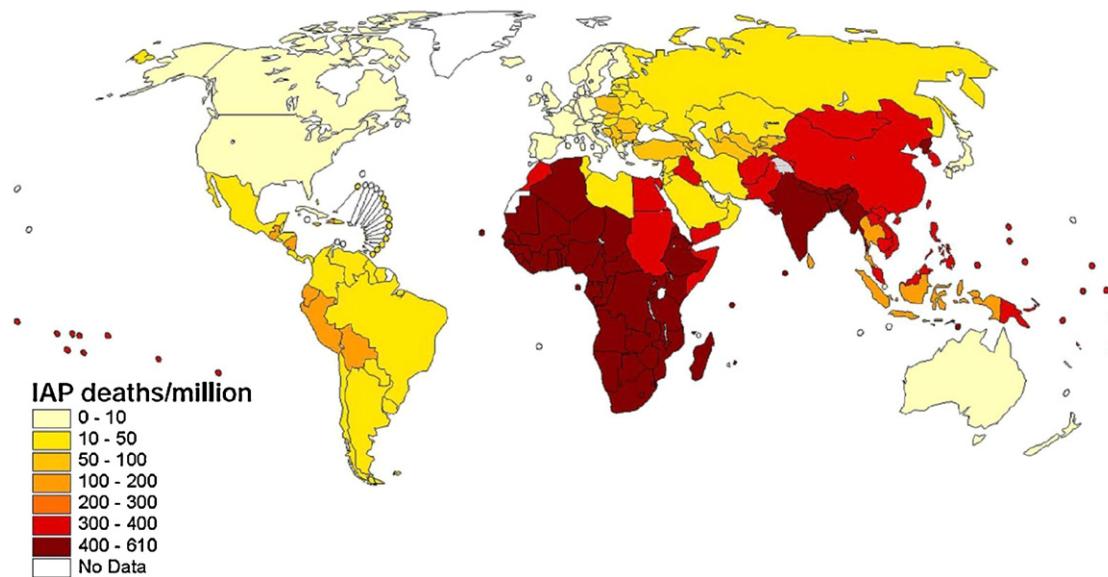[h] Not to be exceeded more than once per year.

**Fig. 1.** Global distribution estimates of deaths caused by indoor smoke from solid fuels by WHO sub-region for 2000.
Source: Ref. [47].

relative risks or odds ratios to global estimates of the household number relying on such fuels. IAP from solid fuel use and urban outdoor air pollution are in fact estimated to cover 3.1 million premature deaths worldwide every year and 3.2% of the global burden of disease expressed in disability-adjusted life years (DALYs) [46]. If this burden is evaluated on a regional basis, it varies significantly due to many contributing factors (Fig. 1). For instance, almost 80% of ill health effects occur in Africa and Southeast Asia. Globally, indoor smoke from solid fuels ranks as the eighth risk factor. This rises to fourth (after (1) childhood and maternal underweight, (2) unsafe sex, and (3) unsafe water, sanitation, and hygiene) in developing countries (∼40% of the world population) [47]. Indoor smoke risks present with a high mortality thus ranks higher than micronutrient deficiencies and tobacco risks. Hence, to minimize the exposure to cooking related emissions, efforts should be directed to improve cooking devices, development of alternate energy sources (such as sun light), living environments, and cooking behavior.

It is important to note that cooking emissions can also exert influences on climate change. For instance, solid fuel dependency exacerbates deforestation which indirectly contributes to the build-up of greenhouse gases (e.g., $CO_2$). Deforestation can also cause soil erosion, pollution of streams with sediment and debris, loss of biodiversity, and alteration of vector-borne disease transmission patterns [48]. Moreover, these emissions themselves contain a wide array of pollutants that can contribute to the global climate change.

## 7. Future directions

The results of our review confirm that a wide array of HAPs is released during food preparation using common solid fuels and the main materials (and ingredients) for cooking. The level of pollutants released via such activities can pose serious threats to human health, especially to those performing the cooking and their household members. The health effects of such exposure are not restricted to the respiratory tract but can readily cross the alveolar–capillary barrier to reach vital body organs through the circulatory system. It is thus important to monitor IAP in residential settings, restaurant kitchens, and dining areas. In addition, a better

understanding of the toxic effects of IAP is critical in establishing the safety of indoor air.

It is an interesting modern paradox that most legislation in developed countries governs the allowed concentration of HAPs in ambient outdoor air, and yet the citizens which this legislation is designed to protect spend the majority of their time in indoor locations, especially at home, where the concentrations of these regulated pollutants are often much higher. While it is unlikely that regulatory air quality legislation will ever penetrate the threshold of the domestic private home, it seems increasingly important to educate the public of the potential dangers of IAP so that they may take informed choices about their behaviors, and if desired install abatement and extraction technologies to improve their IAQ.

Despite the recognition of the potent role of cooking emission, it has scarcely been investigated in relation to possible human health impact. Most studies were directed to emission estimates for selected cooking procedures under certain conditions, while epidemiological studies are lacking for particular cooking procedures. Future research should thus be directed towards a comprehensive survey of the most common cooking procedures with respect to HAPs emission and their direct or indirect impacts on human health and the surrounding atmosphere.

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