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Pollutant emissions from biomass burning: A review on emission characteristics, environmental impacts, and research perspectives

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ABSTRACT

Biomass is one most abundant resource on the earth providing important energies in support of socioeconomic development in many areas. Burning of biomass fuels comprises to nearly 10% of the total energy from anthropogenic combustion processes; however, as the burning is usually incomplete, this process yields products of incomplete combustion posing consequently significant impacts on air quality, human health, and climate change. Here, we analyzed spatiotemporal characteristics in intentional and unintentional biomass burning from different sectors, discussed impacts of biomass burning emissions on indoor and outdoor air quality, and consequent influences on human health. The global total consumption amount of biomass including both natural and anthropogenic sources was approximately 7900 Tg in 2019, with significantly large regional and sectorial discrepancies among regions. Globally, anthropogenic biomass burning amounts increased gradually, but notably in some developing countries like China residential consumption of biomass fuels, as one large sector of biomass use, decreased over time. Uncommercial biomass consumption needs to be accurately quantified. There are relatively rich datasets of pollutant emission factors from biomass burning, including laboratory and field tests, but still large variations exit and contribute substantially to the uncertainty in emission inventory. Global primary $PM_{2.5}$, black carbon and organic carbon emissions from biomass burning were about 51, 4.6, and 29 Tg, respectively, contributing to nearly 70%, 55%, and 90% of the total emission from all sources, and emissions from the residential sector and open fires are major sources. Brown carbon emissions from biomass burning attracts growing interests but available studies adopted different methodologies challenging the comparability of those results. Biomass burning emissions polluted not only ambient air but more severely indoor air quality, adversely affecting human health. Future studies that should be emphasized and promoted are suggested.

1. Introduction

Biomass is derived from organic matter synthesized directly or indirectly by photosynthesis in green plants. It is one most abundant resource, with the majority on land (Slade et al., 2014); however, although biomass is rich on earth, only a small fraction has been effectively utilized by the human now. The global biomass potential including woody biomass, straw, energy crops, and other residues, is estimated to be about 100 EJ/year, being largely distributed in Asia, Africa, North America, and South America (Balat, 2009).

As one important energy source, the burning of biomass fuels contributes to approximately 10% of the total energy from solid fuels, but this percentage varies largely among different regions (WBA, 2021). In many developing countries or regions like tropical

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Africa and south Asia, there is still high reliance on traditional solid biomass for cooking and/or heating, while in some developed countries they are committed to the development of clean and renewable biofuels to react with environmental pollution and climate change issues (Balat et al., 2009; Li, Hu, Wang, et al., 2022). Despite of substantial contributions to the energy in support of socioeconomic development, traditional biomass fuels producing enormous air pollutants such as aerosols and volatile organic compounds (VOCs) during the incomplete burning process are associated serious indoor and outdoor air pollution, and subsequent health risks (Sun et al., 2019a; Tomlin et al., 2021; Zhang et al., 2021a). In fact, as one renewable energy, biomass has significant climate advantages. The carbon dioxide (CO_2) emissions from biomass burning could be reabsorbed in the regrowth process of vegetation, which is often known as carbon neutrality (Walker et al., 2010). Nevertheless, regional overuse of biomass may result in unsustainability and noticeable carbon emissions (Bailis et al., 2015; Jiang et al., 2022). The application of bioenergy and carbon capture and storage (BECCS) to mitigate greenhouse gases concentrates growing interests, and has been placed great expectations in mitigation scenarios in various integrated assessment models (IAMs) (Fuss et al., 2014; Fajardy et al., 2017). It is even warned that BECCS needs to be applied as early as possible for the maximum effect (Xu et al., 2022).

Nowadays, direct burning of biomass, intentionally or unintentionally, is still one important way in biomass consumption. Incomplete biomass burning is always accompanied by major air pollutant emissions. Those carbon-containing substances would have significant but different impacts on the ecosystem. In this study, by analyzing existing energy consumption and inventory data and synthesizing findings from over two hundred publications in literature, we firstly reviewed biomass burning amounts intentionally or unintentionally in different sectors and its spatiotemporal variation characteristics, discussed emission measurements and estimates of airborne emissions from biomass burning, and then summarized environmental and health impacts of air pollutants from the biomass burning. Finally, from a research perspective, we suggested some directions that should be emphasized and promoted in future studies.

2. Amounts of biomass burned intentionally or unintentionally

Biomass burning analyzed here includes open burning such as wildfires and field burning of agricultural wastes and grasses intentionally or unintentionally during the harvest season, and also those as energy sources in anthropogenic sectors like industry and residential households. According to the PKU-fuel database (http://inventory.pku.edu.cn/) which is developed from compiled data of national statistics, International Energy Agency (IEA) and Food and Agriculture Organization (FAO) database, and questionnaires surveys, the global consumption amount of biomass including both natural and anthropogenic sources was approximately 7900 Tg in 2019, with 54%, 3%, 26%, and 17% burned as wildfires, open straw burning, residential energy source, and others (including power plants, industry and transportation sectors), respectively. The consumption amounts and sectorial distribution of biomass vary expectedly in different regions (Fig. 1). Asia and Africa regions are the two continents with the highest biomass burning amounts, together accounting for 61% of the global total burning amount. In Africa, wildfires are significant, but in Asia, anthropogenic activities, particularly residential energy usage, play an important role in consuming biomass. In Oceania, almost all biomass burning derives from natural sources. The biomass consumptions are similar in Europe, North America, and South America, where, apart from natural sources, consumption in other anthropogenic sectors but not residential use contributed significantly.

Natural biomass burning amounts are large in countries like Australia, Russia, Democratic republic of Congo (Congo DR), Brazil, and Angola. The burning amounts from these countries made up to nearly half of the global total natural consumption. In these countries, wildfires accounted for 70–95% of the total biomass consumption, but the second-largest source of biomass use in each country is different. For instance, Brazil is significantly reliant on biomass fuel for power production and industrial energy supply, accounting for 84.2% of total anthropogenic biomass usage. Congo DR and Angola's biomass fuels are important residential energy source, while in Russia, agricultural burning amount is high. Anthropogenic biomass burning, being mostly utilized as biofuels, is significant in countries like India, Nigeria, China, United States and Brazil (from large to small). In fact, India is the country with the largest biomass consumption, in both anthropogenic use and the total consumption. Similar to India, the household use of biomass fuels accounts for the majority of the biomass utilization in Nigeria and China.

Over the past several decades, the global consumption amount of anthropogenic biomass burning as energy sources increased gradually. Open burning of agricultural wastes in field had an upward trend until the early 2000s, and then descended. Wildfires fluctuated over time without obvious changing trends observed. Historical changes of regional and sectorial shares of biomass burning expectedly varied. For example, in Asia, residential biomass consumption increased but then decreased, with a peak near the early 1990s, but the consumption in Africa was continuously increasing. Differently, the residential biomass consumption in Europe, North America and Oceania did not significantly change over time, but the consumption in other anthropogenic sectors increased and was already higher than the consumption in residential sector. For instance, in North America, the proportion of anthropogenic biomass consumed from domestic and other sectors changed from 51.6% to 6.0% in 1960, to 15.5% and 40.8% by 2019. Generally, residential biomass energy usage is expected to drop in the long run as the energy structure of developing nations shifts. However, because biomass is a renewable and carbon-free energy, its usage in power plants and industry may continuously grow. Meanwhile, climate change may result in more frequent forest fires, leading in a likely rising trend in open biomass burning (Daniau et al., 2012; Abatzoglou et al., 2016).

3. Pollutant emissions from biomass burning

3.1. Emission factor measurements

Incomplete burning of biomass yields various gaseous and particulate pollutants. There are some reviews on air pollutant emission factors (EFs) from open biomass burning (Akagi et al., 2011; Burling et al., 2011), and the burning as energy sources in sectors like residential use (Butt et al., 2016; Jetter et al., 2012; Mutlu et al., 2016; Oanh et al., 1999), summarizing emission factor data from literature studies, analyzing factors like fuel properties and burning conditions that can affect pollutant formations and emissions, and use of those emission factors in developing emission inventories and/or standards. Compilation of available EFs data from biomass burning is out of the scope of this short review, but main research processes and those desiring more foci are discussed.

With growing number of emission measurement studies on biomass burning, there are relatively rich EF datasets of some air pollutants such as CO, primary $PM_{2.5}$, black carbon (BC) and organic carbon (OC), but it still contributed largely to the overall uncertainty in emission inventory as, for example, there are numerous

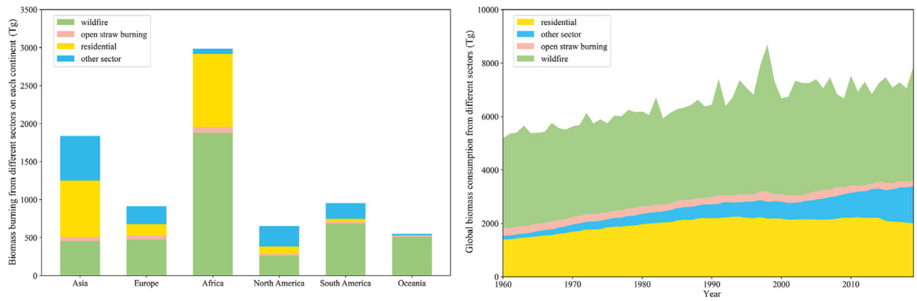

Fig. 1. Sectorial shares of biomass burned in different regions (left) and historical changes in the biomass use (right). Data are from the PKU-FUEL database, and available from the website.

different fuel-stove combinations in different burning conditions producing products of incomplete combustion (PICs) differently by several times. For some hazardous air pollutants such as ultrafine particles (UFPs) and trace toxic organics, their emission characteristics from biomass burning are not well understood yet (Shen et al., 2017; Cai et al., 2019). A few studies pointed out that for some advanced stoves or forced-draft stoves, the biomass burning may produce much more finer particles, e.g., those with diameter less than 30 nm, compared to the biomass burning in traditional or natural-draft stoves (Just et al., 2013; Wei et al., 2014; Zhang and Smith, 1999). Besides some highly concerned toxic and emerging pollutants, characterizing emission component profiles including typical major components like elemental carbon (EC, sometimes is considered to be equal to BC in value), metals, and water-soluble ions, is important in source apportionment and evaluation of biomass burning impacts. There are several programs aiming at a full characteristics of emission profiles for biomass burning, as well as fossil fuels in different sources.

Pollutant EFs or characterization of emission component profiles from biomass burning can be studied in laboratory simulation or real-world field tests (Bruns et al., 2015; Li et al., 2016, 2021a). For open biomass burning emissions, many were conducted in laboratory chambers (Ruiz-Garcia et al., 2018; Sun et al., 2018) and results were found to be generally close to the field testing when the combustion efficiency differences were considered (Dhammapala et al., 2006; Du et al., 2018). However, as the impacts of stoves are not considered, results from the biomass burning in chambers are not representative for residential biomass burning, no matter EFs are calculated based on the full capture method or the carbon-balance method. Consequently, more studies started to evaluate pollutant emissions for different fuel-stove combinations in laboratory or field conditions (Deng et al., 2018; Bhattacharya et al., 2002), and some studies pointed out that the field-based emission measurements provided results that were in line with the actual situation in real-world, thus, should be considered with priority in developing pollutant emission inventories (Bilsback et al., 2019). For many PICs, but not all, real-world emissions are found to be higher than those obtained from laboratory-based emission measurements, and moreover, the field-based results have higher variabilities (Coffey et al., 2017). Reasons for the observed differences between field and laboratory based EFs have not been well discovered, which was thought to be associated with the influence of factors like lower combustion efficiency, super-emitters in field, random and uncontrolled fire operation behaviors, and inefficient burning periods with high peaks that are not well simulated in laboratory (Bhattu et al., 2019; Roden et al., 2009; Sen et al., 2014; Shen et al., 2021). Combustion efficiency or modified combustion efficiency may only explain the observed difference partly (Du et al., 2018).

Laboratory-based emission studies are also easier to conduct, and in the early years provided valuable database for many air pollutant emissions from different fuel-stove combinations in developing countries. For instance, Zhang et al. (2000) tested emissions of CO, SO_2, NO_x, particle, and some VOC species which had been widely used in solid fuel combustion emission impacts in developing countries. Jetter et al. (2012) evaluated thermal performance and emissions of CO, $PM_{2.5}$, and UFPs for biomass cookstoves following the water boiling test protocol. Laboratory studies also have obvious advantages in evaluating influencing factors or potential ones from controlled orthogonal tests and studying pollutant formation mechanisms (Dhammapala et al., 2007). For instance, in a simulated kitchen, Shen et al. (2013a, 2013b) studied the differences in air pollutant emissions from the biomass burning under different biomass moisture levels, fuel feeding rates, and air supply conditions. Some laboratory-based pyrolysis or combustion experiments were conducted to evaluate the volatiles and soot from the fuel decomposition and burning, providing insights on pollutant formation mechanism knowledge and control countermeasures. Thus, it is expected that both laboratory and field-based measurements should be developed, considering their differential advantages and study objectives, and it is important to investigate discrepancies, if they exist, for the same fuel-stove combination under the same testing procedure, and the causes explaining differences from these two approaches.

3.2. Emission inventory development

With pollutant EFs and fuel consumption data, airborne emissions from incomplete biomass burning can be estimated at global, regional, and national scales. There are several widely used global or regional emission inventories of air pollutants from biomass and/or non-biomass burning sources (Bond et al., 2004; Luo, Han, et al., 2020; Shi et al., 2015). Some countries or agencies also have their own inventories of air pollutants from multiple sources in different sectors (Streets et al., 2003; Wu et al., 2021; Zhang et al., 2008). According to the PKU study, primary $PM_{2.5}$, black carbon (BC) and organic carbon (OC) emissions from biomass burning including both wildfires and anthropogenic biomass burning were 51 (42–66 as interquartile range), 4.6 (3.8–6.1), and 29 (24–39) Tg respectively, contributing to 70%, 55%, and 92% respectively, of the global total emissions from all sources. Biomass burning emission of CO was nearly half of the total, but for SO_2, it is expectedly very low at less than 5% (Ren et al., 2021). Globally, for most pollutants, biomass burning-associated emissions are largely from the residential emission and open fires. They account for more than 90% of the emissions from biomass burning in terms of major all pollutants apart from SO_2. BC emissions from residential biomass combustion can account for about half of the BC from biomass burning. But for other pollutants, open fires predominantly contribute to the biomass burning associated emissions.

For some climate-relevant components like BC and brown carbon (BrC), their emissions from incomplete biomass burning are highly concerned and studied in the last two decades (Pandey et al., 2020; Shen et al., 2019), but available estimates are still associated with relatively high uncertainties (Wang et al., 2012). Recently, Xu, Ren, et al. (2021) updated global estimates of BC and analyzed driving factors in its historical trend. The study showed that anthropogenic BC was 6.2 (4.8–8.3) Tg by 2017, and with the inclusion of randomly varied wildfire emissions, the amount was about 8.54 Tg in 2017. By 2017, residential biomass burning contributed to one-third of the total BC emission. Available studies on BrC emissions from biomass burning used different quantification or qualitative methods, of which results are hard to be comparable directly (Aung et al., 2016; Tian et al., 2019). Xiong et al. (2022) firstly developed a global inventory of brown carbon in aerosol from combustion sources, finding that wildfires contributed to nearly half of the total brown carbon in aerosol, following by the residential emission. High emissions were found in Africa, south and east Asia where wildfires and/or residential emissions were major emitters. Chemical components of airborne BrC are very complex and nowadays due to limitations in methodologies, instruments and knowledge gaps, it is nearly high challenged to fully characterize physiochemical properties of BrC in detail. Characterization of light absorption properties and spectroscopy characteristics might be an option in promoting better understanding of BrC in aerosols from the biomass burning, as well as in other sources and ambient air, and furthermore support the evaluation of climate impacts of carbonaceous aerosols.

There are notable spatial and sectoral disparities in pollutant emissions resulting from biomass burning on the global scale (Fig. 2). Tropical African regions have high air pollutant emissions from wildfires, while for anthropogenic biomass burning, pollution emissions are very high in Asia, particularly in the east and south regions. Countries such as India, China, Indonesia and Pakistan have high emission amounts. But in terms of emission densities, west Europe and tropical Africa had relatively high emission densities. For the per-capita emission, it is still countries such as Nigeria, Congo and Indonesia tropical Africa and Southeast Asia, and a few countries in Europe such as Finland Having high biomass burning emissions per-capita. In many developing countries, the residential sector is the largest anthropogenic biomass emission source, while in most developed countries, biofuels in power plant and industry account for the majority of anthropogenic sources. Meanwhile, the utilization of liquid biofuels is progressively expanding within the transportation sector, generating lower but unignorable emissions along major land and maritime routes. There are significant spatial variations in both emission amounts and sectorial contributions

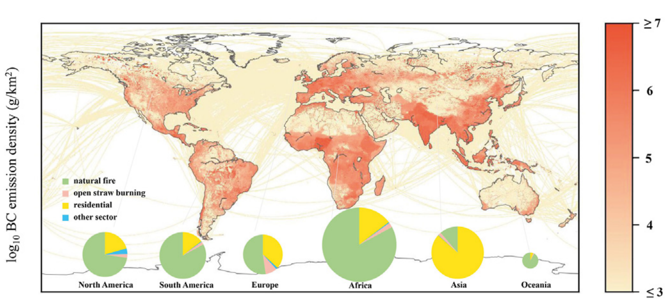

Fig. 2. Global estimates black carbon (BC) from biomass burning including natural and anthropogenic sources, and the sectorial distribution of BC emission in different regions.

within each region and country, for example, in China biomass burning emissions are mainly in rural areas and enrich in southwest and northeast areas where biomass resources are relatively abundant (Wu et al., 2020; Yun et al., 2020). The spatial characteristics may change over time due to different control countermeasures on field burning and transition speeds in household energy systems (Shen, Xing, et al., 2022; 2022b; Wu et al., 2020).

Generally, historical changes in global biomass burning emissions are basically consistent with biomass energy consumption, however, there are also differences noted in some pollutants and sectors due to control policies and technologies. For example, $PM_{2.5}$, BC and OC emissions from global anthropogenic biomass burning started to decline since the early 1990s. The trends are somewhat different among regions and countries. Anthropogenic biomass burning emissions in Asia are mainly contributed by those from China and India. Chinese biomass burning emissions decreased rapidly due to the energy transition after the early 1990s (Huang et al., 2015), which also dominated Asian emission trend. However, in India and many countries in Africa, pollutant emissions from biomass burning are showing increasing trends in the past few decades.

4. Biomass burning emission impacts on air quality

4.1. Contribution to outdoor air pollution

Biomass burning emissions obviously affect air quality (Pouliot et al., 2008; Vakkari et al., 2018). High levels of typical air pollutants like CO, levoglucosan, PMs and BC during the period of wildfires, prescribed burning and agricultural fires, are often observed in the place near the fire burning area but the nearby urban and residential areas due to air transport, with different degrees of changes in ambient concentrations of air pollutants (Hung et al., 2021; McClure & Jaffe, 2018; Schneider et al., 2021; Wang et al., 2007; Zhang et al., 2022). For instance, in 2010, the large-scale wildfires in the European part of Russia significantly affected air quality in Moscow characterized by high organic carbon to elemental carbon ratio, high ratios of levoglucosan in organic carbon, and accumulation of carbonyl compounds (Popovicheva et al., 2014), and the fires did also affect air quality in many surrounding areas (Diapouli et al., 2014; Portin et al., 2012). During the biomass burning period in September 2011 in Australia, it was reported that the average concentration of most air pollutants reached the highest level for the year and were nearly 10 times of the annual average (He et al., 2016). Atmospheric chemistry in open fire plumes is also of growing interests (Singh et al., 2020; Xu et al., 2021b). It was found that ozone production chemistry had rapid transition in chemical regimes and may be predicted as a function of VOCs and OH (Xu et al., 2021b). Impacts of biomass burning to ambient air pollution can be quantitatively estimated from tracer methods like K^+, acetonitrile, levoglucosan, and/or their ratios, but also typical source apportionment models such as receptor models and chemical transport models be coupled with emission inventories (Ballesteros-González et al., 2020). For instance, using the WRF-CMAQ (weather research and forecasting and community multi-scale air quality model), Pimonsree and Vongruang (2018) modelled biomass burning impacts on particles during a smog episode in March 2012, finding its contribution of nearly 90%. For the western US record-breaking wildfires in 2020, a CMAQ simulation estimated that its contribution to surface $PM_{2.5}$ in the contiguous US was about 25%, with larger contributions in the pacific coast and mountain regions (Li et al., 2021b).

Besides wildfires, open burning of agricultural straws in field and biomass burning in indoor stoves also significantly affect ambient air quality. These emission impacts have distinct spatiotemporal characteristics and historical trends compared to the natural wildfires, and distinct countermeasures and control policies are purposed or have been taken on anthropogenic biomass burning. Field burning of agricultural waste is predominate during or shortly after the harvest, resulting in high levels of multiple air pollutants that adversely affects human health and visibility (Rahman et al., 2020; Wang et al., 2020a). This usually occurs in rural areas, but the impacts are not limited to the rural region and rural population due to regional air transport (Bikkina et al., 2019; Mogno et al., 2021; Uranishi et al., 2019; Xu et al., 2018). For instance, by using the dual-carbon isotope fingerprints, it was found that large-scale open burning of post-harvest crop straw in the nearby rural area significantly affected air quality in Delhi during the winter and autumn (Bikkina et al., 2019). By using acetonitrile and levoglucosan as organic tracers, Wang et al. (2007) estimated that in October 2004, biomass burning contributed to 3.0–16.8% and 4.0–19.0% of ambient $PM_{2.5}$ in sub-urban and urban Guangzhou, respectively. One study estimated that in October 2014, open biomass burning contributions were as high as 50–60% in northeastern and southwestern China, while the relative contributions were lower in the northern, eastern and central regions (Kalluri et al., 2020). By using a global chemistry transport model simulation, Chan (2017) suggested that biomass burning contributed near 40% BC and 28% CO in Hong Kong during March 2014, and on an annual average, biomass burning contributed 12% and 16%, respectively, with strong impacts of emissions from the southeast Asian region. In some countries like China, a series of countermeasures has been effectively taken to control air pollution emissions from agricultural waste burning (Sun et al., 2019; Yang et al., 2020). Available studies confirmed significant improvements in ambient air quality during the agricultural crop straw burning period since 2012 when the local government took actions on open burning controls, though there were 2–3 years lag (Kalluri et al., 2020). It was estimated that the ban policy in 2018 reduced ambient $PM_{2.5}$ by 10–67% compared to that in 2015 in northeast China (Yang et al., 2020). Note that there are still debates on the burning ban policy as it is thought to be a preferable easy and inexpensive approach in dealing with large amounts of straws by farmers for centuries (Cheng et al., 2022; Usmani et al., 2020). Besides the burning ban policy, some areas started to think about transition policy of "legitimate burning" which opens a window for open burning, during which high levels of biomass burning tracers were unexpectedly observed (Cheng et al., 2022). So far, there are few studies on environmental outcomes and consequent impacts on human health of these transition policies, which should be assessed especially from not only short but long-term perspectives.

Different from significant peaks or very unusually high pollution from relatively ephemeral open fires, biomass burning as energy sources in anthropogenic sectors like the burning in residential stoves and industrial boilers has much smaller variations from day to day, though the seasonal differences may exist. Residential biomass burning is one major source of fine particles (Vicente and Alves, 2018; Wang et al., 2020b), as globally approximately 2.8 billion people heavily rely on traditional solid fuels for daily cooking and/or heating, but its emissions and consequent impacts are different in regions and study periods. A number of studies assessed contributions of residential biomass, or residential solid fuel use including both biomass and coals, on regional air quality (Zhang et al., 2021b). It was estimated that in 2010 globally ~12% ambient $PM_{2.5}$ were from household cooking activities burning biomass fuels, with a range of nearly zero in higher-income regions to 37% in southern Africa, and the contributions in east and south Asia were 10% and 26%, respectively (Chafe et al., 2014). The impacts of residential biomass burning on air quality are mostly concentrated in developing countries, and highly concerned in densely populated countries like India and China. With updated emission inventories and using atmospheric chemical transport models, household source contributions to ambient $PM_{2.5}$ in urban and rural India ranged from 10% to 27%, with the contributions to secondary organic portion of $PM_{2.5}$ at about 16–80% (Rooney et al., 2019). It was even assumed that ambient air quality in India may be achieved by eliminating pollutant emissions from the household sector (Chowdhury et al., 2019). In China, it was estimated that in winter 2013, space heating burning biomass and coals in residential stoves in peri-urban Beijing contributed to about two-fifths of hourly ambient $PM_{2.5}$ (Liao et al., 2017). Studies based on updated residential biomass and coal use information from field survey and questionnaires and regional chemical transport models estimated that nationally residential combustion emission contributed to about 15–20% of ambient $PM_{2.5}$ in China, with high relative contributions in the northeast and southwest regions and in cold seasons (Li et al., 2019; Shen et al., 2019; Yun et al., 2020).

4.2. Polluting indoor air quality

Biomass burning emissions affect ambient air quality, but moreover significantly and directly on indoor air. As most people spend long time indoors, indoor air exposure contributes largely to the total inhalation exposure (Luo, Zhang, et al., 2020; Smith et al., 2007; Tigala et al., 2018). By taking both indoor and outdoor exposure into consideration, the impacts of household biomass use would be significantly magnified from its sharing in the energy consumption, to air pollution and air pollution associated health outcomes (Yun et al., 2020). Indoor air pollution, or in some studies known as household air pollution, associated with daily use of solid fuels like biomass and coals has been recognized as be one top environmental risk factor causing millions of premature deaths every year (Epstein et al., 2013; Li, Jiang, et al., 2017; Sun et al., 2018, 2019b). Field measurements clearly demonstrated that indoor air pollutant concentrations could seriously exceed the limits being set to protect human health, for example the $PM_{2.5}$ mass concentrations may reach several hundred $\mu g/m^3$ in poorly vented settings burning solid fuels (Aquilina & Camilleri, 2022; Dai et al., 2018; Huang, Liu, et al., 2023). Even in households using clean modern energies like gas and electricity, due to the village contamination and neighborhood effect, the indoor $PM_{2.5}$ concentration and personal exposure level would be still above the WHO guideline (Du et al., 2018; Shupler et al., 2020). Direct contamination of indoor air from biomass burning is believed to be associated with the process of fugitive leakages of biomass burning in stoves (Du et al., 2021). This process has been recognized but not systematically studied resulting in large data and knowledge gaps in the indoor leakage fractions. Two laboratory-based experiments were carried out to quantify indoor fugitive leakages (Du et al., 2021; Ruiz-Garcia et al., 2018), however, this appeared to underestimate the fractions, for example the indoor leakage fractions of CO and $PM_{2.5}$ were less than 5%. Recently, Shen et al. (2020) developed a new method to quantify indoor fugitive leakages in field conditions, and results showed that the leakages could be as high as 20–40% for $PM_{2.5}$ during the burning of biomass or coals in residential stoves. Indoor leakages are important in better understanding of indoor air pollution and health impacts of indoor biomass burning, but available studies so far on indoor leakages are very rare, and more works are needed to build a basic database of indoor leakage fractions of major air pollutants, and to evaluate influencing factors across fuel-stove combinations and burning conditions.

5. Biomass burning emission impacts on health and climate change

PICs from biomass burning can significantly affect human health, with the impacts varying largely across regions and time (Adam et al., 2021; Lacey et al., 2017). For instance, it was estimated that in Africa, approximately 780,000 premature deaths annually were attributable to natural emissions, and 43,000 deaths were linked to biomass burning from the agricultural sector (Bauer et al., 2019). Biomass burning emissions in the fire season of 2019 in Brazil were estimated to cause 10% of all $PM_{2.5}$-related premature deaths in Brazil (Nawaz & Henze, 2020). In China, residential biomass burning caused comparable amounts of premature deaths associated with residential coal use (Yun et al., 2020), though these had distinct spatial distributions. Cooking with biomass fuels was found to be correlated with higher risks of cognitive impairment and cognitive decline (Deng et al., 2021).

Transition to modern energies can have significant health benefits. In China, from 1992 to 2012, the spontaneous clean transition in rural area resulted in less biomass use and avoided nearly 130,000 premature deaths after accounting for population growth, aging and mortality rate changes (Shen et al., 2019). Transition to gas fuels for residential use in India can reduce ambient $PM_{2.5}$ by 25% and preventing 34,800 premature deaths and one-quarter of the healthy life lost due to $PM_{2.5}$ (Conibear et al., 2020). As mentioned above, there have been rapid changes in biomass use in many regions and countries, thus it is interesting and important to characterize consequent health outcomes or benefits resulting from these changes. Adverse health outcomes associated with biomass burning emissions are not only from primary $PM_{2.5}$ or its precursors, but hazardous toxic organics like polycyclic aromatic hydrocarbons (PAHs) and its derivatives which are carcinogenic and largely from incomplete burning of carbon-fuels (Ravindra et al., 2008). Though epidemiology studies showed significant associations between adverse health outcomes and biomass use or pollutants from biomass burning emissions, the mechanisms are not well understood yet (Adam et al., 2021; Pardo et al., 2020). One study found that biomass burning samples from the Brazilian Amazon had comparable oxidative potential but higher levels of reactive oxygen and nitrogen species compared to samples collected from Atlanta and laboratory-generated secondary aerosols (Tuet et al., 2019). The reactive oxidative species (ROS) generation and cell viability in human lung cell lines of particles from residential biomass burning was found to be higher than from other sources like power plants and diesel vehicle exhausts (Jin et al., 2016; Wu et al., 2022). The toxicology of biomass burning emissions would change under the atmospheric processing (Wong et al., 2019). While some mechanisms have been purposed, the complex processes need more evidences to a solid conclusion.

As some carbon-containing compounds are also climate-relevant, biomass burning emissions also contribute unignorably to climate forcing (Hamilton et al., 2018; Liu et al., 2020; Mallet et al., 2020), besides those associated with land use change during biomass growth and harvest. Biomass burning is an important source of atmospheric iron causing direct radiative forcing associated with magnetite (Matsui et al., 2018; Moteki et al., 2017). Biomass smoke from the southern Africa was showed to enhance the brightness of stratocumulus over the southeastern Atlantic Ocean (Lu et al., 2018). Biomass burning may also produce ice-active minerals in the bottom ash and emitted particles, posing ice-nucleation activities high enough to be related to clouds (Jahn et al., 2020). One recent study showed that the air pollution resulting from the extensive Australian wildfires in 2019–2020 resulted in a strong negative aerosol radiative forcing of -14.8 to -17.7 W/m^2, decreasing surface temperature by 3.7–4.4 °C, that was nearly a same order of magnitude as the radiative cooling from volcanic eruptions (Chang et al., 2021).

Though in many cases biomass fuels are considered to be carbon neutral (Somerville 2006) and low in SO_2 emissions (Ren et al., 2021), by taking other climate forcers such as CH_4, BC, and OC into the consideration, air pollutant emissions from biomass burning had non-ignorable impacts on climate change (Haywood & Boucher, 2000; Jiang et al., 2022; Yang et al., 2021). It was estimated that the radiative forcing attributed to emissions from biomass and fossil fuel combustions were 68.2 ± 36.8 and 849 ± 225 mW/m^2, respectively (Jiang et al., 2022). In evaluating climate impacts of air pollutants emitted from the biomass burning, there are grown concerns on many short-lived climate forcers like NO_x, BC and also BrC, as a part of the organic carbon in aerosol but has light absorption ability at short wavelengths. When BC deposited on the surface of snow/ice, it can darken the snow/ice surface, affect the energy balance due to its light absorption properties, and further lead to acceleration of the melting of the cryosphere (e.g., glaciers, snow cover, and sea ice) (Kang et al., 2020). A recent study illustrated that BrC from biomass burning imposes strong circum-Arctic warming (Yue et al., 2022). Biomass burning might be a major source of BrC, however, as mentioned above, inventories of brown carbon at either global or regional scales are limited. Available estimates are rough from simple assumptions and have much high uncertainties (Liu et al., 2015; Washenfelder et al., 2015; Yan et al., 2017). Assessing climate impacts of biomass burning is complex and challenged as this involves not only emissions of various air compounds influencing radiative forcing directly or indirectly, but also changes in the land use that needs to be considered using approaches like a life-cycle analysis.

6. Mitigation potentials of anthropogenic burning emissions

For anthropogenic biomass burning emissions, especially those in the residential sector, improved stoves and biomass pellets are thought to be practical approaches that may mitigate air pollutant emissions from the incomplete burning processes. Stove upgrading and clean fuels can reduce pollutant emissions obviously. In many countries, improved stoves are deployed to replace traditional ones, though the technologies of these so-called improved stoves are not identical. Biomass burning in forced-draft stoves, gasifier or semi-gasifier stoves generally has lower emissions of many, but not all, air pollutants compared to the burning in traditional or natural-draft stoves (Shen et al., 2021). Urmee and Gyamfi (2014) reviewed improved cookstove technologies and available programs finding that the success of intervention programs depended on factors like compatibility of technical parameters of stoves with social expectations, consistency with local needs and culture, attitude of the users, and the stove cost. Recent developments and studies on improved biomass stoves were reviewed by Memon et al. (2020). Field campaigns were carried out to synchronously evaluate pollutant emissions, indoor air quality, personal exposure and health impacts in adopting improved stoves (Dickinson et al., 2015). For example, the stove projects in Peru found significant reductions in kitchen CO and $PM_{2.5}$ after the installation of new wood stoves, also reductions in personal exposure, and the urinary hydroplaned PAHs metabolites were reduced by 19–52% (Li et al., 2011). There were some studies finding insignificant changes in either indoor air quality or the health benefits, which may be due to complex situation like stacked use, behavior changes, and interaction of other influencing factors in field conditions (Abdo et al., 2021; Ezzati et al., 2017; Mortimer et al., 2017; Ochieng et al., 2013; Piedrahita et al., 2016; Shen, Xing, et al., 2022; Smith-Sivertsen et al., 2009). In some conditions, improved stoves are fueled with new fuels like briquettes or pelletized biomass, expectedly hoping to more reductions in air pollutant emissions.

Raw biomass fuels can be transformed into solid, gaseous, liquid ones, or other value-added products. Densified biomass fuel is one popular biomass conversion technology that is storable, transportable and low-cost with the simple operation (Bajwa et al., 2018). Pelletized biomass fuels have obvious advantages over traditional biomass fuels such as higher densities and uniform dimensions, and some wood pellets have lower ash contents but higher calorific values that are favorable in fuel burning. To achieve the target of co-reductions in CO_2 and air pollutants, and the goal of renewable energy development, many countries are sharply minimizing unorganized burning of biomass waste and vigorously developing densified solid biofuel (Angulo-Mosquera et al., 2021). The potential production of densified biomass fuel in China is estimated to be equal to 460 million ton standard coal (Yan et al., 2017). According to the fuel shape, densified biomass fuel can be divided into briquette (square section of 30×30 mm^2 and length of 30–80 mm), pellet (cylinder with the diameter of 5–12 mm and length of 10–30 mm), and rod (hexagonal cross-section type with the diameter of 50–60 mm, length of 500 mm and a 20 mm central-through hole) ones (Zhou et al., 2016). According to the feedstock type, densified biomass fuel can be divided into woody biomass and non-woody biomass (such as agricultural straw, shell, and husk) (Bajwa et al., 2018). The volume of densified biomass fuel is about 1/7 of raw biomass, and its energy density is equal to intermediate soft coal (Dumroese et al., 2011). Compare to raw biomass, the combustion efficiency of densified biomass fuel is increased by 20% (Gunukula et al., 2019). Its greenhouse gases emission is 1/9 (Tahir et al., 2010) and NO_X emission is 1/5–1/10 of coal burning as well as almost zero SO_2 emission (Chen et al., 2015). Laboratory emission measurements observed significantly lower emissions of air pollutants for biomass pellets compared to raw biomass (Chen et al., 2016; Shen, Tao, et al., 2012; 2017b; Zhang et al., 2014). But it is worthy to note that field emissions would be different from those observed in laboratory conditions, and not all air pollutants would be lower than the emissions from the raw biomass burning, for example, a study showed that PAHs and oxygenated PAHs emission reductions were not significant for pellets burned in a modern burner compared to the biomass burning in a brick stove (Shen, Wei, et al., 2012). Partly due to higher combustion temperatures and enhanced flaming conditions, particles would be finer and the fractions of very fine particles like those below 30 nm would be higher although the total number concentrations of ultrafine particles were lower (Just et al., 2013; Shen, Gaddam, et al., 2017). Biomass pellets have been widely used in boilers and heating stoves in many European areas. One estimate showed that more than 60% reductions in fine organic aerosol during the winter and 30–50% EC reduction in large parts of Europe were possible by replacing the current residential wood combustion technologies with pellet stoves (Fountoukis et al., 2014). In China, nowadays biomass pellets are only available in several pilot programs and the large-scale utilization of this did not occur yet, which is associated with concerns on stove change, accessibility and affordability of biomass pellets. Toxicity of emission smokes would be different in pellet burning emissions compared to the uncompressed fuels, resulting from changes in physiochemical components of the emissions. All these should be concerned, evaluated and assessed before large-scale deployments of pellets and improved biomass stoves were carried out.

There are high interests on the co-firing of biomass and coals. Coals play a significant role in industrial production, power generation and citizen life. Nearly 40% of electricity is generated by coal combustion (IEA, 2016). However, coal burning emits a large quantity of pollutants and CO_2, which is a great obstacle to achieving low-carbon goal. Biomass, as a carbon-neutral fuel or partly neutral, is renewable, relatively clean and easily available. Partial substitution of coal by biomass may reduce pollutants emissions, fulfill low-carbon goal, and achieve energy demands, which is a good way to achieve sustainable development goal. Co-firing of biomass and coal has been adopted in some power plants in many developed countries and also some developing countries like China (Roni et al., 2017). Co-burning technologies can be divided into three categories: (1) direct mixed combustion; (2) indirect mixed combustion; and (3) parallel mixed combustion (Agbor et al., 2014). Direct mixed combustion refers to that pretreated biomass is directly mixed with pulverized coal into the boiler for combustion. Indirect coupled combustion uses biomass gas being produced from the biomass gasification to the boiler and then mixed with pulverized coal for combustion. Parallel coupled combustion is that biomass and coal burn in separate boilers, and produce steam separately to generate power using a turbine. Besides industrial use, it recently receives interests in the residential sector by co-firing or mixed coal-biomass briquetting fuels (Li, Hu, Hao, et al., 2022; Qi et al., 2017), but such studies are very rare at this stage.

Biomass fuels have distinct characteristics of elements and proximate analysis compared to coals, like higher volatile matter contents and lower calorific values, lower ignition temperature and burnout temperature (Sami et al., 2001; Sharma et al., 2021). Fuel burning processes includes water evaporation phase, volatile matters devolatilization and combustion phase, and fixed carbon combustion phase. Because of different physical and chemical properties, synergistic effects of mixed burning of coal and biomass can change combustion and emission performance (Wu et al., 2013). Biomass combustion releases more heats during volatile matters devolatilization and combustion phases compared to the fixed carbon combustion phase, while coal combustion releases heat mostly during the fixed carbon combustion period. When these two are mixed, the heats form earlier volatile matter devolatilization and combustion of biomass fuels can accelerate volatile matters devolatilization and combustion of coal to improve combustion performance. Available studies on co-firing of biomass and coals mostly focused on thermogravimetric analysis, combustion characteristics, kinetics analysis, and emissions (Fei et al., 2021; Qi et al., 2017; Sahu et al., 2014). As seen from the kinetics analysis, partial substitution of coal with biomass improves combustion reactivity by lowering activation energy and the catalytic effect of inorganic elements and the porous structure of biomass char (Sahu et al., 2014; Wang et al., 2009; Ye et al., 2022). The co-burning can improve thermal efficiencies and combustion efficiencies producing less SO_2 and NO_x based on delivered energy due to low sulfur and nitrogen contents with the increase of biomass ratio within a proper blend ratio range (Qi et al., 2017; Guo et al., 2021). However, the mixed burning may increase heavy metals (e.g. arsenic, cadmium, arsenic and lead) emissions (Sharma et al., 2021). The combustion performance and the emission performance are influenced by factors like fuel physicochemical properties, blend ratio, combustion temperature, oxygen concentration and additives (Sharma et al., 2021). Some studies conducted life cycle assessment (LCA) to assess the environmental loads and economic benefits of mixed burning of coal and biomass from raw material production/processing, raw material transportation, energy conversion, product transport/processing, and end use (Beagle & Belmont, 2019; Chen et al., 2020; Yang et al., 2019). For instance, it was calculated that in China, 20% biomass co-firing with coal reduced the environmental loads, including global warming potential, acidification potential, creation of photochemical ozone potential, human toxicity potential, and soot potential, by 15%, but had a longer dynamic payback period and lower internal rate of return compared with the coal-fired plants (Chen et al., 2020). But there are also some obvious shortcomings like alkali-induced and silicate melt-induced slagging, agglomeration, corrosion, high fuel cost and low boiler efficiency (Niu et al., 2016; Xu et al., 2020) that should be evaluated in the co-firing approach. In addition, as noted co-burning of biomass and coals in residential stoves are rarely evaluated yet and worthy to be elucidated (Bahargul et al., 2020; Zhou et al., 2018; Li, Hu, Hao, et al., 2022).

7. Perspectives in research

7.1. Improve estimates on open burning fires

Knowledge on the absolute amounts of biomass burned and relative distributions in different sectors and regions are the basis of researches and countermeasures on biomass combustion emissions, however, available information are often associated with high uncertainties as many biomass fuels burned are non-commercial and usually estimated indirectly. For open burning of agricultural wastes, the amounts of biomass fuels, mainly straws of different plants, are usually estimated from the grain production, grain-straw ratio, and fractions burned in field, of which many parameter values were from field observation or default assumptions (Li, Hu, et al., 2017; Peng et al., 2016). In recognizing relatively high uncertainties of this approach, a few studies estimated field burning biomass from the burning areas and fire points based on the satellite observation (Shon., 2015). This is believed to be relatively accurate and has been widely applied in growing number of studies on open biomass burning (Duncan et al., 2003; Howard et al., 2014; Verhegghen et al., 2016). Mao et al. (2016) analyzed research progress on estimating biomass burning emissions based on satellite observation, and suggested that though satellite observation-based studies had developed very fast, there were high uncertainties in these estimates due to factors like random and scattered distribution of biomass burning events and limitation in the spatiotemporal resolution of satellite information. Recently, Wooster et al. (2021) summarized history of active fire remote sensing, reviewed characteristics and applications of technologies deployed, and suggested that future works should focus on active fire detection algorithms and database, development of Earth observation sensors and mission, a better understanding of errors and uncertainties, products and observational effects, etc.

7.2. Data gaps and biases in residential biomass use

Besides open burning, large amounts of biomass fuels are consumed in residential stoves, but this large sector has relatively high uncertainties in the mass of biomass fuels burned. In many developing countries and some regions in developed countries, traditional biomass fuels like crop straws and woody materials are still used for daily cooking and/or heating. The global estimate of population using traditional solid fuels was about 2.8 billion, and changed slightly over time though more proportions of people having access to modern clean energies (Carter et al., 2020; Stone et al., 2021). As most biomass fuels burned in households are non-commercial and lack of reliable statistics on its consumption, some studies estimated residential consumption amounts indirectly from the straw yields and assumed ratios. Fuel-weighting campaigns were carried out to get daily fuel consumption (Lam et al., 2017), however, such programs, including a few initially funded by the carbon trading programs, are very limited. To obtain household energy consumption structure, questionnaire surveys were often taken and some national household survey projects were available. Most surveys often asked primary energy used, ignoring the pervasive stacking phenomena, while more studies highlighted multiple energy use due to factors like different household demands, access and affordability to modern energies, inability of a single energy to meet all needs, stove upgrading, awareness of energy saving and environmental protection, etc. (Guta, 2014; Ravindra et al., 2019; Shen, Xing, et al., 2022). Multiple use, or known as stacking, results in high uncertainties or even biases in the results from the single energy survey, but also seriously affect accurate estimation and evaluation of clean interventions (Shankar et al., 2020). In response to this bottleneck, efforts have been made by considering secondary or third energy sources in the survey (Pullinger et al., 2021), or asking the time-sharing fractions of all possible energy sources (Shen, Xiong, et al., 2022; Tao et al., 2018; Zhu et al., 2019). The latter new approach has been successfully used in some national-scale surveys in China, finding that the previous studies overestimated the use of biomass significantly in rural China (Tao et al., 2018), and revealing substantial uptakes of clean modern energies in rural households towards universal access to affordable modern energy and sustainable development (Shen, Xing, et al., 2022; 2022b). The World Health Organization also led some household surveys in some pilot countries or regions using a newly designed questionnaire taking multiple energy use into consideration. However, results from these new approaches are still limited and should be promoted in future in a better understanding of household biomass, as well as non-biomass fuel, use and its rapid changes under the socioeconomical development, particularly in densely populated developing countries.

7.3. Highly and spatiotemporally resolved CO_2 and pollutant emission inventories

Most emission inventories so far do generally capture spatiotemporal characteristics of criteria air pollutant emissions from biomass burning, and these inventories have been further applied in air quality modelling, impact assessment, development and evaluation of control policies. Temporal and spatial resolutions of these inventories are critical. Highly resolved inventories are more critical in assessing population exposure and impacts on human health of the emissions. Future efforts should focus on development and improvement of emission inventories from biomass burning at higher temporal and spatial resolutions, and with lower uncertainties based on more reliable EFs and accurate information on energy consumption activities. Identification of drivers in biomass burning emission changes is important, but not well studied yet. Owing to fast changes in socioeconomic conditions, utilization, suspension and abandonment of traditional solid biomass fuels, as well as consequent pollutant emissions change very rapidly, especially in some fast-developing countries. Thus, inventories should be updated timely, which is not an easy task. This should include CO_2, and air pollutants including but not limited to CO, NOx, VOCs, BC, etc. Aa mentioned though many studies assume the equivalence of CO_2 emissions from biomass burning and carbon sinks resulting from reabsorption during biomass regrowth, that is carbon-neutral, the unsustainability of regional biomass sources and temporal disparities in emissions and absorption may result in net CO_2 emissions (Bailis et al., 2015; Sterman et al., 2018). Besides climate impacts, some studies have highlighted concerns on adverse health outcomes owing to high CO_2 exposure, especially in indoor environments from combustion sources (Azuma et al., 2018; Jacobson et al., 2019; Li et al., 2021c).

7.4. Comprehensive evaluation of impacts on air quality, human health and climate

Impacts of biomass burning, as either wildfires, field burning of agricultural wastes, or the burning in indoor stoves, on regional air quality, human health and climate have obvious spatiotemporal variations, and distinct historical trends. For instance, while reduced emissions and improved regional air quality associated with Amazonian deforestation rates and biomass burning activity, recent studies pointed out that in the Cercado region, the fire burning increased and the surface ozone was increasing, that partly offset the air quality benefits (Pope et al., 2020). A recent study found that in China high emission spots of biomass burning emissions moved from the southwest to north under the unbalanced socioeconomic development and regional differences in biomass burning control countermeasures (Wu et al., 2020). While emissions and impacts of biomass burning, either at the global, regional, or local scales, have been assessed in many past studies, the evaluation is complex. Besides hundreds of air pollutants having distinct fates and health/climate impacts, interaction and feedback effect between BC emissions from wildfire emissions and meteorological conditions is one example increasing the complexity of biomass emission evaluation (Huang, Ding, et al., 2023). More works are needed to promote a systematic comprehensive understanding, which include accurate basic databases of biomass consumption and pollutant emissions with lower uncertainties and higher spatiotemporal resolutions, especially those in real-world conditions; apportionment of major air pollutants and relative contributions of biomass burning in different sectors; source-oriented health and climate impact assessment of biomass burning; evaluation of historical changes and future prediction of biomass burning emissions and its impacts on ecosystem including air quality, human health and climate change; scientific evidences in support of strategies and policies to control biomass burning emissions.

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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