ADVANCING EARTH AND SPACE SCIENCES

GeoHealth

RESEARCH ARTICLE
10.1029/2024GH001130

Long-Term Impacts of Global Solid Biofuel Emissions on Ambient Air Quality and Human Health for 2000–2019

Debatosh B. Partha[1,2], Ying Xiong[1,3], Noah Prime[4], Steven J. Smith[4], and Yaoxian Huang[1]

[1]Department of Civil and Environmental Engineering, Wayne State University, Detroit, MI, USA, [2]Now at Department of Earth, Environmental and Planetary Sciences, Northwestern University, Evanston, IL, USA, [3]Now at Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, USA, [4]Pacific Northwest National Laboratory, Joint Global Change Research Institute, College Park, MD, USA

Key Points:

- Global solid biofuel emissions increased up to 23.61 μg/m^3 $PM_{2.5}$ and 13.69 ppbv O_3 concentrations during 2000–2019
- An annual total of 1.11–1.43 million deaths occurred globally associated with solid biofuel-attributable $PM_{2.5}$ and O_3 exposure
- Reduced solid biofuel usage in households may have the potential to improve global air quality and health co-benefits

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

Y. Huang,
yaoxian.huang@wayne.edu

Citation:

Partha, D. B., Xiong, Y., Prime, N., Smith, S. J., & Huang, Y. (2025). Long-term impacts of global solid biofuel emissions on ambient air quality and human health for 2000–2019. *GeoHealth*, *9*, e2024GH001130. https://doi.org/10.1029/2024GH001130

Received 12 JUN 2024
Accepted 5 FEB 2025

Author Contributions:

Conceptualization: Yaoxian Huang
Data curation: Debatosh B. Partha
Formal analysis: Debatosh B. Partha
Investigation: Debatosh B. Partha
Methodology: Debatosh B. Partha, Ying Xiong, Yaoxian Huang
Resources: Yaoxian Huang
Software: Debatosh B. Partha, Ying Xiong, Yaoxian Huang
Supervision: Yaoxian Huang
Validation: Ying Xiong
Visualization: Debatosh B. Partha

Abstract Globally, solid biofuels (SB) have been widely used for household cooking and energy production for decades due to electricity shortages and socio-economic barriers to adopting renewable energy alternatives. This has detrimental effects on air quality, human health, and climate through trace gas and aerosol emissions. Despite numerous studies, the long-term consequences of SB emissions remain poorly understood. Here, we use the Community Earth System Model and the Community Emissions Data System emission inventory to investigate the SB emission impacts on air quality and human health for 2000–2019. Global SB emission increased the ambient $PM_{2.5}$ (particulate matter with aerodynamic diameters ≤2.5 μm) and ozone (O_3) concentrations up to 23.61 μg/m^3 and 13.69 ppbv, with significant effects found in India, China, and the Rest of Asia (ROA). Our study estimates total annual premature deaths (APDs) associated with global SB-attributable $PM_{2.5}$ and O_3 exposure as 1.11 million [95% confidence interval (95% CI): 1.00–1.22 million] in 2000 up to 1.43 million (95% CI: 1.30–1.56 million) in 2019. China's SB emissions and associated APDs have reduced substantially, whereas India and ROA had a major leap in both estimates in 2019 compared to 2000. China's progress in cutting residential SB emissions accounts for its improvements. Our study urges the reduction of SB usage and emissions to potentially improve overall air quality and human health conditions, especially in highly populated, low- and middle-income countries, where the poor air quality and associated health burden attributable to SB emissions are estimated to be higher.

Plain Language Summary Long-term solid biofuel emissions from residential, commercial, energy, and industrial sectors, adversely impact ambient air quality related to particulate matter and ozone, causing substantial negative health impacts on both global and regional scales. We employed a global chemistry-climate model in this study to understand the long-term impacts of global solid biofuel emissions on ambient air quality and human health during 2000–2019. We found that solid biofuel emissions have significant impacts on ambient air quality, increasing the levels of fine particulate and surface ozone, with major impacts found over Asia (e.g., China and India), central Europe, and sub-Saharan Africa. This translates to substantial human health impacts, with an annual total of 1.11–1.43 million premature deaths associated with solid biofuel emissions for 2000–2019. Our study highlights the significant benefits of the mitigation of solid biofuel emissions for air quality and human health.

1. Introduction

Solid fuels, including fossil fuels (e.g., coal, coke, etc) and biofuels (wood, charcoal, agricultural residue, animal waste, etc) play an important role in sustaining global energy in terms of serving as one of the primary fuels for household cooking, heating, and lighting (Kiehbadroudinezhad et al., 2023; Shemfe et al., 2015). However, global solid fuel emissions have negatively impacted ambient & indoor air quality (Archer-Nicholls et al., 2016; Liu et al., 2016), climate (Archer-Nicholls et al., 2019; Huang et al., 2018; Kodros et al., 2015; Lacey et al., 2017) and human health (Huang et al., 2021; Partha et al., 2022; Zhao et al., 2018). With the global gradual transition to clean energy, such as natural gas and electricity, the total number of households that primarily depended on solid fuels worldwide has declined from 62% in 1980 to 41% in 2010 (Bonjour et al., 2013) with a substantial decrease in the percentage of the global population using biomass from 45% to 28% and coal from 10% to 2% (Stoner et al., 2021). Although fewer people are using solid fuels as their primary energy source globally in recent years, solid fuels exclusively derived from biomass are still common for household cooking & heating in low-and middle-income countries (LMICs), and the associated impacts of solid biofuel burning on air quality and

Writing – original draft: Debatosh B. Partha
Writing – review & editing: Ying Xiong, Yaoxian Huang

human health are less clear, specifically in the residential, energy, industry, and transportation sectors. The recent (Global Bioenergy Statistics Report, 2023) shows that around 66% of the total power generated in combined heat & power (CHP) plants is from solid biofuel usage, indicating high consumption in this power plant class.

Moreover, residential heating and cooking through solid biofuel burning results in disproportionately higher exposure to indoor air pollution due to incomplete combustion and poor ventilation that has a larger impact on human health compared to the ambient air pollution caused by solid biofuel burning (Fullerton et al., 2008). Burning of solid biofuels like wood and plant material is observed to result in 339–520 μg/m^3 and 417–658 μg/m^3 $PM_{2.5}$ respectively in the indoor environment under different ventilation settings (Hu et al., 2014) where the cookstove solid biofuel burning is observed to supply up to 23.1 μg/m^3 $PM_{2.5}$ to the ambient environment (Huang et al., 2021). However, accounting for the health impacts of indoor solid biofuel emission is complicated due to the need for indoor versus outdoor exposure metrics (see discussion).

Solid biofuel emissions are important sources of short-lived climate forcers (SLCFs), such as primary organic matter (POM), black carbon (BC), carbon monoxide (CO), nitrogen oxides (NO_x), nonmethane volatile organic compounds (NMVOCs), ammonia (NH_3) and sulfur dioxide (SO_2), which severely downgrade ambient air quality (Huang et al., 2021). In addition, SLCFs are either important O_3 precursors (NMVOCs, CO, and NO_x) or precursors (SO_2, NH_3, NO_x, and NMVOCs) for secondary organic and inorganic aerosols (Huang et al., 2020). Solid biofuel emissions also cause significant climate change by emitting long-lived greenhouse gases (GHGs) like methane (Anenberg et al., 2017) and indirectly contribute to carbon dioxide emissions when biofuel usage causes deforestation. On top of that, exposure to indoor air pollutants emitted from solid biofuel burning causes 2.6 million premature deaths each year (GBD, 2017).

In recent years, the impacts of global solid biofuel emission on ambient & indoor air quality, climate change, and human health may have increased and these impacts attracted the attention of researchers worldwide (Butt et al., 2016; Kodros et al., 2015; Lelieveld, 2017; Lelieveld et al., 2015; Silva et al., 2016). Previous studies have established a strong association between solid biofuel emissions and negative influence on ambient air quality and human health for either $PM_{2.5}$ (Archer-Nicholls et al., 2016; Carter et al., 2016; Chowdhury et al., 2019; Liu et al., 2016; Reddington et al., 2019) or O_3 (Conibear et al., 2018; Rooney et al., 2019) for a specific year. Moreover, our previous study by Huang et al. (2021) performed a quantitative and qualitative analysis of the combined impact of $PM_{2.5}$ and O_3 exposure from solid biofuel cookstove emission on ambient air quality and human health for the year 2010 and found that the combined exposure of $PM_{2.5}$ and O_3 caused 0.38 million annual premature deaths (APDs) and 8.10 million years of lives lost (YLLs) in 2010. However, the long-term trends and impacts of the global solid biofuel emissions on ambient $PM_{2.5}$ and O_3 air quality and human health are not well understood and documented yet.

In this study, we employed the Community Atmosphere Model version 6, coupled with chemistry (CAM6-Chem) along with global exposure-response models to quantify the long-term impacts of the global solid biofuel emissions on ambient air quality and human health during 2000–2019. Section 2 describes the methods for CAM6-Chem model simulations and health burden quantifications associated with long-term $PM_{2.5}$ and O_3 exposure from solid biofuel emission. We report the results in Section 3, with discussions and conclusions in Section 4.

2. Methods

2.1. CAM6-Chem Model Simulation

For this study, we use a state-of-the-science chemistry-climate model named Community Atmosphere Model version 6, coupled with chemistry (CAM6-Chem) (0.95° × 1.25° resolution, 56 vertical levels) from Community Earth System Model version 2.2.0 (CESM2.2) to simulate the global ambient $PM_{2.5}$ and O_3 exposure from solid biofuel emission for select 5 years (i.e., 2000, 2005, 2010, 2015, and 2019) with one prior year of the year of interest as a model spin-up. For the current study, the recent release of CEDS (v2021_04_21) emission inventory from O'Rourke et al. (2021) was incorporated as CAM6-Chem model inputs and was re-gridded from the original inventory resolution of 0.5° latitude × 0.5° longitude to CAM6-Chem model resolution of 0.95° latitude × 1.25° longitude resolution for inventory-specific SLCF species that included BC, CO, NH_3, NO, POM, SO_2 and 22 NMVOC species including benzene, toluene, xylene, IVOC, SVOC, Bigalk, Bigene, C_2H_2, C_2H_4, C_2H_6, C_2H_5OH, HCN, C_3H_6, C_3H_8, CH_2O, CH_3CHO, CH_3CN, CH_3COCH_3, CH_3COOH, CH_3OH, HCOOH, and MEK from all-source anthropogenic emissions and solid biofuel emissions. The anthropogenic sources in our simulation include open biomass burning emissions from Coupled Model Intercomparison Project Phase 6 (CMIP6) emission inventories for the year 1750–2015 (Van Marle et al., 2017). In the current study, we bias-corrected the CAM6-Chem model-simulated all-source anthropogenic $PM_{2.5}$ concentrations by multiplying with scaling factors from the study of Donkelaar et al. (2021) due to a large underestimation of $PM_{2.5}$ concentrations by the CAM6-Chem model. Model evaluation of the downscaled $PM_{2.5}$ concentrations against the ground observations of China, India, Europe, and the United States for 2015 was carried out in our previous study (Xiong et al., 2022) which indicated that $PM_{2.5}$ is mostly underestimated by CAM6-Chem model in China, India, and Europe with a normalized mean bias (NMB) of −47.4%, −26.9%, and −39.6% and is overestimated with a NMB of +38.3% in the United States. In that study, we also validated all-source anthropogenic O_3 concentrations based on the Tropospheric Ozone Assessment Report (TOAR) during 2010–2014 due to the unavailability of TOAR O_3 observations in 2015 which indicated an overestimation of in-situ O_3 by CAM6-Chem model with a mean bias of 8.0 ppbv specifically over United States and Germany. In comparison with TOAR, CAM6-Chem is found to be overestimating the surface O_3 concentrations in the northern hemisphere (Young et al., 2018) specifically in the southeast US during summertime (Emmons et al., 2020), where a recent study by (Schwantes et al., 2022) highlighted the importance of relying on finer resolution models like Multi-Scale Infrastructure for Chemistry and Aerosols (MUSICA), resolving CAM-Chem's chemical & physical process complexity and using updated meteorological fields to reduce the higher model bias of surface O_3 concentrations. We acknowledge that this overestimation of surface O_3 concentrations may induce an overestimated health burden that is, APDs associated with chronic obstructive pulmonary disease (COPD) attributable to solid-biofuel emitted O_3 exposure, especially for contiguous US (CONUS). Overall, $PM_{2.5}$ and O_3 concentrations were in good agreement with the in-situ observations within the factor of 2.

To analyze the net impacts of solid biofuel emission, we ran 2 sets of model simulations for each pair of years (i.e., 1999–2000; 2004–2005; 2009–2010; 2014–2015, and 2018–2019): one is the control simulation (aka "CTRL") which had emissions from all anthropogenic sources including solid biofuel emission and a sensitivity simulation (aka "SBOFF") where we turned off the emissions of solid biofuel from all anthropogenic emissions by deducting each species' emission of solid biofuel burning from all-source anthropogenic emission. The re-gridded CEDS emission inventory data files for CTRL and SBOFF cases were then used as input files for CAM6-Chem model simulation that simulated different pollutant concentrations including $PM_{2.5}$ and O_3 in each chemistry and emission timesteps of the model. From the difference between the monthly outputs of CTRL and SBOFF simulations, we then analyzed the net impacts of solid biofuel emission on air quality in terms of annual average $PM_{2.5}$ concentrations and annual mean daily maximum 8-hr average O_3 concentrations (MDA8) for each grid box. Similar approaches using the CEDS emission inventory analysis and CAM6-Chem model simulations were applied in our prior study (Xiong et al., 2022) to analyze the impacts of gasoline and diesel emissions on $PM_{2.5}$ and O_3 pollution and associated health impacts. This justifies the methodology for incorporating all-source and specific fuel-type emission inventories to understand the net impacts of emissions from a particular fuel type on air quality and human health.

2.2. Health Impact Assessment Attributable to $PM_{2.5}$ and O_3 Exposure

We estimated the impacts of solid biofuel (SB) emissions on human health by calculating $PM_{2.5}$- and O_3-attributable APDs and YLLs for the adult population over 25 years of age. Premature deaths are defined as any deaths that happen before the mean age of death in a particular population. For example, the USA's average age of death is around 75 years, and the death of any person before 75 years old will be identified as a premature death. YLLs are defined as the years lost from each person's life expectancy due to premature deaths. If the person mentioned earlier dies at age 60 and the average life expectancy in the USA is 75 years, then the person lost 15 years of his/her life and all these years lost will be identified as YLLs.

The methodology for calculating the SB-emitted $PM_{2.5}$ -and O_3-attributable APDs and YLLs in terms of four non-communicable diseases (NCDs) that is, stroke, COPD, lung cancer, ischemic heart disease (IHD), and one other disease, lower respiratory infections (LRIs) is similar to the methods used in our previous study (Huang et al., 2021), where we rely on the widely used non-linear concentration-response function (CRF) of Global Exposure Mortality model (GEMM) (R. Burnett et al., 2018) to quantify the number of APDs due to 4 NCDs + LRI for each region and then used the APD estimates of each region to calculate the YLLs for each region (Text S1 in Supporting Information S1). Based on GEMM, APD is calculated as a function of the global gridded population density of 2.5 min (approximately 5 km) resolution (CIESIN—Columbia University, 2018), the baseline mortality rate (BMR) (GBD 2019 Risk Factors Collaborators, 2020) for the population older than 25 years in 5-year age intervals up to over 80 years old for 2000, 2005, 2010, 2015, and 2020 years and lastly the hazard ratio (HR). HR is a function of $PM_{2.5}$ and MDA8 O_3 exposure from our CAM6-Chem model-simulated outputs. Additionally, HR from GEMM for $PM_{2.5}$ attributable health burden analysis is a function of non-linear shapes, like θ, α, μ, and ν, defined by the transformation of concentrations that covers the variety of shapes modeled by the CRF. The attribution method and subtraction method from our recent study, Xiong et al., 2022, were incorporated to quantify the mortality from solid biofuel emitted $PM_{2.5}$ and MDA8 O_3 exposure respectively. To quantify the $PM_{2.5}$-attributable mortality from solid biofuel emission ($M_{SBPM2.5}$), we followed the attribution method and calculated the mortality due to $PM_{2.5}$ exposure from CTRL simulation ($M_{CTRLPM2.5}$) and then multiplied $M_{CTRLPM2.5}$ with $PM_{2.5}$ fraction from solid biofuel which is the ratio of the SB-emitted $PM_{2.5}$ and all-anthropogenic source emitted $PM_{2.5}$ concentrations shown in Equation 1 below. $PM_{2.5,\ CTRL,i,\ j}$ and $PM_{2.5,\ SBOFF,i,j}$ indicate the model-simulated $PM_{2.5}$ concentrations from CTRL and SBOFF simulations in each grid box (i, j) respectively.

$$\mathrm{M}_{\mathrm{SBPM2.5},i,j,h,a} = \frac{\mathrm{PM}_{2.5,\mathrm{CTRL},i,j} - \mathrm{PM}_{2.5,\mathrm{SBOFF},i,j}}{\mathrm{PM}_{2.5,\mathrm{CTRL},i,j}} \times M_{\mathrm{CTRLPM2.5},i,j,h,a} \tag{1}$$

$$\mathrm{M}_{\mathrm{SBO3},i,j,h,a} = M_{\mathrm{CTRLO3},i,j,h,a} - M_{\mathrm{SBOFFO3},i,j,h,a} \tag{2}$$

$$\mathrm{YLL}_{\mathrm{SBPM2.5},i,j,h,a} = \frac{\mathrm{PM}_{2.5,\mathrm{CTRL},i,j} - \mathrm{PM}_{2.5,\mathrm{SBOFF},i,j}}{\mathrm{PM}_{2.5,\mathrm{CTRL},i,j}} \times \mathrm{YLL}_{\mathrm{CTRLPM2.5},i,j,h,a} \tag{3}$$

$$\mathrm{YLL}_{\mathrm{SBO3},i,j,h,a} = \mathrm{YLL}_{\mathrm{CTRLO3},i,j,h,a} - \mathrm{YLL}_{\mathrm{SBOFFO3},i,j,h,a} \tag{4}$$

We also followed the subtraction method to quantify the health burden of $PM_{2.5}$ exposure from solid biofuel emission but ultimately used the attribution method as the subtraction method results in negative or unrealistic premature mortality estimates for specific regions such as eastern and central Europe (ECEurope), northern Africa & Middle East (NAME), Latin America (LATIN), western Europe (WEurope), the United States of America (USA), Canada, and rest of the world (ROW) compared to the already reported values in McDuffie et al. (2021) (details in Table S7 in Supporting Information S1). To quantify the O_3-attributable mortality from solid biofuel emission, we use the subtraction method shown in Equation 2 where we subtracted the O_3-attributable mortalities calculated from SBOFF simulation output ($M_{SBOFFO3,i,j,h,a}$) from the O_3-attributable mortality from CTRL simulation ($M_{CTRLO3,i,j,h,a}$) in each grid box (i, j). We then calculated the combined estimate of $PM_{2.5}$ and O_3-attributable mortalities in 5-year age interval groups (a) and in each grid box (i, j) for each year and each health point (h) (i.e., each NCD) to obtain the regional APDs. We followed a similar approach of attribution and subtraction shown in Equations 3 and 4 to calculate the YLLs due to 4 NCDs + LRI caused by $PM_{2.5}$ and MDA8 O_3 exposure from solid biofuel emission (Text S1 in Supporting Information S1) during 2000–2019. Uncertainty and 95% confidence intervals (CI) for $PM_{2.5}$-attributable premature mortalities are calculated based on mean, upper, and lower bounds of the GEMM model-fit parameter (θ) from R. Burnett et al. (2018) and 95% CI for O_3-attributable premature mortalities are calculated based on mean, upper, and lower bounds of log-linear slope (η) between COPD-associated HR and O_3 concentrations from Turner et al. (2016).

To understand the SB usage & emissions as well as its air quality and human health impacts on different regions, we followed the regional classification methodology of Huang et al. (2020) by dividing the world into 11 regions, which are India, China, Sub-Saharan Africa (SSA), rest of Asia (ROA), NAME, WEurope, ECEurope, LATIN, USA, ROW and Canada (Table S1 in Supporting Information S1). We incorporated country mask data (0.1° latitude × 0.1° longitude resolution) from the UN Statistics Division (https://unstats.un.org/unsd/methodology/m49/) to specify each country/region and re-gridded $PM_{2.5}$ and O_3 exposure from 0.95° latitude × 1.25° longitude to 0.1° latitude × 0.1° longitude (roughly 10 km) resolution to be consistent with the country mask data. We further classified the 11 regions either as developed (Canada, USA, ROW, and WEurope) or developing countries (India, China, LATIN, ECEurope, ROA, SSA, and NAME) based on the International Monetary Fund classification (IMF, 2019).

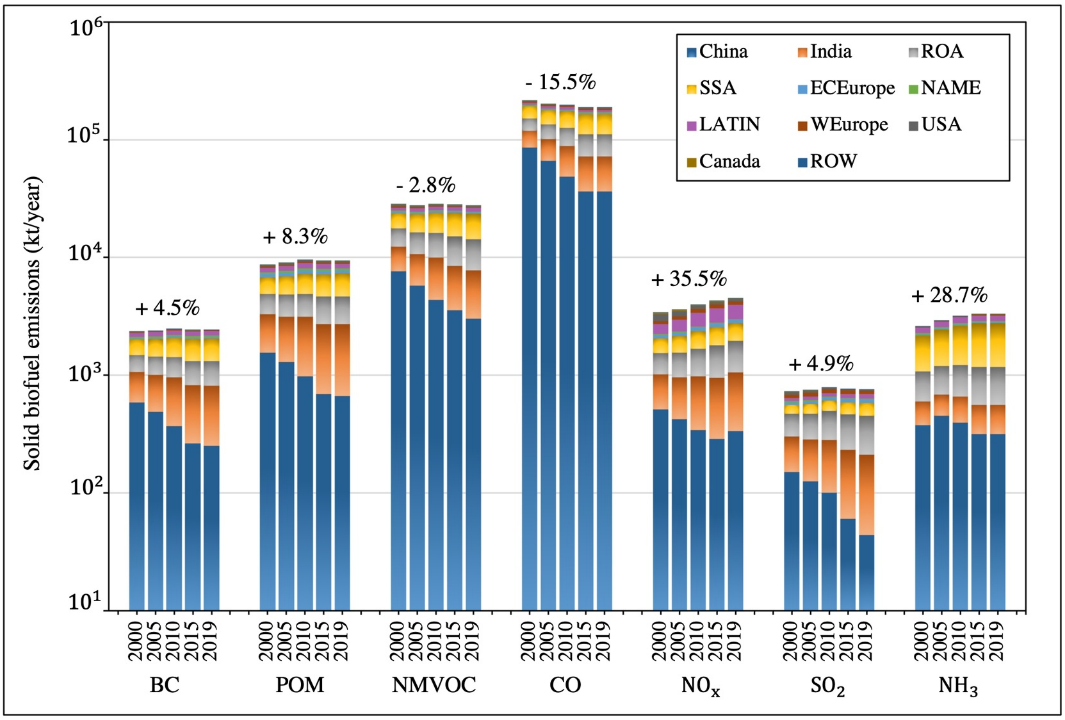

Figure 1. Global annual total emissions of SLCF species with regional impacts from the solid biofuel sector in select years: 2000, 2005, 2010, 2015, and 2019. The percentages inserted denote emission changes in 2019 relative to 2000.

3. Results

3.1. Trends of Global, Regional, and Sectoral Solid Biofuel Emissions

Figure 1 shows the global annual total emissions of different SLCF species from solid biofuel burning from residential, industrial, energy, and transportation sectors combined along with the regional emission impacts of each species for select years that cover the study period of 2000–2019. These global and regional emission estimates are retrieved from the CEDS2021 (O'Rourke et al., 2021) emission inventory which also includes emissions from other dominant fuel types such as coal, diesel, gasoline, etc besides solid biofuel. From 2000 to 2019, China, India, ROA, and SSA had the major share (64%–88.7%) in almost all SLCF species' emissions, followed by ECEurope, NAME, LATIN, WEurope, USA, Canada, and ROW (Table S2 in Supporting Information S1).

Specifically, global solid biofuel-attributable CO emissions from all sectors ranged from 187.79 to 214.29 TgC/yr which is more than double of the all-sector CO emission from coal burning reported in CEDS2021 as 70.80 to 86.11 TgC/yr during 2000–2019. Additionally, to provide a comparative context of SB emissions with other dominant fuel types, CO emissions from gasoline and diesel ranged from 143.44 to 218.24 TgC/yr and 25.84 to 30.40 TgC/yr respectively from 2000 to 2015 (Xiong et al., 2022). Solid biofuel's long-term CO emission trend indicates a 15.5% decrease in 2019 compared to 2000 mainly due to the substantial reductions of CO emissions in China (−57.5%) because of reduced solid biofuel usage and increased combustion efficiency in residential sectors and iron, steel, and construction material industries (Zheng, Chevallier, et al., 2018; Zheng, Tong, et al., 2018). The declining trend of CO emissions in China is also acknowledged in the Multi-resolution Emission Inventory for China (MEIC, www.meicmodel.org/).

Global NMVOC emissions associated with solid biofuel burning ranged from 27.57 to 28.49 Tg/yr during 2000–2019, which decreased slightly by 2.8% in 2019 relative to the year 2000. This is most likely due to the counterbalancing effect of increasing NMVOC emissions in ROA (+21.9%), SSA (+51.4%), LATIN (+22.8%), and decreasing emissions in China (−60.4%), NAME (−36%), ECEurope (−7%), WEurope (−23.1%), USA (−54.6%), CANADA (−31%) and ROW (−64.1%), respectively.

The total emission estimates of CO and NMVOC are followed by the emissions of POM, NO_x, NH_3, BC, and SO_2. During 2000–2019, global net POM emissions (8.67–9.57 TgC/yr) from solid biofuel remained relatively stable, of which the trend indicates a marginal global emission increase in 2019 by 8.3% with respect to 2000. This was possible due to the emission offsetting effect by China's major POM reduction (−57%) on the POM emissions increases over India (+17.5%), ROA (+21.6%), SSA (+39.4%), and WEurope (+37.8%) (Dao et al., 2022) that resulted in a minimal increase of the net POM emissions in 2019. Global solid biofuel-emitted NO_x emissions considerably increased by 35.5% in 2019 (4.54 Tg NO_2/yr) relative to the year 2000 (3.41 Tg NO_2/yr), which was probably due to the dominating synergistic increasing effect of regional NO_x emission over India (+43.7%), ROA (+73.6%), SSA (+57.3%), ECEurope (+54.1%), LATIN (+95.6%), and WEurope (+71.2%) over the rest of the regions. Global solid biofuel-emitted NH_3 emissions ranged from 2.60 to 3.29 Tg/yr during 2000–2019. This 28.7% increase in NH_3 emissions in 2019 can be explained by the substantial increase of SB usage in the SSA region (+44.1%) likely attributable to increased agricultural activities, fertilizer use, and crop residue burning (Hickman et al., 2021).

BC emissions from solid biofuel sectors ranged from 2.35 to 2.47 TgC/yr globally and stayed relatively stable due to the dominating emission offsetting effects exerted by the major reduction of solid biofuel-emitted BC in China (−57.2%), and in developed regions like ROW (−39.8%), Canada (−21.1%), USA (−20.9%) in 2019 even though SSA (+39.4%), WEurope (+57.6%) and ROA (+20%) experienced an increase in BC emission. Similarly, global solid biofuel-emitted SO_2 emissions also remained stable in 2019 with a minor increase of 4.9% from 2000, most likely due to the dominating emission offsetting effects deployed by the substantial declines of solid biofuel-emitted SO_2 emissions in China (−70.9%), USA (−73.1%), and Canada (−54.8%), even though other regions had increased SO_2 emissions in 2019.

Based on the long-term trend, we observe the global annual total emissions of BC, POM, and SO_2 peak in 2010 and later decrease in 2019 but NO_x and NH_3 continued to rise from 2000 until 2019. On the other hand, global annual total NMVOC and CO emissions from solid biofuel sectors were at peak in 2000 that ultimately decreased in 2019. A similar trend for BC, POM, $NH_{3,}$ and CO emissions from solid biofuel was also observed in the study of McDuffie et al., 2020. As China is the dominant region in emitting a major amount of SLCFs from solid biofuel usage shown in Figure 1, the reduction in every species emission in China helped to achieve the emission offsetting effect that either reduced or kept the long-term emission trends relatively stable. Reducing emissions in China is attributable to the major implementation of improved heating and cooking devices in residential households, numerous emission control strategies, and stringent emission standards in industry and energy sectors that promote the alternative and reduced use of solid biofuels (Zheng, Chevallier, et al., 2018; Zheng, Tong, et al., 2018). On the other hand, India experienced an increase in every SLCF species' emissions in 2019 likely due to the uncontrolled and increased usage of solid biofuels as the primary source of bioenergy in several sectors for example, residential, industrial, and energy sectors (Implementation of Bioenergy in India, 2021). Similar to India, SSA also experienced an increase in solid biofuel-attributable emissions and dominated global BC, POM, NMVOC, CO, and NH_3 emissions in 2019 due to the severe scarcity of electricity and large dependency on solid biofuels for cooking, heating, and energy production (Mensah et al., 2021). ROA accounted for 27.6% of the SO_2 emissions during 2000–2019 associated with solid biofuel sectors relative to the global annual total emissions from solid biofuels, which is probably due to the limited resources and underdeveloped SO_2 capture technologies for fugitive emissions as well as high usage of solid biofuels in residential, industrial and energy sectors and facilities. Developed countries/regions like the USA, Canada, and ROW mostly experienced extensive declines in long-term emissions during 2000–2019 because of the major shift to natural gas and electricity for heating and cooking in residential households and improved processing & state-of-the-art technologies and policies to minimize emissions from a variety of sectors.

From the sectoral emission analysis within the 11 regions (Figure S2–S12 in Supporting Information S1), residential, commercial & other (RCO), hereafter referred to as the residential sector, is the dominant one that emitted the majority of the SLCF species emission among all solid biofuel sectors during 2000–2019. China's annual total solid biofuel emissions plunged as we observed a major reduction of emissions from the residential sector whereas energy-sourced BC, POM, NMVOC, and NO_x emissions increased in 2019 with respect to 2000. This is primarily due to substantial reductions in solid biofuel usage in Chinese households where oil and gas replaced the traditional solid biofuels and China utilized this excess amount of solid biofuels in the energy sector after 2012 which explains the emission spike in the energy sector (Implementation of Bioenergy in China Country Reports, 2021). Unlike China, the residential solid biofuel emissions either increased or stayed stable in India for the year 2019, with a spike in 2010 which was also noted in the Implementation of Bioenergy in India (2021) report. The spike in 2010's emissions can be explained by India's major inclination toward bioenergy usage (Implementation of Bioenergy in India, 2021) in recent years. Additionally, India's solid biofuel emissions from industrial and energy sectors are relatively negligible mostly due to the high dependency on coal but experienced relatively moderate emissions of POM, NO_x, and SO_2 anyway from solid biofuel burning. In ROA, the residential sector caused the majority of the solid biofuel emissions whereas industrial and energy sectors also had a fair share of the regional annual total emissions associated with solid biofuel sources. Similar to ROA, SSA experienced considerable NO_x emissions from solid biofuel burning in both residential and industrial sectors, where, for other species emissions, only residential solid biofuel burning dominated.

In ECEurope, most of the NO_x and SO_2 emissions came from industrial and energy usage of solid biofuels where the energy sector also had a fair amount of BC and POM emissions along with the dominance of the residential sector in all species emissions. Like ROA and SSA, industrial solid biofuel burning emitted a fair amount of NO_x in NAME in the early 2000s, which was later dropped in 2019. Although residential solid biofuel burning was the dominant source of all SLCF emissions from 2000 to 2019 in NAME, emissions from this sector decreased slightly in 2019 compared to the year 2000. Potentially, the industrial solid biofuel burning dominated the NO_x and SO_2 emissions with respect to other sectors in the LATIN region whereas, in WEurope, solid biofuel burning in the energy sector dominated the SO_2 emission along with a considerable emission of BC, POM, and NO_x.

In the United States, solid biofuel-emitted BC, POM, NMVOC, and CO mainly declined in the residential sector during 2000–2019 whereas NO_x and SO_2 mainly declined in the industrial sector followed by the energy sector. Industrial solid biofuel burning mainly emitted NH_3 in 2000 which then shifted to the residential sector after 2005 and increased substantially in 2019, which is most likely due to the absence of strict NH_3 emission control policies and advanced capture technologies in USA's residential settings. In Canada, solid biofuel-emitted BC from residential, industrial, and energy sectors spiked in 2015 probably due to the increased interest in solid biofuel usage instead of fossil fuels in recent years (Natural Resources Canada, 2016). Strictly within solid biofuel burning, POM, NMVOC, and CO emissions mostly came from the residential sector of Canada whereas NO_x, SO_2, and NH_3 emissions came from the industrial sector, although each species' emission is relatively lower compared to the other regions, and the total emissions from all sources are decreasing in the long-term.

Similar to LATIN, USA, and Canada, industrial solid biofuel usage resulted in increasing NO_x and SO_2 emissions in ROW, within which, Australia dominated the emission compared to New Zealand and Greenland, mostly due to the recent efforts of increased industrialization and usage of renewable biofuel instead of fossil fuels and coal to achieve net-zero carbon emission and to shift from export-dependent economy to a self-sufficient economy (Energy Policy Review Australia, 2023; Wood et al., 2022) The declining trend of residential emission of all SLCF species in ROW indicates a decreased usage of solid biofuels in this sector due to the growing interest of using electric stoves, furnaces, and natural gas for cooking and heating in this region.

3.2. Impacts of Global Solid Biofuel Emissions on Air Quality

Although the relationship between the emissions of different SLCFs and their impacts on air quality is not linear, the substantial amount of SB species emissions and large emission estimates from developing countries have direct implications for regional and global ambient $PM_{2.5}$ and O_3 air quality. Spatiotemporal variability of CAM6-Chem model-simulated $PM_{2.5}$ and O_3 concentrations attributable to solid biofuel emission along with the net long-term change of concentrations in 2019 with respect to 2000 are shown in Figures 2 and 3 respectively. Globally, annual average ambient $PM_{2.5}$ (μg/m^3) and O_3 (ppbv) concentrations from SB emission ranged from 0.11 to 0.13 μg/m^3 and 0.48–0.63 ppbv during 2000–2019, with the highest $PM_{2.5}$ and O_3 concentrations estimated up to 23.61 μg/m^3 and 13.69 ppbv in 2010 respectively (Table S3 in Supporting Information S1) although most of the SLCFs emissions (except for BC, POM, and SO_2) were not highest in 2010, thus indicating the nonlinear relationship between emission and air quality impacts. Annual mean $PM_{2.5}$ and O_3 concentrations decreased by 4.2% and 15.9% whereas annual maximum $PM_{2.5}$ and O_3 concentrations went up by 36.5% and 20.7% in 2019 compared to 2000 with a large net reduction in eastern China, central Australia, western Kazakhstan and Turkmenistan and a net increase in India & African countries like Nigeria and Congo as shown in Figure 2f. Supported by the declining trend of SLCF species emission from SB burning, China had major declines in surface annual mean (max) $PM_{2.5}$ and O_3 concentrations from 0.03 (14.61) μg/m^3 to 0.01 (10.11) μg/m^3 and 0.04 (8.98) ppbv to 0.02 (6.28) ppbv in 2019 (Table S3 in Supporting Information S1) shown in Figures 2 and 3.

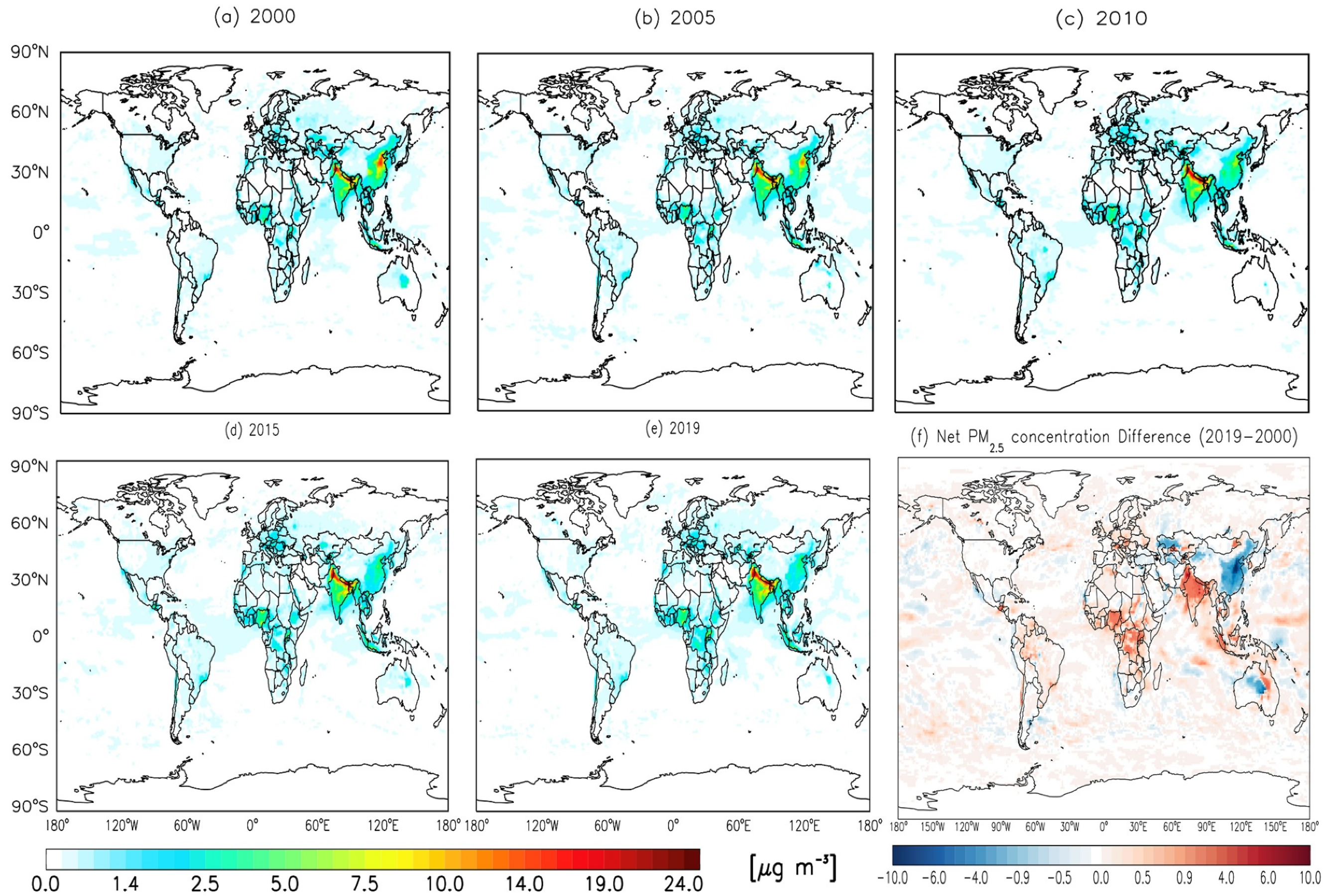

Figure 2. Global spatial distribution of annual average $PM_{2.5}$ concentrations from solid biofuel emissions for (a) 2000, (b) 2005, (c) 2010, (d) 2015, (e) 2019, and (f) net $PM_{2.5}$ concentration difference (i.e., 2019 minus 2000) respectively. The left color bar is for subplots (a–e), and the right color bar is for subplot (f).

The hotspots for $PM_{2.5}$ and O_3 concentrations are gradually diminishing over eastern China, especially after 2010. China's substantial decline in $PM_{2.5}$ and O_3 concentrations from SB emissions can be largely attributed to national initiatives such as the enactment of the National Air Quality Action Plan in 2013 and the Blue-sky Action Plan on 3 July 2018. These measures mandated a decrease in solid biofuel use in the residential sector and promoted the adoption of other renewable energy sources, such as solar, hydro, and wind power, mainly in the electricity sector. Consequently, the reliance on solid biofuel dropped from 70% to 30% in China, with oil and natural gas replacing it for residential heating and cooking (Dou Kejun, 2021).

Contrary to China, we estimate an increasing maximum annual average $PM_{2.5}$ and O_3 concentrations in ROA ranging from 16.92–23.61 μg/m^3 to 10.75–13.69 ppbv and in India ranging from 16.60–20.74 μg/m^3 to 10.20–12.48 ppbv during 2000–2019 with lowest and highest estimates in 2000 and 2010 respectively (Table S3 in Supporting Information S1). The ROA includes countries/regions like Southeast Asia, Oceania, High-income Asia Pacific, Central Asia, North Korea, Bhutan, Bangladesh, Nepal, and Pakistan. These elevated $PM_{2.5}$ and O_3 concentrations are primarily linked to the heavy reliance on solid biofuels for domestic cooking and heating, coupled with the inability of the general population to afford advanced alternative technologies like electric cookstoves in certain regions. Apart from ROA, significant impacts on air quality from solid biofuel-emitted $PM_{2.5}$ and O_3 are observed in eastern China, northern India, western Africa, central Europe, and the eastern and western parts of South America.

In regions other than China, India, and ROA, major reductions in the maximum annual average concentrations of $PM_{2.5}$ and O_3 (ppbv) were estimated in ROW (6.73–2.99 μg/m^3; 1.59–0.94 ppbv), whereas $PM_{2.5}$ concentrations increased but O_3 concentrations decreased in ECEurope (2.68–2.87 μg/m^3; 2.33–1.36 ppbv), WEurope (2.04–2.56 μg/m^3; 1.66–1.26 ppbv), USA (1.46–1.53 μg/m^3; 1.73 to 1.28 ppbv), and Canada (1.03–1.79 μg/m^3; 1.40 to

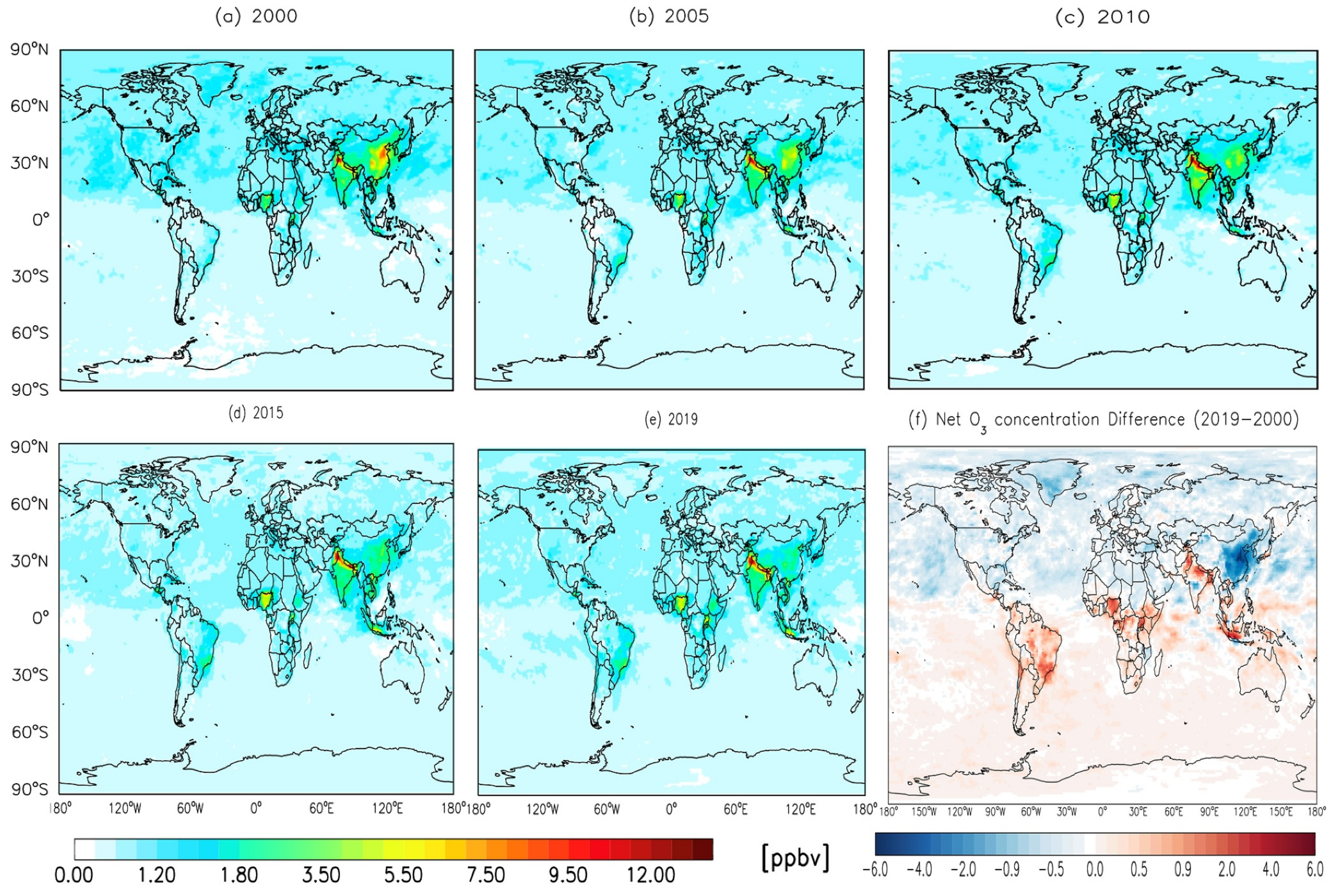

Figure 3. Global spatial distribution of annual average O_3 concentrations from solid biofuel emissions for (a) 2000, (b) 2005, (c) 2010, (d) 2015, (e) 2019, and (f) net O_3 concentration difference (i.e., 2019 minus 2000) respectively. The left color bar is for subplots (a–e), and the right color bar is for subplot (f).

0.97 ppbv). Meanwhile, notable spikes of both $PM_{2.5}$ and O_3 concentrations from SB emissions were estimated in SSA (6.80–8.78 μg/m^3; 5.14–8.41 ppbv), NAME (6.41–8.67 μg/m^3; 3.45–4.70 ppbv), and LATIN (4.35–6.66 μg/m^3; 3.04–4.59 ppbv) during the study period.

3.3. Long-Term Impacts of Global Solid Biofuel Emissions on Human Health

The spatial distribution of global APDs attributable to SB-emitted $PM_{2.5}$ and MDA8 O_3 exposure during 2000–2019 is shown in Figure 4 along with regional & global estimates shown in Figure 5. Relatively large APD estimates were found in India (especially north India), Eastern China, central Europe, African countries like Ethiopia, Uganda, Nigeria, Ghana, Senegal, etc., Asian countries like Bangladesh, Burma, Thailand, Indonesia, Malaysia, Cambodia, Vietnam, Philippines, North and South Korea and Japan. Globally, $PM_{2.5}$ and MDA8 O_3 exposures from all anthropogenic sources caused 5.43 million (M) (95% CI: 4.78–6.08 M); 5.92 M (95% CI: 5.22–6.59 M); 6.45 M (95% CI: 5.22–6.59 M); 7.25 M (95% CI: 6.41–8.07 M), and 8.09 M (95% CI: 7.16–9.01 M) APDs in 2000, 2005, 2010, 2015, and 2019, respectively (Table S6 in Supporting Information S1). These estimates were within a factor of 2 compared with the global studies of (R. T. Burnett et al., 2022) {8.9 M (95% CI: 7.5–10.3 M)}, (Lelieveld et al., 2020) {8.8 M (95% CI: 7.11–10.41 M)}, and (Weichenthal et al., 2022) {10.8 M (95% CI: 10.7–10.9 M)}. Additionally, we calculate YLLs from all anthropogenic emission sources as 130.76 M (95% CI: 115.01–146.07 M); 142.08 M (95% CI: 126.41–157.34 M); 151.01 M (95% CI: 133.97–167.57 M); 168.27 M (95% CI: 147.92–186.59 M), and 190.86 M (95% CI: 169.08–211.89 M) in 2000, 2005, 2010, 2015, and 2019, respectively. Similar YLL estimates within the factor of 2 were estimated in (Lelieveld et al., 2020) as 232.95 M (95% CI: 184.84–277.74 M)} for 2015.

Within this global estimate, SB-emitted $PM_{2.5}$ and MDA8 O_3 exposure caused 1.11 M (95CI: 0.99–1.22M); 1.12 M (95% CI: 1.02–1.23M); 1.29 M (95% CI: 1.17–1.41M); 1.27 M (95% CI: 1.15–1.38M) and 1.43 M (95%

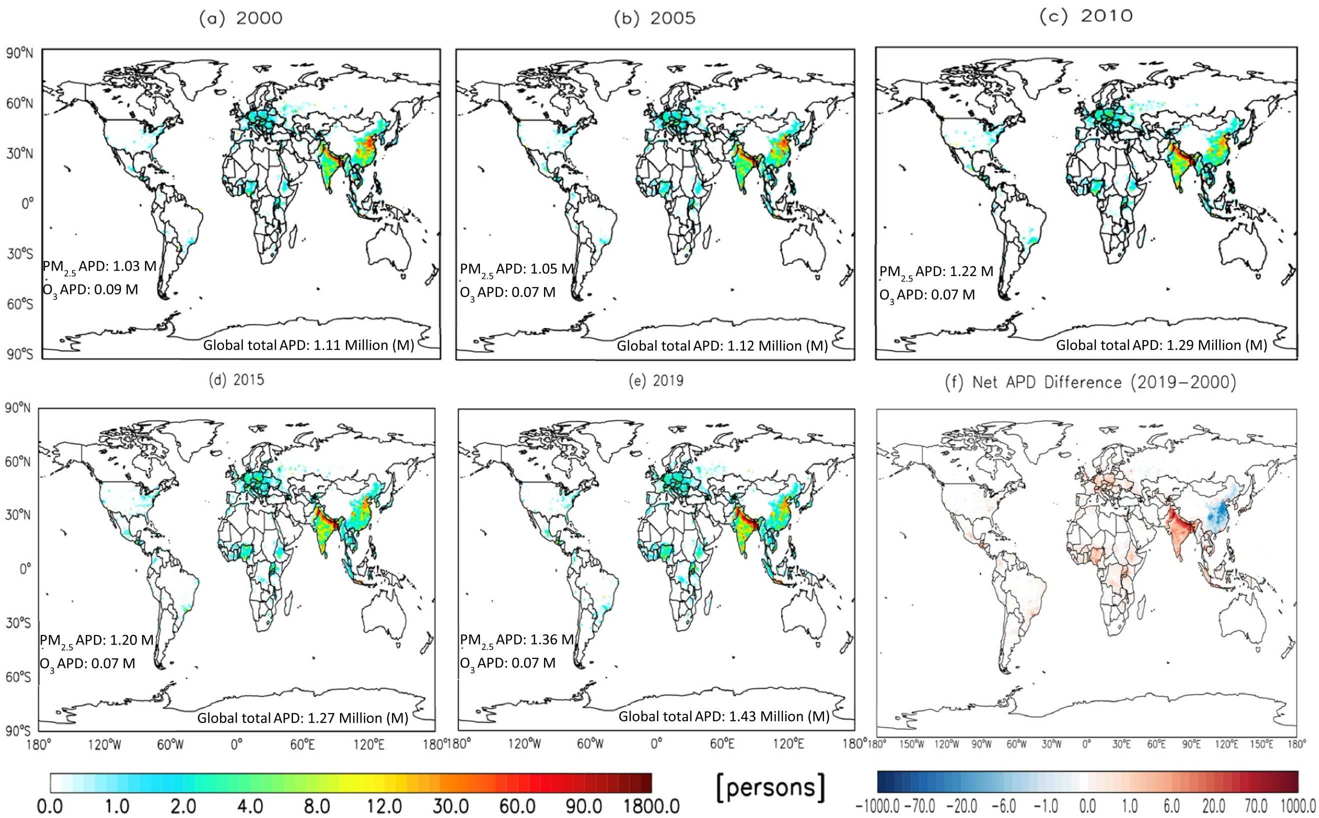

Figure 4. Global spatial distribution of annual total $PM_{2.5}$- and O_3-attributable premature deaths attributable to the global solid biofuel emissions for (a) 2000, (b) 2005, (c) 2010, (d) 2015, (e) 2019, and (f) net APD difference (i.e., 2019 minus 2000) respectively. The left color bar is for subplots (a–e) and the right color bar is for subplot (f). The horizontal resolution of the plot is 0.1° latitude × 0.1° longitude.

CI: 1.30–1.56M) APDs in 2000, 2005, 2010, 2015 and 2019, respectively. APDs from SB-emitted $PM_{2.5}$ and MDA8 O_3 exposure accounted for 17.5%–20.4% of the global total APDs from all anthropogenic $PM_{2.5}$ and O_3 sources during 2000–2019, representing a significant one-fifth of the global total APDs. Furthermore, both global and regional data indicate that $PM_{2.5}$-attributable APDs greatly outnumber those caused by MDA8 O_3 within the SB sector where about 92.3%–95.1% of the combined $PM_{2.5}$ and O_3-related APDs from 2000 to 2019 were due to $PM_{2.5}$ exposure alone, which aligns with the findings from our earlier study (Huang et al., 2021) for the year 2010.

Regional differences in SB-attributable APD estimates depend on the regional SB-emitted SLCF emission budget (Table S2 in Supporting Information S1), attributable $PM_{2.5}$ and MDA8 O_3 exposure (Table S3 in Supporting Information S1), population-weighted $PM_{2.5}$ and MDA8 O_3 exposure (Table S4 in Supporting Information S1), the population size and all-cause 4 NCDs + LRI baseline mortality rate (BMR) of each country/region (Table S5 in Supporting Information S1). Although age-group-specific BMR values in 5-year age intervals were used to calculate the health burden, we include the mean values of regional BMR for all-cause 4 NCDs + LRI to provide a comparing context of 4 NCDs + LRI BMR from all possible causes including SB pollution among the regions. Relative contributions of these various estimates are directly reflected in the SB-attributable APD estimates. When compared among 11 regions, areas with higher SB emission (which provides a general idea of consumption), pollutant exposure, populations, and BMR experience higher APD burden compared to the areas with lower emission, exposure, population, and BMR. In this study, major regional APD share to the global estimates mainly comes from China (19.6%–42.4%), India (25.1%–36.6%), and ROA (16.9%–24.7%) which combinedly caused from 80.5% up to 84.3% of the global total APDs associated with SB-emitted $PM_{2.5}$ and MDA8 O_3 exposure. In contrast, the rest of the 8 regions cumulatively caused only 15.7%–19.5% of the global total APDs during the study period, mostly due to the lower regional emissions from SB burning, BMR, and population count in those regions.

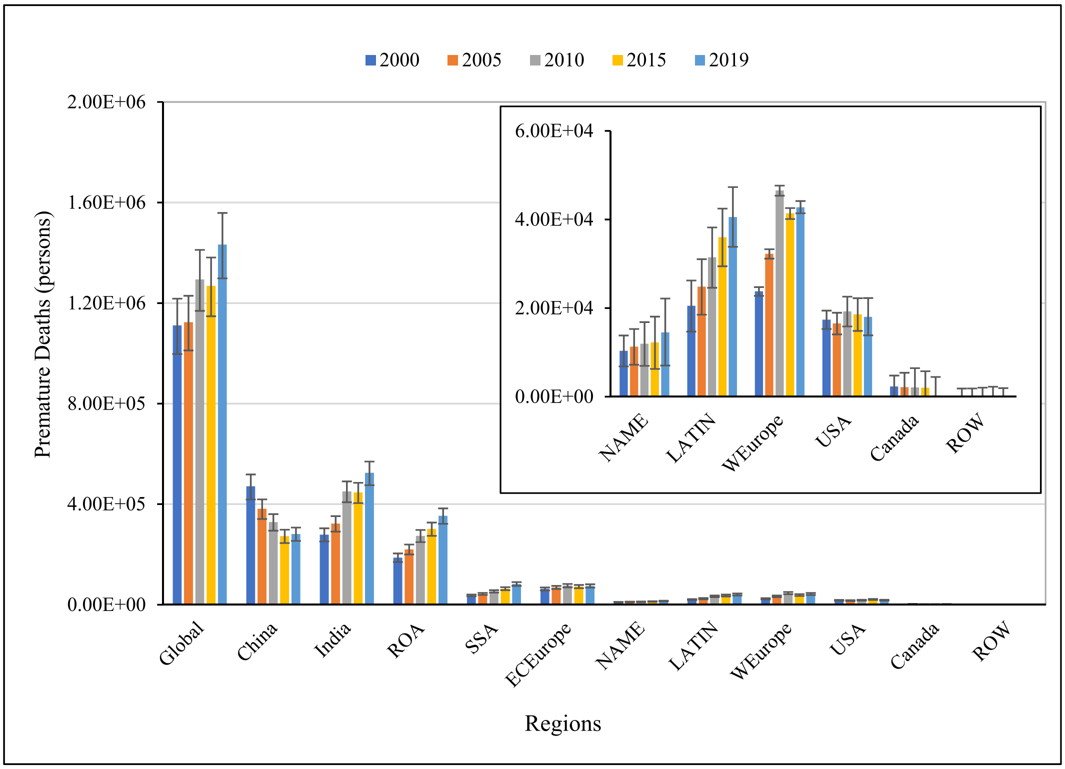

Figure 5. Global and regional total $PM_{2.5}$ -and O_3-attributable APDs attributable to solid biofuel emissions for 2000–2019. Error bars represent 95% confidence intervals.

Here, we assume SB emission thus attributable $PM_{2.5}$ and MDA8 O_3 exposure possed higher relative contributions on regional APD estimates compared to all-cause 4 NCDs + LRI BMR and population count as we observed in China, even though the population count increased to 1414 million from 1229, due to the reduction of SB-emitted $PM_{2.5}$ and MDA8 O_3 exposure, the premature deaths per 100,000 population (Table 1) decreased from 38 to 20 persons in 2019 compared to 2000. Mean 4 NCDs + LRI BMR also decreased in China which was also the case for India, ROA, and SSA but that did not ultimately result in lower premature deaths per 100,000 population in these regions as they experienced increased $PM_{2.5}$ and MDA8 O_3 exposure in 2019 compared to 2000 from solid biofuel emission. We acknowledge the complexity of the relationship among such factors

Table 1
Global and Regional SB-Emitted $PM_{2.5}$ -and O_3 -Induced APDs per 100,000 Population (With 95% Confidence Interval)

Economic status	Countries/Regions	2000	2005	2010	2015	2019
Developing	China	38 (34, 42)	30 (27, 33)	25 (22, 27)	20 (18, 22)	20 (18, 22)
	India	28 (25, 30)	30 (27, 32)	38 (35, 42)	35 (32, 38)	38 (34, 41)
	ROA	18 (16, 19)	20 (18, 21)	23 (21, 25)	24 (21, 26)	26 (23, 28)
	ECEurope	19 (17,21)	21 (19, 23)	24 (22, 26)	23 (21, 25)	23 (21, 25)
	SSA	6 (6, 7)	6 (6, 7)	7 (6, 7)	7 (6, 7)	8 (7, 8)
	NAME	2 (2, 3)	2 (2, 3)	2 (2, 3)	2 (2, 3)	2 (2, 3)
	LATIN	4 (4, 5)	5 (4, 5)	6 (5, 7)	6 (5, 7)	6 (5, 7)
Developed	WEurope	6 (6, 7)	9 (8, 10)	12 (11, 13)	10 (9, 11)	10 (9, 11)
	USA	6 (6, 7)	6 (5, 6)	6 (5, 7)	7 (6, 7)	5 (5, 6)
	Canada	8 (7, 9)	7 (6, 8)	6 (6, 7)	7 (6, 7)	1 (1, 1)
	ROW	0 (0,0)	1 (1, 1)	0 (0, 0)	1 (0,1)	0 (0, 0)
	Global	19 (17, 21)	18 (16, 20)	20 (18, 21)	18 (16, 19)	18 (16, 20)

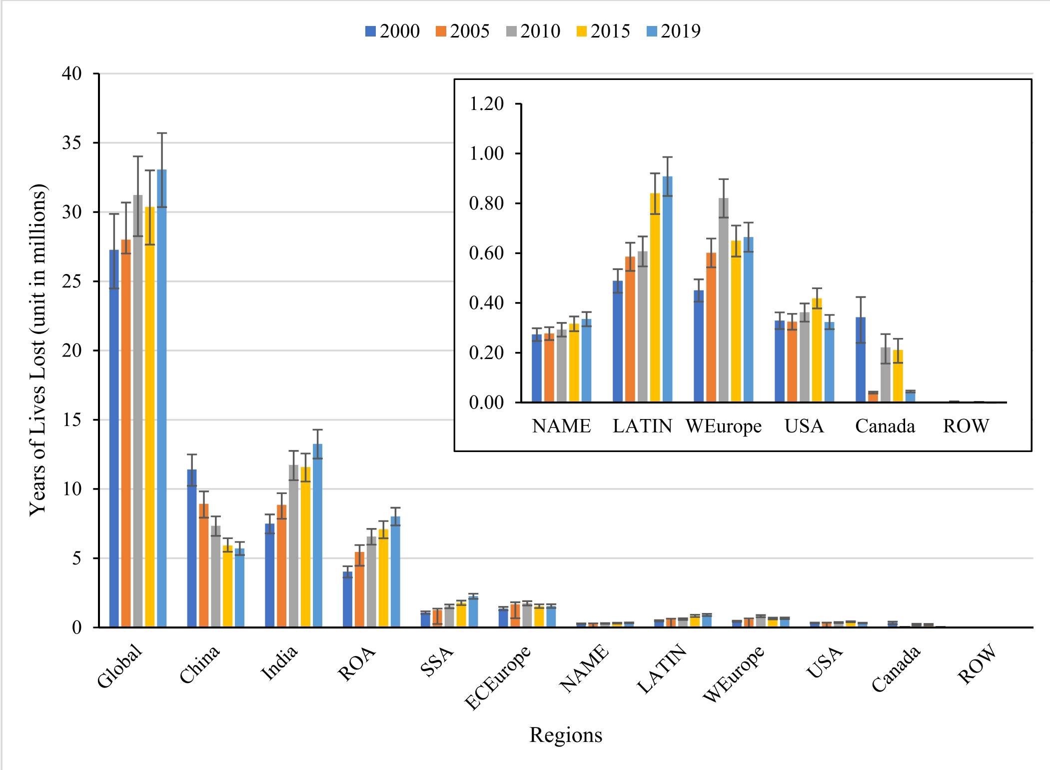

Figure 6. Global and regional annual total $PM_{2.5}$ -and O_3-attributable YLLs attributable to solid biofuel emissions for 2000–2019. Error bars represent 95% confidence intervals.

contributing to cause-specific health burden analysis needs further investigation to better understand the relative contribution of individual factors.

Global and regional estimates of SB-emitted $PM_{2.5}$ -and MDA8 O_3-attributable APD per 100,000 population (i.e., APD rate) (with 95% CI) based on the regional economic status (developing and developed) are listed in Table 1. The estimated premature deaths per 100,000 population are much higher in developing countries such as China (20–38 persons), India (28–38 persons), ROA (18–26 persons), ECEurope (19–24 persons), SSA (6–8 persons), LATIN (4–6 person) and NAME (2 people) than those in developed countries/regions like WEurope (6–12 person), USA (5–7 persons), Canada (1–8 persons) and ROW (0–1 persons). This is because developing countries are more dependent on solid biofuel for household cooking and heating than developed countries where electricity and natural gas are the main household fuels. From the global perspective, 4 NCDs + LRI diseases from SB-emitted $PM_{2.5}$ and MDA8 O_3 exposure caused around 18–20 premature deaths on average per 100,000 population each year during 2000–2019.

During this 20-year study period, an increasing trend of the global APDs attributable to $PM_{2.5}$ and MDA8 O_3 exposure from all sources and SB-sector is observed with an alarming rate of up to 48.8% and 28.9% respectively in 2019 compared with 2000. Although China had a substantial share in the global APD burden shown in Figure 5, the country managed to achieve a significant decline of 40.2% APDs associated with SB-emitted $PM_{2.5}$ and MDA8 O_3 exposure in 2019 compared to 2000. Along with China, Canada (−87.5%) and ROW (−105.0%) have shown a decreasing trend of total APDs in 2019. All other countries/regions have shown an increasing trend of the total SB-attributable APDs, for example, India (+88.2%), ROA (+88.8%), SSA (+121.6%), ECEurope (+18.9%), NAME (+40.0%), LATIN (+97.7%), WEurope (+79.8%) and USA (+3.6%) in 2019.

Global and regional YLLs attributable to SB-attributable $PM_{2.5}$ and MDA8 O_3 exposure during 2000–2019 are shown in Figure 6. Worldwide, SB-attributable $PM_{2.5}$ and MDA8 O_3 exposure caused around 27.72 M (95% CI: 24.48–29.86 M); 28.01 M (95% CI: 25.33–30.54 M); 31.23 M (95% CI: 28.26–34.02 M); 30.36 M (95% CI: 27.65–33.01 M) and 33.07 M (95% CI: 30.36–35.70 M) YLLs in 2000, 2005, 2010, 2015, and 2019 respectively.

Almost identical to the regional APD estimates, China, India, and ROA combined had a substantial share (81.02%–84.13%) of the global annual total YLLs each year from 2000 to 2019 where the rest of the countries/regions only accounted for 15.9%–18.98% of the global annual total YLLs burdens. China was estimated to have the major burden of the global annual total YLLs (17.3%–41.8%) each year associated with SB-attributable $PM_{2.5}$ and MDA8 O_3 exposure followed by India (27.5%–40.1%) and ROA (14.8%–24.3%) during the study period.

The long-term trend of the global YLLs estimate shows that SB-attributable annual total YLLs increased globally up to 21.3% in 2019 compared to 2000. Long-term regional trends of $PM_{2.5}$ -and O_3 -attributable YLLs from SB emission show that most of the regions/countries like India (7.5–13.26 M), ROA (4.03–8.02 M), SSA (1.08–2.26 M), ECEurope (1.37–1.55 M), LATIN (0.49–0.91 M), WEurope (0.45–0.66 M), and NAME (0.27–0.34 M) experienced increased annual total YLLs burden in 2019 compared to 2000, where China (11.41–5.71 M), USA (0.33–0.32 M), Canada (0.34–0.04 M), and ROW (to near zero value) had a declining YLLs estimate in 2019.

4. Discussions and Conclusions

In our study, we quantify the long-term impacts of $PM_{2.5}$ and MDA8 O_3 exposure from solid biofuel emissions on ambient air quality and human health during 2000–2019 on a global scale. We incorporate a state-of-the-science chemistry-climate modeling, CAM6-Chem (0.9° latitude × 1.25° longitude resolution) from NCAR CESM coupled with recently released CEDS2021 emission inventory for 2000, 2005, 2010, 2015, and 2019 to simulate $PM_{2.5}$ and O_3 concentrations from solid biofuel emission. Maximum ambient $PM_{2.5}$ and O_3 concentrations were up to 23.61 μg/m^3 and 13.69 ppbv respectively, both estimated in ROA in 2010, along with major hotspots located over China, India, SSA, and NAME. We note that the CAM6-Chem model does not simulate nitrate aerosols (Huang et al., 2020), for which there may be some uncertainties in simulated $PM_{2.5}$ concentrations but such uncertainties should be relatively low as the NO_x emission from the solid biofuel burning is relatively low, and will not have a substantial impact on the CAM6-Chem-simulated $PM_{2.5}$ outputs.

Global APDs caused by the four NCDs + LRI diseases from SB-emitted $PM_{2.5}$ and MDA8 O_3 exposure were estimated from 1.11 M (95% CI: 0.99–1.22M) to 1.43 M (95% CI: 1.30–1.56M) where global YLLs were estimated from 27.72 M (95% CI: 24.48–29.86 M) to 33.07 M (95% CI: 30.36–35.70M) during 2000–2019. Our previous study Huang et al. (2021) estimated 23.1 μg/m^3 $PM_{2.5}$ and 5.7 ppbv O_3 exposure from global solid biofuel cookstove emissions in 2010 that caused up to 0.38 M (95% CI: 0.35–0.41 M) APDs and 8.10 M (95% CI: 7.38–8.70 M) YLLs which is around 30% of the 2010 APDs [1.29 M (95% CI: 1.17–1.41M)] and YLLs [31.23 M (95% CI: 28.26–34.02 M)] estimated in our current study from all-sector solid biofuel emissions. The APDs and YLLs estimates of the current study can be explained based on the findings of our previous study (Huang et al., 2021) as the current study includes SB emissions from residential, commercial & other (RCO), industry, energy, and transportation sectors where the previous study focused on SB usage in cookstove only and can be considered as the residential solid biofuel usage. Our current findings are consistent with Huang et al. (2021), given that more sectors of solid biofuel emissions were included, resulting in 3.39–3.86 times health burden estimates attributable to the emission.

Compared to the other studies, our APD estimates from SB emission are 1.65–3.64-times higher than the already reported premature death estimates in varying years (Anenberg et al., 2010; Butt et al., 2016; Chafe et al., 2015; McDuffie et al., 2021; Silva et al., 2016). This is mostly because of the incorporation of different regional & global emission inventories, fuel types, chemistry-climate model configurations, varying model resolutions, exposure-response models, and previous versions of GBD data sets (e.g., GBD2010). Additionally, previous studies may have only focused on $PM_{2.5}$-attributable mortalities and/or on a group of acute diseases different from the 4 NCDs + LRI that we focused on while calculating the health burden. Anenberg et al. (2010) and Silva et al. (2016) used MOZART (Model for OZone and Related chemical Tracers (versions 2 and 4) to simulate $PM_{2.5}$ and O_3 concentrations where we used CAM6-Chem model simulated outputs. They also used HR derived from the IER model which is significantly lower than the HR derived from the GEMM model which may lead to the lower estimates of APDs in previous studies. The BMR used in our study is derived from a newer version of GBD data sets (GBD2019) which is much higher than the BMR used by Silva et al. (2016) retrieved from Lozano et al. (2012) or in Anenberg et al. (2010) from WHO database (WHO, 2008) which may also lead to a higher estimate of APDs and YLLs in our study. Also, previous studies focused either only on lung cancer and cardiopulmonary disease (Anenberg et al., 2010) or on IHD, COPD, lung cancer, and stroke (Silva et al., 2016) where we focus on lung cancer, IHD, COPD, stroke, and the LRI which results in higher estimates of APDs and YLLs.

Here we acknowledge the limitation of our study that mainly focused on the impacts of solid biofuel burning on ambient air quality and the associated health effects of the population exposed to this ambient air pollution regardless of indoor or outdoor solid biofuel burning conditions.

We also acknowledge the uncertainty of using GEMM for $PM_{2.5}$ attributable health burden analysis as the model mainly focuses on the outdoor $PM_{2.5}$ exposure and its association with premature deaths due to 4 NCDs + LRI whereas the usage and impacts of solid biofuel on air quality & human health are disproportionately higher in indoor settings (Fullerton et al., 2008). This uncertainty may induce underestimation of the health burden estimates as the study does not explicitly quantify the indoor air pollution and associated health effects of the population using solid biofuels indoors and/or are exposed to this indoor air pollution. Additionally, disparities of health burdens among directly and indirectly exposed populations to solid biofuel emission are not deliberately explored in our study although the populations primarily burning solid biofuels in indoor settings are at higher risk than the population not directly burning solid biofuels or are outdoors.

We also acknowledge the GEMM model fit parameters are mostly from the study of a Chinese male cohort (Yin et al., 2017) with high $PM_{2.5}$ exposure (up to 84 μg/m^3), which needs scrutinized examination to reflect the different levels of $PM_{2.5}$ exposure and population groups on the global scale. Despite such uncertainties, we used GEMM and did not use the updated version FUSION by R. T. Burnett et al. (2022), which compared global health burden estimates calculated from GEMM and FUSION respectively, and did not find a major difference between the mean burden estimates calculated by both models. The study also pointed out that the FUSION model reduced uncertainty in higher global $PM_{2.5}$ concentrations, which is not the case for our study as we estimated the global population-weighted annual mean $PM_{2.5}$ concentrations associated with solid biofuel emissions as 3.16–3.45 μg/m^3 during 2000–2019, substantially smaller than the global population-weighted annual average $PM_{2.5}$ concentrations in 2019 (34.7 μg/m^3) from all sources (Li et al., 2023). This implies that the GEMM model from R. Burnett et al., 2018 is suitable enough for calculating health burdens, particularly from solid biofuel emissions. We also acknowledge the potential of double counting the premature death estimates due to COPD as we separately calculated COPD health burden from $PM_{2.5}$ and MDA8 O_3 exposure for the same age group in each grid point. The largest influence of such double counting would mostly be observed at locations with common hotspots of elevated $PM_{2.5}$ and O_3 exposure respectively such as northern India, eastern China, central Europe, and Nigeria. Additionally, as open biomass burning emission is included in our simulation, indirect health effects of solid biomass consumption due to any increase in deforestation-related burning are not included as methodological difficulties prevent clear attribution of any such effect (Gao et al., 2011).

Based on the relative impacts of $PM_{2.5}$ and O_3 exposure on health, we observe that 92.3%–95.1% of the global total $PM_{2.5}$ -and MDA8 O_3 -attributable APDs from SB emissions are solely caused by $PM_{2.5}$ exposure during 2000–2019. $PM_{2.5}$ is often observed to have disproportionately higher impacts on different health outcomes compared to other major air pollutants (Partha et al., 2025) for which, $PM_{2.5}$ exposure reduction to a safe level must be prioritized to ensure improved global and regional public health. Developing regions for example, China, India, and ROA combined had a substantial share of the global annual total APDs (80.5%–84.3%) and YLLs (81.02%–84.13%) associated with SB-attributable $PM_{2.5}$ and MDA8 O_3 exposure during 2000–2019. This is mainly due to the large dependency on solid biofuels for household cooking, heating, and other uses in these regions. On the other hand, developed regions like WEurope, the USA, Canada, and ROW, only had 3.9%–5.1% of the global total APDs and 2.9%–3.8% of the global annual total YLLs during the study period. The premature deaths per 100,000 population in developing regions were also higher than most of the developed regions. This notable difference between APD and YLL burden between developing and developed regions is mostly because of the substantial gap between the economic status, technological advancement, environmental awareness toward air pollution control practice, national efforts of environmental justice, development and enactment of air pollution control policies, smart energy-resource budgeting agendas, advanced renewable systems for households and other important sectors, for example, energy and industry.

On a long-term scale, global SB-attributable APDs and YLLs increased up to 28.9% and 21.3% respectively in 2019 compared to 2000, which indicates the urgency to reduce solid biofuel usage on the global scale. Although China shares a substantial burden in global SB species emission, the country achieved substantial declines in SB usage and associated emissions which led to the decline of annual mean SB-emitted $PM_{2.5}$ and O_3 concentrations in China by 53.9% and 45.7% respectively in 2019. This decline had a direct impact on China's APDs and YLLs which also reduced by 40.2% and 49.9% in 2019. To achieve such a declining trend, China had to implement several air pollution action plans in recent years to reduce the use of solid biofuels as a source of energy. The 13th 5-Year Plan for Energy Development (2016–2020) set targets for reducing coal consumption and increasing the usage of clean energy resources, such as natural gas and other renewable energy resources, to improve air quality (Implementation of Bioenergy in China Country Reports, 2021). The "Prevention and Control Action Plan for Air Pollution" (2013–2017, 2018–2020, and 2021–2025) in China included measures to reduce the use of solid biofuels as well as associated $PM_{2.5}$ and PM_{10} concentrations in the residential sector by promoting the use of clean energy sources, such as electricity and natural gas for heating and cooking (Feng et al., 2019). These plans focus on improving air quality in the north and northeast regions of China, where air pollution impacts are more severe. These plans include a range of measures such as shutting down small coal-fired boilers, replacement of traditional solid biofuel usage with advanced technology, promoting the use of clean energy in the residential sector, and increasing the use of natural gas, electricity, and comparatively cleaner renewable energy sources than solid biofuel in residential, energy and industrial sectors. China's recent initiatives should be closely followed by the other regions, especially LMICs like India, ROA, SSA, and NAME which may reduce the overall impacts of solid biofuel emissions on air quality, and health impacts. As we have considered upstream solid biofuel emission related to extraction or production only and did not quantify the impacts of alternative cleaner renewable resources on air quality, and health burden, further investigation is needed to properly understand the structured reduction and adoption criteria of other renewable energy resources for ultimate health burden mitigation.

The long-term aspect of our study opens unlimited possibilities of various research opportunities to understand the big picture of the global and regional impacts of solid biofuel emissions on air quality and human health that are closely connected with the development and enactment of air pollution control policies over the past 20 years. Globally, SB trade for modern usage increased more than 5 times from 56 petajoules (PJ) to 300 PJ from 2000 to 2010 (Lamers et al., 2012), which consists of just one-third (around 38%) of the global total SB usage (Chum et al., 2011). This trade amount of SB will be substantially higher if conventional heating & cooking usage (i.e., two-thirds of the global total SB usage) is taken into account in rural environments, which is critically disadvantageous for the global air quality and human health. Our study could be used as a scientific reference for global and national policymakers and for the governments to mitigate such large dependency on long-term solid biofuel usage, especially in LMICs, through displaying adverse air quality and health outcomes linked to this emission for the past 20 years and by adopting cleaner household energy programs and smart energy-resource budgeting.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data of CESM CAM6-Chem model-simulated $PM_{2.5}$ and O_3 concentrations and associated premature deaths from global solid biofuel emission from 2000 to 2019 are available publicly at Partha (2024).

Acknowledgments

This study is supported by the National Science Foundation (AGS-2111428). We would like to acknowledge high-performance computing support from Cheyenne (https://doi.org/10.5065/D6RX99HX) provided by NCAR's Computational and Information Systems Laboratory, sponsored by NSF. We also thank the Grid supercomputer at Wayne State University for supporting the data analysis.

References

Anenberg, S. C., Henze, D. K., Lacey, F., Irfan, A., Kinney, P., Kleiman, G., & Pillarisetti, A. (2017). Air pollution-related health and climate benefits of clean cookstove programs in Mozambique. *Environmental Research Letters*, *12*(2), 025006. https://doi.org/10.1088/1748-9326/aa5557

Anenberg, S. C., Horowitz, L. W., Tong, D. Q., & West, J. J. (2010). An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling. *Environmental Health Perspectives*, *118*(9), 1189–1195. https://doi.org/10.1289/ehp.0901220

Archer-Nicholls, S., Carter, E., Kumar, R., Xiao, Q., Liu, Y., Frostad, J., et al. (2016). The regional impacts of cooking and heating emissions on ambient air quality and disease burden in China. *Environmental Science and Technology*, *50*(17), 9416–9423. https://doi.org/10.1021/acs.est.6b02533

Archer-Nicholls, S., Lowe, D., Lacey, F., Kumar, R., Xiao, Q., Liu, Y., et al. (2019). Radiative effects of residential sector emissions in China: Sensitivity to uncertainty in black carbon emissions. *Journal of Geophysical Research: Atmospheres*, *124*(9), 5029–5044. https://doi.org/10.1029/2018JD030120

Bonjour, S., Adair-Rohani, H., Wolf, J., Bruce, N. G., Mehta, S., Prüss-Ustün, A., et al. (2013). Solid fuel use for household cooking: Country and regional estimates for 1980-2010. *Environmental Health Perspectives*, *121*(7), 784–790. https://doi.org/10.1289/ehp.1205987

Burnett, R., Chen, H., Szyszkowicz, M., Fann, N., Hubbell, B., Pope, C. A., et al. (2018). Global estimates of mortality associated with longterm exposure to outdoor fine particulate matter. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(38), 9592–9597. https://doi.org/10.1073/pnas.1803222115

Burnett, R. T., Spadaro, J. V., Garcia, G. R., & Pope, C. A. (2022). Designing health impact functions to assess marginal changes in outdoor fine particulate matter. *Environmental Research*, *204*, 112245. https://doi.org/10.1016/j.envres.2021.112245

Butt, E. W., Rap, A., Schmidt, A., Scott, C. E., Pringle, K. J., Reddington, C. L., et al. (2016). The impact of residential combustion emissions on atmospheric aerosol, human health, and climate. *Atmospheric Chemistry and Physics*, *16*(2), 873–905. https://doi.org/10.5194/acp-16-873-2016

Carter, E., Archer-Nicholls, S., Ni, K., Lai, A. M., Niu, H., Secrest, M. H., et al. (2016). Seasonal and diurnal air pollution from residential cooking and space heating in the eastern Tibetan Plateau. *Environmental Science and Technology*, *50*(15), 8353–8361. https://doi.org/10.1021/acs.est.6b00082

Center for International Earth Science Information Network - CIESIN - Columbia University. (2018). *Gridded Population of the World, Version 4 (GPWv4): Population density, revision 11*. Palisades. Retrieved from https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11

Chafe, Z. A., Brauer, M., Klimont, Z., van Dingenen, R., Mehta, S., Rao, S., et al. (2015). Household cooking with solid fuels contributes to ambient $PM_{2.5}$ air pollution and the burden of disease. *Environmental Health Perspectives*, *122*(12), 1314–1320. https://doi.org/10.1289/ehp.1206340

Chowdhury, S., Dey, S., Guttikunda, S., Pillarisetti, A., Smith, K. R., & Girolamo, L. D. (2019). Indian annual ambient air quality standard is achievable by completely mitigating emissions from household sources. *Proceedings of the National Academy of Sciences of the United States of America*, *166*(22), 10711–10716. https://doi.org/10.1073/pnas.1900888116

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., et al. (2011). Bioenergy. *Renewable Energy Sources and Climate Change Mitigation*, 209–332. https://doi.org/10.1017/CBO9781139151153.006

Conibear, L., Butt, E. W., Knote, C., Spracklen, D. V., & Arnold, S. R. (2018). Current and future disease burden from ambient ozone exposure in India. *GeoHealth*, *2*(11), 334–355. https://doi.org/10.1029/2018gh000168

Dao, X., Ji, D., Zhang, X., He, J., Sun, J., Hu, J., et al. (2022). Significant reduction in atmospheric organic and elemental carbon in $PM_{2.5}$ in 2+26 cities in northern China. *Environmental Research*, *211*, 113055. https://doi.org/10.1016/j.envres.2022.113055

Donkelaar, V. A., Hammer, M. S., Bindle, L., Brauer, M., Brook, J. R., Garay, M. J., et al. (2021). Monthly global estimates of fine particulate matter and their uncertainty. *Environmental Science and Technology*, *55*(22), 15287–15300. https://doi.org/10.1021/acs.est.1c05309

Dou Kejun, W. Z. R. D. (2021). Implementation of bioenergy in China country reports. Retrieved from http://english.www.gov.cn/policies/latest_releases/2018/07/03/content_281476207708632.htm

Emmons, L. K., Schwantes, R. H., Orlando, J. J., Tyndall, G., Kinnison, D., Lamarque, J. F., et al. (2020). The Chemistry Mechanism in the Community Earth System Model Version 2 (CESM2). *Journal of Advances in Modeling Earth Systems*, *12*(4). https://doi.org/10.1029/2019MS001882

Energy Policy Review Australia. (2023). Retrieved from www.iea.org/t&c/

Feng, Y., Ning, M., Lei, Y., Sun, Y., Liu, W., & Wang, J. (2019). Defending blue sky in China: Effectiveness of the "air pollution prevention and control action plan" on air quality improvements from 2013 to 2017. *Journal of Environmental Management*, *252*, 109603. https://doi.org/10.1016/j.jenvman.2019.109603

Fullerton, D. G., Bruce, N., & Gordon, S. B. (2008). Indoor air pollution from biomass fuel smoke is a major health concern in the developing world. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, *102*(9), 843–851. https://doi.org/10.1016/j.trstmh.2008.05.028

Gao, Y., Skutsch, M., Drigo, R., Pacheco, P., & Masera, O. (2011). Assessing deforestation from biofuels: Methodological challenges. *Applied Geography*, *31*(2), 508–518. https://doi.org/10.1016/j.apgeog.2010.10.007

GBD 2019 Risk Factors Collaborators. (2020). Global burden of 87 risk factors in 204 countries and territories, 1990–2019: A systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*, *396*(10258), 1223–1249. https://doi.org/10.1016/S0140-6736(20)30752-2

Global Bioenergy Statistics Report. (2023). Retrieved from https://www.worldbioenergy.org/global-bioenergy-statistics/

Global Burden of Disease Collaborative Network. (2017). *Global Burden of Disease Study 2016 (GBD 2016) results*. Institute for Health Metrics and Evaluation (IHME). Retrieved from http://ghdx.healthdata.org/gbd-results-tool

Hickman, J. E., Andela, N., Dammers, E., Clarisse, L., Coheur, P. F., Van Damme, M., et al. (2021). Changes in biomass burning, wetland extent, or agriculture drive atmospheric NH3 trends in select African regions. *Atmospheric Chemistry and Physics*, *21*(21), 16277–16291. https://doi.org/10.5194/acp-21-16277-2021

Hu, W., Downward, G. S., Reiss, B., Xu, J., Bassig, B. A., Hosgood, H. D., et al. (2014). Personal and indoor $PM_{2.5}$ exposure from burning solid fuels in vented and unvented stoves in a rural region of China with a high incidence of lung cancer. *Environmental Science and Technology*, *48*(15), 8456–8464. https://doi.org/10.1021/es502201s

Huang, Y., Partha, D. B., Harper, K., & Heyes, C. (2021). Impacts of global solid biofuel stove emissions on ambient air quality and human health. *GeoHealth*, *5*(3). https://doi.org/10.1029/2020GH000362

Huang, Y., Unger, N., Harper, K., & Heyes, C. (2020). Global climate and human health effects of the gasoline and diesel vehicle fleets. *GeoHealth*, *4*(3), 1–13. https://doi.org/10.1029/2019GH000240

Huang, Y., Unger, N., Storelvmo, T., Harper, K., Zheng, Y., & Heyes, C. (2018). Global radiative effects of solid fuel cookstove aerosol emissions. *Atmospheric Chemistry and Physics*, *18*(8), 5219–5233. https://doi.org/10.5194/acp-18-5219-2018

IMF. (2019). World economic and financial surveys world economic outlook database-WEO groups and aggregates information.

Implementation of bioenergy in China Country Reports. (2021). Retrieved from http://english.www.gov.cn/policies/latest_releases/2018/07/03/content_281476207708632.htm

Implementation of bioenergy in India. (2021). Retrieved from https://www.ieabioenergy.com/wp-content/uploads/2021/11/CountryReport2021_India_final.pdf

Kiehbadroudinezhad, M., Merabet, A., Ghenai, C., Abo-Khalil, A. G., & Salameh, T. (2023). The role of biofuels for sustainable MicrogridsF: A path towards carbon neutrality and the green economy. *Heliyon*, *9*(2), e13407. https://doi.org/10.1016/j.heliyon.2023.e13407

Kodros, J. K., Scott, C. E., Farina, S. C., Lee, Y. H., L'Orange, C., Volckens, J., & Pierce, J. R. (2015). Uncertainties in global aerosols and climate effects due to biofuel emissions. *Atmospheric Chemistry and Physics*, *15*(15), 8577–8596. https://doi.org/10.5194/acp-15-8577-2015

Lacey, F. G., Henze, D. K., Lee, C. J., Van Donkelaar, A., & Martin, R. V. (2017). Transient climate and ambient health impacts due to national solid fuel cookstove emissions. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(6), 1269–1274. https://doi.org/10.1073/pnas.1612430114

Lamers, P., Junginger, M., Hamelinck, C., & Faaij, A. (2012). Developments in international solid biofuel trade—An analysis of volumes, policies, and market factors. *Renewable and Sustainable Energy Reviews*, *16*(5), 3176–3199. https://doi.org/10.1016/j.rser.2012.02.027

Lelieveld, J. (2017). Clean air in the anthropocene. *Faraday Discussions*, *200*, 693–703. https://doi.org/10.1039/c7fd90032e

Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., & Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*, *525*(7569), 367–371. https://doi.org/10.1038/nature15371

Lelieveld, J., Pozzer, A., Pöschl, U., Fnais, M., Haines, A., & Münzel, T. (2020). Loss of life expectancy from air pollution compared to other risk factors: A worldwide perspective. *Cardiovascular Research*, *116*(11), 1910–1917. https://doi.org/10.1093/cvr/cvaa025

Li, C., van Donkelaar, A., Hammer, M. S., McDuffie, E. E., Burnett, R. T., Spadaro, J. V., et al. (2023). Reversal of trends in global fine particulate matter air pollution. *Nature Communications*, *14*(1), 5349. https://doi.org/10.1038/s41467-023-41086-z

Liu, J., Mauzerall, D. L., Chen, Q., Zhang, Q., Song, Y., Peng, W., et al. (2016). Air pollutant emissions from Chinese households: A major and underappreciated ambient pollution source. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(28), 7756–7761. https://doi.org/10.1073/pnas.1604537113

Lozano, R., Naghavi, M., Lim, S. S., Ahn Mph, S. Y., Alvarado, M. B., Andrews Mph, K. G., et al. (2012). Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: A systematic analysis for the Global Burden of Disease Study 2010. *Lancet*, *380*(9859), 2095–2128. https://doi.org/10.1016/s0140-6736(12)61728-0

McDuffie, E. E., Martin, R. v., Spadaro, J. v., Burnett, R., Smith, S. J., O'Rourke, P., et al. (2021). Source sector and fuel contributions to ambient PM2.5 and attributable mortality across multiple spatial scales. *Nature Communications*, *12*(1), 3594. https://doi.org/10.1038/s41467-021-23853-y

McDuffie, E. E., Smith, S. J., O'Rourke, P., Tibrewal, K., Venkataraman, C., Marais, E. A., et al. (2020). A global anthropogenic emission inventory of atmospheric pollutants from sector- and fuel-specific sources (1970-2017): An application of the Community Emissions Data System (CEDS). *Earth System Science Data*, *12*(4), 3413–3442. https://doi.org/10.5194/essd-12-3413-2020

Mensah, T. N. O., Oyewo, A. S., & Breyer, C. (2021). The role of biomass in sub-Saharan Africa's fully renewable power sector – The case of Ghana. *Renewable Energy*, *173*, 297–317. https://doi.org/10.1016/j.renene.2021.03.098

Natural Resources Canada. (2016). Solid biomass fuels. Retrieved from https://publications.gc.ca/site/eng/9.814395/publication.html

O'Rourke, P. R., Smith, S. J., Mott, A., Ahsan, H., McDuffie, E. E., Crippa, M., et al. (2021). CEDS v_2021_04_21 Release Emission Data (v_2021_02_05) [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.4741285

Partha, D. B. (2024). Long_term_SB_Impacts [Dataset]. *figshare*. https://doi.org/10.6084/m9.figshare.26012284.v1

Partha, D. B., Cassidy-Bushrow, A. E., & Huang, Y. (2022). Global preterm births attributable to BTEX (benzene, toluene, ethylbenzene, and xylene) exposure. *Science of the Total Environment*, *838*, 156390. https://doi.org/10.1016/j.scitotenv.2022.156390

Partha, D. B., Yasmin, S., & Nath, H. (2025). Preterm births attributable to criteria air pollutant exposure in Bangladesh during 2015-2019. *Environmental Pollution*, *368*, 125742. https://doi.org/10.1016/j.envpol.2025.125742

Reddington, C. L., Conibear, L., Knote, C., Silver, B. J., Li, Y. J., Chan, C. K., et al. (2019). Exploring the impacts of anthropogenic emission sectors on $PM_{2.5}$ and human health in South and East Asia. *Atmospheric Chemistry and Physics*, *19*(18), 11887–11910. https://doi.org/10.5194/acp-19-11887-2019

Rooney, B., Zhao, R., Wang, Y., Bates, K. H., Pillarisetti, A., Sharma, S., et al. (2019). Impacts of household sources on air pollution at village and regional scales in India. *Atmospheric Chemistry and Physics*, *19*(11), 7719–7742. https://doi.org/10.5194/acp-19-7719-2019

Schwantes, R. H., Lacey, F. G., Tilmes, S., Emmons, L. K., Lauritzen, P. H., Walters, S., et al. (2022). Evaluating the impact of chemical complexity and horizontal resolution on tropospheric ozone over the conterminous US with a global variable resolution chemistry model. *Journal of Advances in Modeling Earth Systems*, *14*(6). https://doi.org/10.1029/2021MS002889

Shemfe, M. B., Gu, S., & Ranganathan, P. (2015). Techno-economic performance analysis of biofuel production and miniature electric power generation from biomass fast pyrolysis and bio-oil upgrading. *Fuel*, *143*, 361–372. https://doi.org/10.1016/j.fuel.2014.11.078

Silva, R. A., Adelman, Z., Fry, M. M., & West, J. J. (2016). The impact of individual anthropogenic emissions sectors on the global burden of human mortality due to ambient air pollution. *Environmental Health Perspectives*, *124*(11), 1776–1784. https://doi.org/10.1289/EHP177

Stoner, O., Lewis, J., Martínez, I. L., Gumy, S., Economou, T., & Adair-Rohani, H. (2021). Household cooking fuel estimates at global and country level for 1990 to 2030. *Nature Communications*, *12*(1), 5793. https://doi.org/10.1038/s41467-021-26036-x

Turner, M. C., Jerrett, M., Pope, C. A., Krewski, D., Gapstur, S. M., Diver, W. R., et al. (2016). Long-term ozone exposure and mortality in a large prospective study. *American Journal of Respiratory and Critical Care Medicine*, *193*(10), 1134–1142. https://doi.org/10.1164/rccm.201508-1633OC

Van Marle, M. J. E., Kloster, S., Magi, B. I., Marlon, J. R., Daniau, A. L., Field, R. D., et al. (2017). Historic global biomass burning emissions for CMIP6 (BB4CMIP) based on merging satellite observations with proxies and fire models (1750-2015). *Geoscientific Model Development*, *10*(9), 3329–3357. https://doi.org/10.5194/gmd-10-3329-2017

Weichenthal, S., Pinault, L., Christidis, T., Burnett, R. T., Brook, J. R., Chu, Y., et al. (2022). How low can you go? Air pollution affects mortality at very low levels. *Science Advances*, *8*(39). https://doi.org/10.1126/sciadv.abo3381

Wood, T., Reeve, A., & Suckling, E. (2022). The next industrial revolution: Transforming Australia to flourish in a net-zero world. Retrieved from https://grattan.edu.au/report/next-industrial-revolution/

World Health Organization (WHO). (2008). The Global Burden of Disease: 2004 update (Geneva).

Xiong, Y., Partha, D., Prime, N., Smith, S. J., Mariscal, N., Salah, H., & Huang, Y. (2022). Long-term trends of impacts of global gasoline and diesel emissions on ambient $PM_{2.5}$ and O_3 pollution and the related health burden for 2000-2015. *Environmental Research Letters*, *17*(10), 104042. https://doi.org/10.1088/1748-9326/ac9422

Yin, P., Brauer, M., Cohen, A., Burnett, R. T., Liu, J., Liu, Y., et al. (2017). Long-term fine particulate matter exposure and nonaccidental and cause-specific mortality in a large national cohort of Chinese men. *Environmental Health Perspectives*, *125*(11), 117002-1–117002-11. https://doi.org/10.1289/EHP1673

Young, P. J., Naik, V., Fiore, A. M., Gaudel, A., Guo, J., Lin, M. Y., et al. (2018). *Tropospheric ozone assessment report: Assessment of global-scale model performance for global and regional ozone distributions, variability, and trends*. Elementa. University of California Press. https://doi.org/10.1525/elementa.265

Zhao, B., Zheng, H., Wang, S., Smith, K. R., Lu, X., Aunan, K., et al. (2018). Change in household fuels dominates the decrease in $PM_{2.5}$ exposure and premature mortality in China in 2005–2015. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(49), 12401–12406. https://doi.org/10.1073/pnas.1812955115

Zheng, B., Chevallier, F., Ciais, P., Yin, Y., Deeter, M. N., Worden, H. M., et al. (2018). Rapid decline in carbon monoxide emissions and export from East Asia between years 2005 and 2016. *Environmental Research Letters*, *13*(4), 044007. https://doi.org/10.1088/1748-9326/aab2b3

Zheng, B., Tong, D., Li, M., Liu, F., Hong, C., Geng, G., et al. (2018). Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions. *Atmospheric Chemistry and Physics*, *18*(19), 14095–14111. https://doi.org/10.5194/acp-18-14095-2018