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Substantial health benefits of strengthening guidelines on indoor fine particulate matter in China

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ABSTRACT

In 2020, China for the first time developed guidelines for indoor fine particulate matter ($PM_{2.5}$) in the draft document of indoor air standards, while the associated health implication remains unclear. Here, we first estimated the $PM_{2.5}$ associated premature deaths was 965 thousand in 2019, with the indoor $PM_{2.5}$ of outdoor origin accounting for 72.9%. Then, we examined the dynamic mortalities under a scenario matrix of 36 conditions, by incorporating various shared socioeconomic pathways in 2035, the draft guidelines and the contributions of ambient $PM_{2.5}$ to indoor exposure. Although it may be improbable, the averages of premature deaths associated with ambient $PM_{2.5}$ will be 1018–1361 thousand in 2035 when the worst-case scenario of guidelines mandating a yearly (rather than daily) indoor $PM_{2.5}$ concentration of 75 μg/m^3, compared to the averages of estimation were 816–1304 thousand for better-case scenario of 35 μg/m^3. Under these scenarios, the increase in the number of premature deaths was mainly driven by population aging. In 2035, an ambitious target of yearly indoor $PM_{2.5}$ concentrations of 15 μg/m^3 is anticipated to reduce the number of deaths associated with ambient $PM_{2.5}$ by approximately 25% of the 2019 baseline. Stricter guidelines to restrict the indoor $PM_{2.5}$ concentrations are recommended to mitigate the mortality risk in the future.

1. Introduction

Although the fine particulate matter ($PM_{2.5}$) concentration has been continually declining over the past few years, $PM_{2.5}$ exposure is still a leading risk factor for premature deaths in China (Wang et al., 2020; Wang et al., 2021; Q Zhang et al., 2019). Generally, people spend > 80% of their time indoors (Dong et al., 2020). Ambient $PM_{2.5}$ accounts for ~50% of the indoor $PM_{2.5}$ exposure, whereas indoor $PM_{2.5}$ of outdoor origin (IPOO) accounts for 66–87% of the total mortalities associated with ambient $PM_{2.5}$ (Chang et al., 2017; Yun et al., 2020), reinforcing the importance of reducing both ambient and indoor $PM_{2.5}$ concentrations.

In September 2020, China released the draft of the indoor air quality standard (GB/T 18883-2020); this was the first revision that was released after implementing the original indoor air quality standard published in 2002 (GB/T 18883-2002). Although monitoring indoor air quality at a large scale is quite challenging due to privacy issues, the indoor guideline acts as an appropriate recommendation to shed direct light on protecting human health. Meanwhile, the increasing use of low-cost sensors and mass balance-based models are widely used to simulate indoor exposure, and thus approaching indoor guidelines can serve as a reference value to evaluate indoor pollution. At this stage, the draft GB/T 18883-2020 proposed that daily rather than yearly indoor $PM_{2.5}$ concentrations is reduced to at least 75 μg/m^3, which was close to the first interim target but much higher than final daily guideline of 15 μg/m^3 suggested by world health organization (WHO) in 2021 (World Health Organization. 2021). Therefore, whether such new guideline in China could offer sufficient protection remains unclear. More

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importantly, due to the ongoing urbanisation in China, the age structure and population size are changing rapidly. These changes can significantly offset the health benefits offered by improvements in air quality (Wang et al., 2019; Yue et al., 2020). Evaluating the detrimental effects of poor indoor air quality requires a comprehensive understanding of how these dynamic factors drive the $PM_{2.5}$-associated disease burden in the future.

Recently, the central government projected a range of long-term objectives to achieve socialist modernisation by 2035, indicating a move from vision to action with a new focus on public health. To attain this goal, appropriate policies and/or quality standards for healthcare and environmental protection are essential. Our research aimed to estimate the health implications of the indoor $PM_{2.5}$ guideline for 2035 and, based on our analysis, propose appropriate strategies to determine indoor air quality guidelines.

2. Methods

2.1. Overview

The flowchart of this study was illustrated in the Supplementary Material (SM), in Fig. S1. In brief, we calculated the permissible ambient $PM_{2.5}$ concentration based on indoor $PM_{2.5}$ guidelines and further estimated $PM_{2.5}$-associated deaths using the global burden of disease (GBD) approach. In step 1, the number of premature deaths caused by ambient $PM_{2.5}$ pollution in 2019 was estimated. The number of provincial premature deaths that occurred due to IPOO was determined in step 2. In step 3, we projected 36 scenarios under various indoor $PM_{2.5}$ guidelines, contributions of outdoor $PM_{2.5}$ to indoor exposure ($w_{ambient}$) and shared socioeconomic pathways (SSPs) for 2035, the year by which the long-range objectives proposed by the Chinese government are expected to be achieved. Finally, we estimated the economic loss in step 4.

2.2. Estimating mortality counts attributable to $PM_{2.5}$ pollution in 2019

Given that few studies evaluated the mortalities attributable to $PM_{2.5}$ pollution in 2019 at the county level, we have followed the GBD approach (Yin et al., 2020a) to achieve this goal. Four types of data were accessed when examining $PM_{2.5}$-associated mortalities: $PM_{2.5}$ pollution data, dose–response curve, mortality rate and population. First, we derived the annual-averaged of ambient $PM_{2.5}$ concentrations in 2019 at a county scale (2898 counties, as illustrated in Fig. S2) in China at a spatial resolution of $0.01^\circ \times 0.01^\circ$ on the grid of $PM_{2.5}$ concentrations (Wei et al., 2020). Six kinds of cause-specific mortality were considered: ischemic heart disease (IHD), stroke, lower respiratory infection (LRI), lung cancer (LC), chronic obstructive pulmonary disease (COPD) and diabetes mellitus type 2 (DM2). The relative risk (RR) of each disease attributable to ambient $PM_{2.5}$ exposure has been reported elsewhere (Yue et al., 2020). Furthermore, the age-standardised mortality rate for each province in 2019 was calculated (SM Table S1) using the age-standardised mortality rate of 2013 and the regional ratio of mortality rates between 2013 and 2019 (SM Tables S2–S3), according to previous studies (Chinese CDC 2020; Zhou et al., 2016). Finally, based on the population in 2010 at the county scale (National Bureau of Statistics, 2010), we estimated the population in 2019 using the adjusted factor of population in each city between 2010 and 2019, as derived from yearly statistical books maintained by local governments.

The $PM_{2.5}$-associated morality counts in individual counties for specific diseases ($M_{i,j}$) were calculated as described in Eq. (1):

$$M_{i,j} = \sum_{t=1} (P_{i,t} \times MR_{i,j,t} \times (RR(c_i,t) - 1)/RR(c_i,t)) \tag{1}$$

where the subscripts i, j and t represent the county, disease and age group, respectively. The parameters P, MR, RR and c represent the population size, mortality rate, RR function and $PM_{2.5}$ concentration, respectively. For LC, COPD, DM2 and LRI, the RR function was not age-dependent, and therefore, the calculation was rewritten as:

$$M_{i,j} = P_i \times SMR_{i,j} \times (RR(c_i) - 1)/RR(c_i)) \tag{2}$$

where SMR is the age-standardised mortality rate. As the county-specific SMR was unavailable, the province-specific SMR was used as tabulated in Table S1 (Chinese CDC, 2020).

The RR for stroke and IHR were age-dependent, but the detailed age structure was not available at either the county or provincial scale. Therefore, we simplified the process of morality estimation for IHD and stroke, as shown below:

$$M_{i,j} = P_i \times SMR_{i,j} \times (\sum_{t=1} FP_{i,t} \times (RR(c_i,t) - 1)/(\sum_{t=1} FP_{i,t} \times RR(c_i,t)) \tag{3}$$

FP is the population fraction of age group t, and the national age structure was used. As the $SMR_{i,j}$ for IHD and stroke were 0.045–0.26% and 0.035–0.20% in China, respectively, we demonstrated that the disparities between the standard (Eq. (1)) and simplified procedures (Eq. (3)) were <0.5% (SM Text S1 and Table S4).

Finally, the total number of premature deaths (TM) was estimated by summing the mortalities from all the diseases, as shown below:

$$TM_i = \sum_{j=1}^{6} M_{i,j} \tag{4}$$

2.3. Estimation of the number of premature deaths associated with IPOO

The mortality counts due to IPOO were estimated based on time-weighted indoor and outdoor $PM_{2.5}$ exposure. First, the IPOO was estimated using the regional infiltration factor (F_{inf-i}):

$$C_{in-i} = F_{inf-i} \times C_{out-i} \tag{5}$$

where C_{in} and C_{out} are outdoor-originated indoor and ambient $PM_{2.5}$ exposures in different counties. The infiltration factor was derived considering the penetration factor, removal rate and air exchange rates (Chen and Zhao, 2011). We adopted provincial infiltration factor that had been estimated in previous study (Hu et al., 2020).

The number of premature deaths associated with IPOO ($M_{indoor-i,j}$) was then projected using the total mortality counts and contributions from IPOO, adjusted by breath ratio and time allocated to various activities, as follows:

$$M_{indoor-i,j} = M_{i,j} \times \frac{FT_{sleep-i} \times C_{in-i} \times Q_{sleep-i} + FT_{indoor-i} \times C_{in-i} \times Q_{indoor-i}}{FT_{sleep-i} \times C_{in-i} \times Q_{sleep-i} + FT_{indoor-i} \times C_{in-i} \times Q_{indoor-i} + FT_{outdoor-i} \times C_{out-i} \times Q_{outdoor-i}} \tag{6}$$

where FT is the fraction of time spend on indoor activities, except sleeping, and outdoor activities, and Q represents the regional breath ratio (Hu et al., 2020; Yao et al., 2020).

Predicting $PM_{2.5}$-associated premature deaths in 2035

To assess the $PM_{2.5}$-associated premature deaths in 2035, a scenario matrix with 36 scenarios was first established. The scenarios considered situations with different indoor $PM_{2.5}$ guidelines, contributions from IPOO and SSPs (Table 1). We set four degrees of indoor $PM_{2.5}$ guidelines, with the daily indoor guideline of maintaining a $PM_{2.5}$ concentration of

Table 1
Scenario matrix for calculating $PM_{2.5}$-associated mortality.

Scenarios	Guideline on indoor $PM_{2.5}$ concentrations ($\mu g/m^3$) [a]	Contributions from outdoor origin	SSP scenarios
SSP1-GD75-35	The worst scenario: 75	35%	SSP1
SSP1-GD75-50	The worst scenario: 75	50%	SSP1
SSP1-GD75-65	The worst scenario: 75	65%	SSP1
SSP2-GD75-35	The worst scenario: 75	35%	SSP2
SSP2-GD75-50	The worst scenario: 75	50%	SSP2
SSP2-GD75-65	The worst scenario: 75	65%	SSP2
SSP3-GD75-35	The worst scenario: 75	35%	SSP3
SSP3-GD75-50	The worst scenario: 75	50%	SSP3
SSP3-GD75-65	The worst scenario: 75	65%	SSP3
SSP1-GD50-35	The moderate scenario: 50	35%	SSP1
SSP1-GD50-50	The moderate scenario: 50	50%	SSP1
SSP1-GD50-65	The moderate scenario: 50	65%	SSP1
SSP2-GD50-35	The moderate scenario: 50	35%	SSP2
SSP2-GD50-50	The moderate scenario: 50	50%	SSP2
SSP2-GD50-65	The moderate scenario: 50	65%	SSP2
SSP3-GD50-35	The moderate scenario: 50	35%	SSP3
SSP3-GD50-50	The moderate scenario: 50	50%	SSP3
SSP3-GD50-65	The moderate scenario: 50	65%	SSP3
SSP1-GD35-35	Promising target: 35	35%	SSP1
SSP1-GD35-50	Promising target: 35	50%	SSP1
SSP1-GD35-65	Promising target: 35	65%	SSP1
SSP2-GD35-35	Promising target: 35	35%	SSP2
SSP2-GD35-50	Promising target: 35	50%	SSP2
SSP2-GD35-65	Promising target: 35	65%	SSP2
SSP3-GD35-35	Promising target: 35	35%	SSP3
SSP3-GD35-50	Promising target: 35	50%	SSP3
SSP3-GD35-65	Promising target: 35	65%	SSP3
SSP1-GD15-35	Ambitious target: 15	35%	SSP1
SSP1-GD15-50	Ambitious target: 15	50%	SSP1
SSP1-GD15-65	Ambitious target: 15	65%	SSP1
SSP2-GD15-35	Ambitious target: 15	35%	SSP2
SSP2-GD15-50	Ambitious target: 15	50%	SSP2
SSP2-GD15-65	Ambitious target: 15	65%	SSP2
SSP3-GD15-35	Ambitious target: 15	35%	SSP3
SSP3-GD15-50	Ambitious target: 15	50%	SSP3
SSP3-GD15-65	Ambitious target: 15	65%	SSP3

Abbreviations: $PM_{2.5}$ refers to fine particulate matter, and SSP refers to shared socioeconomic pathway.
Note: a, we deemed it as yearly average in our estimations.

75 $\mu g/m^3$ designated as the worst-case scenario. In the 14th Five-Year-Plan, since the government sent up air quality target short-term 35 $\mu g/m^3$ in 2030 and long-term 15 $\mu g/m^3$ in 2050, these two values were considered in our research. An additional value of 50 $\mu g/m^3$ was also utilized for comparisons. We then forecasted the mortalities in 2035 by iterating Eqs. (1)–(6) for each scenario, using the similar method to the estimation for 2019. In each scenario, the ambient $PM_{2.5}$ concentration ($c_i^{'}$) in county i was estimated as in Eq. (7):

$$c_i^{'} = min(C_{out-i,2019}, S_{indoor} \times w) \tag{7}$$

where $C_{out-i,2019}$, S_{indoor},w and min are the yearly-averaged ambient $PM_{2.5}$ in 2019, guidelines for indoor $PM_{2.5}$ concentrations and corresponding contribution fractions from ambient $PM_{2.5}$ to indoor $PM_{2.5}$ and minimum function, respectively. The contribution fractions used in 2035 scenarios referred to the values adopted in 2019 estimation (Hu et al., 2020). Of the five scenarios for SSP (Samir and Lutz, 2017), we analysed three commonly adopted scenarios (SSP1, SSP2 and SSP3) and tabulated the corresponding population size and age structure for 2035 in Tables S5–S7. In addition, the baselines of MR for each age group were anticipated to be 30% lower than those in 2019 (Table S8) (Chinese CDC, 2020; Yue et al., 2020), in accordance with the Healthy China 2030 plan (Chinese Central Government, 2018).

2.4. Economic loss analysis

We monetize the non-market value of statistical life (*VSL*) lost to reflect additional impacts from air pollution based on the method developed in our previous study (Xie et al., 2018; Xie et al., 2019; Zhang et al., 2019b), which could represent the majority of the economic burden of the air pollution. We adopt the latest value of statistical life of about 5.10 million Yuan (3.79–6.36 million yuan) from empirical investigations using the willingness to pay method in China (Jin et al., 2020). *VSL* for other years is adjusted by the national average per capita GDP in 2019 and elasticity of 0.5 (Aldy, 2015).

$$VSL_{r,y} = VSL_{base,y0} \times \left(\frac{GDPper_{r,y}}{GDPper_{base,y0}}\right)^{elasticity} \tag{8}$$

where r is region, y is year, *GDPper* is per capita GDP, VSL_{base} is the value of statistical life in the base year. $\Delta Mort_{s,y}$ is the avoided mortality. The valuation of avoided premature mortality is estimated by multiplying *VSL* with the number of avoided deaths.

$$Total\_VSL_{y,s,r} = \Delta Mort_{s,y} \times VSL_{r,y} \tag{9}$$

3. Results

3.1. $PM_{2.5}$ exposure in 2019 in China

In 2019, the lowest annual mean $PM_{2.5}$ concentration of 11.5 $\mu g/m^3$ was found in ZanDa county in Tibet, while the highest concentration (95.4 $\mu g/m^3$) was observed in KunYu, Xinjiang (SM Fig. S2). Of the 2897 counties, approximately 1282 (44.3%) counties exceeded the national recommended guideline of 35 $\mu g/m^3$. We also determined the mean annual $PM_{2.5}$ concentration to be 35.3 ± 11.7 $\mu g/m^3$, which was slightly lower than the population-weighted value of 38.7 $\mu g/m^3$. Compared to the air quality in 2013, there was a ~51.6% decrease in $PM_{2.5}$ concentration in 2019, demonstrating the promise of implementing air pollution prevention and control action plans (Huang et al., 2018).

3.2. Premature deaths due to ambient $PM_{2.5}$ in 2019

The spatial distribution of the total premature deaths due to ambient $PM_{2.5}$ exposure at the county level in 2019 is mapped in Fig. S3 and Fig. 1: the total number of premature deaths attributable to $PM_{2.5}$ was

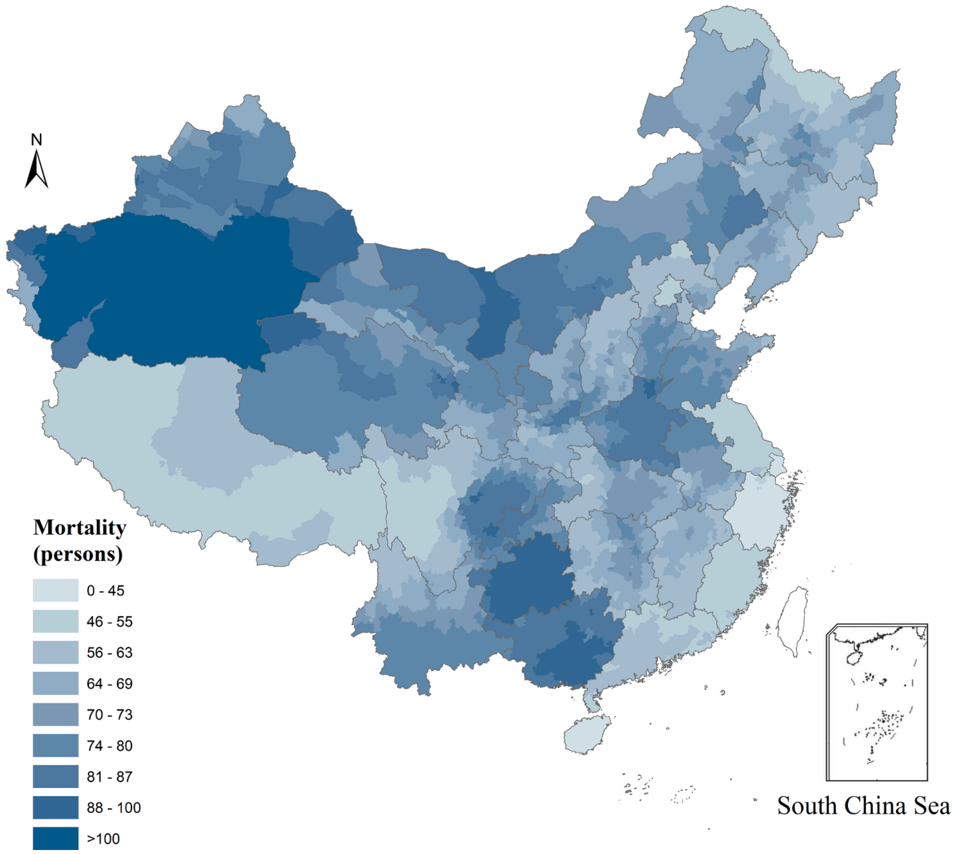

Fig. 1. The spatial distribution of standardised premature deaths per 100,000 persons due to ambient $PM_{2.5}$ exposure in 2019. The estimation for Taiwan was not conducted due to data unavailability.

estimated to be 965,323, which is concurrent with previous estimations (Yin et al., 2020a; Yue et al., 2020). Henan, Shandong, Sichuan, Guangdong and Hebei were the top five provinces with the highest numbers of premature deaths; they had approximately 80,620, 73,135, 66,334, 65,765 and 53,773 deaths, respectively. In contrast, the lowest numbers of premature deaths were seen in Macao, Tibet, Hong Kong, Qinghai, and Hainan; they had about 262, 1798, 3475, 4083 and 4982 deaths, respectively. After adjusting for the population size, the number

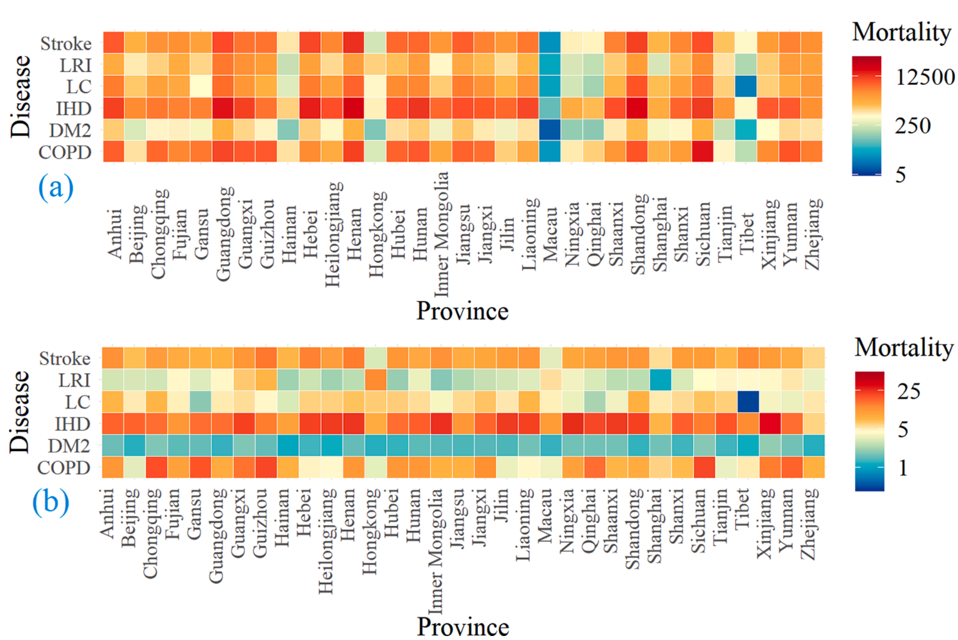

Fig. 2. The number of premature deaths that occurred due to indoor ambient $PM_{2.5}$ of outdoor origin in 2019 (unit: persons). (a) Total mortality; (b) mortality per 100,000 persons. Abbreviations: IHD, COPD, LC, LRI and DM2 refer to ischemic heart disease, chronic obstructive pulmonary disease, lung cancer, lower respiratory infection and diabetes mellitus type 2, respectively.

of premature deaths for every 100,000 persons was calculated to be 37–100, demonstrating that the spatial heterogeneities occurred due to factors such as population size, mortality baseline ratio and $PM_{2.5}$ concentration. Regarding the cause-specific mortality related to $PM_{2.5}$ pollution, the highest contribution was from IHD (36.2%, 349,490), followed by COPD (21.3%, 206,058), stroke (20.8%, 200,553), LC (11.7%, 112,875), LRI (6.9%, 67,368) and DM2 (3.0%, 28,979) (SM Table S9).

Using Eqs. (5)–(6), we evaluated the number of premature deaths due to IPOO. The nationwide IPOO-associated mortality was up to 703,533, which accounted for 72.9% of the total deaths related to ambient $PM_{2.5}$. Overall, the mortality caused by IHD, stroke, COPD, LC, LRI and DM2 was 72–24074, 23–13809, 25–18264, 15–8134, 37–4875 and 9–1586, respectively, across the 33 provinces (Fig. 2a, excluding Taiwan province due to data unavailability). Although IHD was the dominant cause of death in most regions, COPD was the leading cause in some northwestern provinces such as Sichuan, Chongqing, Gansu, Yunnan and Guiyang (Fig. 2b). In certain cold regions such as Heilongjiang, Liaoning, Jilin and Tibet, stroke lead to a higher number of deaths than COPD, likely due to spatial differences in the cause-specific mortality baseline (Zhou et al., 2016). For instance, the mortality baseline attributable to COPD in northwestern China was 2–3 folds higher than the standardised rates in other regions. The mortality baseline caused by stroke was also relatively higher in northeastern China.

3.3. Projection of $PM_{2.5}$-associated deaths in 2035

The ambient $PM_{2.5}$-associated deaths in 2035 under the tested scenarios are tabulated in Table 2. Under the worst-case assumption of guideline mandating a maximum indoor $PM_{2.5}$ concentration of 75 μg/m^3, an uptick in the number of premature deaths (relative to 2019 baseline) was noted in all scenarios, possibly driven by an increase in the proportion of elderly citizens. When a more restrictive ambient $PM_{2.5}$ concentration of 35 μg/m^3 was tested, the number of ambient $PM_{2.5}$-associated premature deaths ranged from 816 to 1304 thousand. When the ambitious target of 15 μg/m^3 was tested, the minimum mortality was reduced to 527 thousand, representing a 45% decrease from the 2019 baseline.

The SSP choices enabled us to assess the global socioeconomic changes up to the year 2100, as determined by the population size and age structure (SM Tables S5–S7). Overall, the mortality counts derived from SSP1 were the highest, followed by SSP2 and SSP3 (Table 2). In some cases, the differences between SSP1 and SSP3 were >20%. For SSP1, the population size was 1339 thousand, with 22.7% of the population aged > 65 years (Table S6); in contrast, for SSP3, the population size was 1389 thousand, with 19.3% of the population aged > 65 years (SM Table S8).

We set a contribution range of 35–65% to observe the influence of $w_{ambient}$ on the number of premature deaths, since previous studies indicated the ambient contributed about ~45% to the indoor exposure (Amato et al., 2014; Hu and Zhao, 2021). Generally, a lower $w_{ambient}$ indicates permissible ambient $PM_{2.5}$ concentrations, which reduces the

Table 2
The estimated number of ambient $PM_{2.5}$-associated cause-specific deaths under various scenarios (unit: thousand).

Scenario	COPD	DM2	IHD	LC	LRI	Stroke	Total
2019 Baseline	206(138–263)	29(21–33)	349(235–468)	113(83–142)	67(54–80)	201(87–307)	965(618–1292)
SSP1-GD75-35	300(200–385)	36(27–42)	496(333–664)	128(93–162)	97(78–115)	278(120–426)	1337(852–1794)
SSP1-GD75-50	306(205–390)	37(27–42)	505(341–672)	132(97–166)	100(80–118)	282(124–431)	1361(874–1818)
SSP1-GD75-65	306(205–390)	37(27–42)	505(341–672)	132(97–166)	100(80–118)	282(124–431)	1361(874–1819)
SSP2-GD75-35	263(175–338)	33(24–38)	426(286–571)	119(87–150)	84(68–100)	241(104–371)	1167(744–1568)
SSP2-GD75-50	268(180–342)	33(25–38)	433(292–578)	123(90–154)	86(70–102)	245(107–374)	1189(763–1589)
SSP2-GD75-65	268(180–342)	33(25–38)	433(292–578)	123(90–154)	86(70–102)	245(107–375)	1189(763–1590)
SSP3-GD75-35	230(153–295)	30(22–35)	365(244–491)	110(80–139)	73(58–86)	209(90–322)	1018(649–1368)
SSP3-GD75-50	234(157–299)	30(22–35)	372(250–497)	114(83–143)	74(60–88)	212(92–325)	1037(665–1387)
SSP3-GD75-65	234(157–299)	30(22–35)	372(250–497)	114(83–143)	75(60–88)	212(93–325)	1037(666–1388)
SSP1-GD50-35	274(177–358)	36(26–41)	460(300–626)	109(77–140)	84(65–103)	258(106–405)	1220(751–1674)
SSP1-GD50-50	298(198–383)	36(27–42)	493(330–660)	126(92–160)	96(77–114)	276(119–424)	1327(843–1784)
SSP1-GD50-65	305(205–390)	37(27–42)	504(340–671)	132(97–166)	100(80–118)	282(123–430)	1359(873–1817)
SSP2-GD50-35	240(155–314)	33(24–38)	395(257–539)	101(71–130)	73(56–89)	224(92–352)	1065(655–1462)
SSP2-GD50-50	261(174–336)	33(24–38)	423(283–568)	117(85–148)	83(67–99)	240(103–369)	1158(736–1559)
SSP2-GD50-65	268(179–342)	33(25–38)	433(292–578)	123(90–154)	86(69–102)	245(107–374)	1187(762–1588)
SSP3-GD50-35	210(135–274)	30(21–34)	338(220–463)	94(66–121)	63(49–77)	194(79–306)	928(571–1275)
SSP3-GD50-50	228(152–294)	30(22–35)	363(242–488)	109(79–138)	72(58–86)	208(89–321)	1010(642–1360)
SSP3-GD50-65	234(157–299)	30(22–35)	371(250–497)	114(83–143)	74(60–88)	212(92–325)	1036(664–1386)
SSP1-GD35-35	239(146–322)	34(24–41)	414(260–579)	87(59–115)	67(47–87)	233(89–378)	1074(626–1523)
SSP1-GD35-50	274(177–358)	36(26–41)	460(300–626)	109(77–140)	84(65–103)	258(106–405)	1220(751–1674)
SSP1-GD35-65	293(193–378)	36(27–41)	486(324–653)	123(88–156)	94(75–112)	272(116–420)	1304(823–1760)
SSP2-GD35-35	209(128–283)	31(22–37)	355(223–498)	81(55–107)	58(41–76)	202(77–329)	937(546–1329)
SSP2-GD35-50	240(155–314)	33(24–38)	395(257–539)	101(71–130)	73(56–89)	224(92–352)	1065(655–1462)
SSP2-GD35-65	257(170–331)	33(24–38)	417(277–562)	114(82–144)	81(65–97)	236(100–365)	1138(719–1,538)
SSP3-GD35-35	183(112–247)	28(20–34)	304(190–427)	75(51–99)	50(35–65)	175(67–286)	816(475–1158)
SSP3-GD35-50	210(135–274)	30(21–34)	338(220–463)	94(66–121)	63(49–77)	194(79–306)	928(571–1275)
SSP3-GD35-65	224(148–290)	30(22–35)	358(237–483)	105(76–134)	70(56–84)	205(87–317)	993(627–1342)
SSP1-GD15-35	147(74–222)	25(12–38)	288(156–441)	41(23–61)	29(13–50)	166(50–299)	698(326–1112)
SSP1-GD15-50	187(105–267)	30(19–39)	344(201–502)	59(37–83)	44(25–65)	196(66–335)	860(452–1291)
SSP1-GD15-65	215(127–297)	33(22–40)	382(233–544)	74(48–99)	56(36–77)	216(78–359)	975(543–1417)
SSP2-GD15-35	129(65–195)	23(11–34)	247(133–379)	38(22–57)	25(11–44)	144(43–259)	607(284–968)
SSP2-GD15-50	164(92–234)	27(17–36)	295(172–431)	55(34–77)	38(21–57)	170(57–291)	749(393–1125)
SSP2-GD15-65	189(111–260)	30(20–37)	327(199–468)	69(45–92)	49(31–67)	187(67–312)	850(473–1235)
SSP3-GD15-35	113(56–170)	21(10–31)	211(113–324)	35(20–53)	22(9–38)	125(37–225)	527(246–842)
SSP3-GD15-50	143(80–204)	25(15–33)	252(147–370)	51(32–71)	33(19–49)	147(49–252)	651(342–979)
SSP3-GD15-65	165(97–228)	27(18–33)	280(170–401)	64(41–86)	42(27–58)	162(58–271)	740(412–1076)

Abbreviations: IHD, COPD, LC, LRI and DM2 refer to ischemic heart disease, chronic obstructive pulmonary disease, lung cancer, lower respiratory infection and diabetes mellitus type 2, respectively.

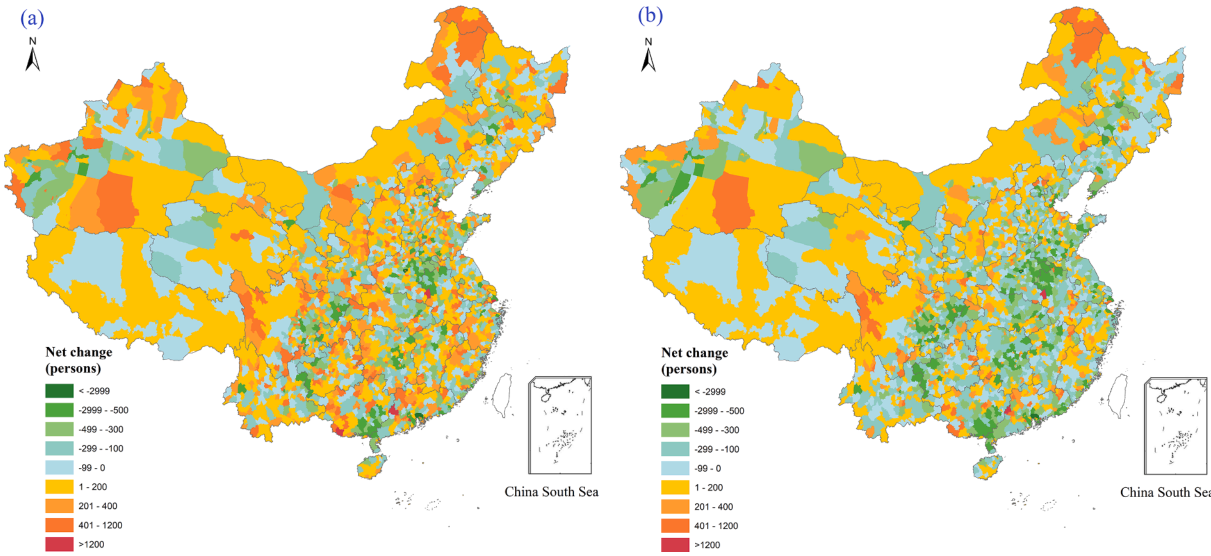

Fig. 3. The total net change in the number of ambient $PM_{2.5}$-associated premature deaths (unit: persons). (a) Between 2019 baseline and SSP2-35-50 scenario; (b) between 2019 baseline and SSP2-15-50 scenario. The estimation for Taiwan was not conducted due to data unavailability.

mortality counts (Table 2). When SSP2-GD35 was used as a case study, the number of $PM_{2.5}$-associated deaths was found to be 937 thousand, based on a $w_{ambient}$ of 35%; increasing the $w_{ambient}$ to 65% also increased the number of deaths to 1138 thousand.

Figs. 3 and S4 show in detail the spatial mortality changes that occurred between the 2019 baseline and two typical scenarios. For example, Fig. 3a and S4a show that, for the SSP2-35-50 scenario, while the number of ambient $PM_{2.5}$-associated premature deaths would decrease by 4740 (compared to the 2019 baseline) in some counties, all the provincial mortality counts would increase to 24–7646. In contrast, maintaining an ambitious indoor $PM_{2.5}$ concentration of 15 μg/m^3 could significantly reduce the number of ambient $PM_{2.5}$-associated premature deaths, especially in Shandong, Henan, Guangdong, Sichuan provinces and West China.

Fig. 4 shows the effects of an aging population, air pollution mitigation and a decrease in mortality baseline on the number of premature deaths. Although the decline in mortality baseline and air purification would reduce the number of $PM_{2.5}$-associated deaths, most of these achievements would be offset by population aging. For example, when the guideline for the indoor $PM_{2.5}$ concentration was set to 35 μg/m^3, the net mortalities attributable to the $PM_{2.5}$ concentration and mortality baseline change were approximately −124 and −247 thousand, respectively, comparing to the population aging contributed to 491 thousand mortalities. Generally, as the maximum-allowed indoor $PM_{2.5}$ concentrations reduce, the effects of mortality baseline and aging population also decrease.

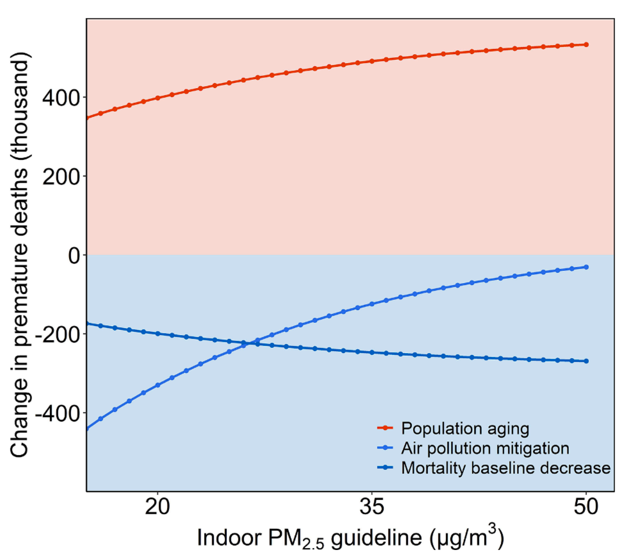

Fig. 4. Changes in the number of deaths in 2035 (compared to 2019 baseline) attributable to population aging, air pollution mitigation and decrease in mortality baseline under various indoor $PM_{2.5}$ guidelines when assuming SSP2 and 50% contribution from outdoor origin.

3.4. Economic loss analysis

Following the willingness-to-pay approach (Jin et al., 2020), we also evaluated the economic losses incurred due to of $PM_{2.5}$-related mortality. Overall, the economic loss was approximately4143 billion CNY in 2019, which is predicted to further increase in 2035 as the total mortality increases in the worst-case scenario of 75 μg/m^3. Economic losses were the highest, 6100 billion CNY, in SSP1-GD75-65 and the lowest, 2356 billion CNY, in SSP3-GD15-35 (Fig. 5). It was not surprising that intensive reductions in ambient $PM_{2.5}$ concentrations could improve health and contribute significant economic benefits. Under SSP2, with a 50% $w_{ambient}$, the economic losses were 5324 billion CNY when the draft guidelines mandated a maximum indoor $PM_{2.5}$ concentration of 75 μg/m^3. In contrast, the economic losses would reduce to 4764 billion CNY and 2911 billion CNY when the recommended concentrations are reduced to 35 μg/m^3 and 15 μg/m^3, respectively. This indicated that significant economic benefits can be gained by implementing stronger policies on the maintenance of indoor air quality.

4. Discussion

Exposure to indoor air pollutants is a mounting public concern, yet the health implications of high indoor $PM_{2.5}$ concentrations remain unclear. Our study first estimated the number of $PM_{2.5}$-associated premature deaths in 2019 as the baseline and then projected the potential health implications of different indoor $PM_{2.5}$ concentrations in the future. We found that the number of $PM_{2.5}$-associated deaths would substantially increase in China for a worst-case scenario of guidelines allowing a maximum indoor $PM_{2.5}$ concentration of 75 μg/m^3, exacerbated by population aging. Reducing the maximum-allowed indoor $PM_{2.5}$ concentrations to 35 μg/m^3 could slightly decrease the number of $PM_{2.5}$-associated deaths, indicating that stronger guidelines to regulate

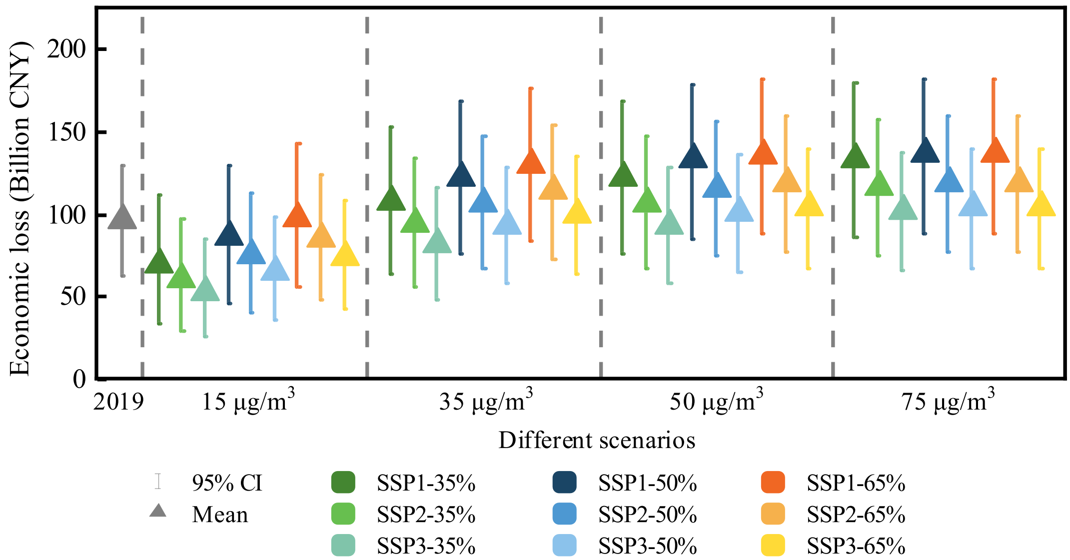

Fig. 5. Economic losses incurred due to $PM_{2.5}$-related mortality in 2019 and under different scenarios in 2035. Abbreviations: 95% CI, 95% confidence interval.

indoor $PM_{2.5}$ concentrations are required. Our study is the first of its kind to investigate future disease burden in China due to indoor $PM_{2.5}$ concentrations as most of the previous studies have focused on the health implications of ambient $PM_{2.5}$ concentrations. Our estimation considers the health benefits of ambient $PM_{2.5}$ rather by strengthening guidelines on indoor $PM_{2.5}$. Besides that, appropriate indoor air quality can reduce the mortality associated with household air, which was out of the scope of our study.

In 2012, the GB 3095-2012 released for the first time the national secondary standard of ambient $PM_{2.5}$ concentrations of 35 μg/m^3, which successfully improved the air quality in China over the last 9 years. In accordance with China's mid- and long-term clean air overall target designs, the government strives to reduce the annual ambient $PM_{2.5}$ concentration to <35 μg/m^3 and <15 μg/m^3 by 2030 and 2050, respectively. To achieve this goal, the government has implemented a large number of air pollution control measures, such as strengthening industrial and vehicle emissions standards, phasing out small polluting factories, upgrading industrial boilers, etc (Q Zhang et al., 2019). However, although the indoor $PM_{2.5}$ varied substantially depending on characteristics of buildings, human activities and ambient exposure, only a few actions have been executed to control the indoor $PM_{2.5}$ pollution. For example, the ministry of health prohibited smoking indoors in 2011, and some provinces vigorously promoted the use of clean energy sources to power indoor devices, especially in winter. The government has been prompted to formulate more documents to guide residents on the reduction of their indoor exposure. The upcoming release of the official GB/T 18883-2020 is also promising as there have been no prior national guidelines on the regulation of indoor $PM_{2.5}$ concentrations prior to this one.

The draft document of GB/T 18883-2020 also proposed the maintenance of daily rather than annual indoor $PM_{2.5}$ concentrations. The worst-case scenario of a daily indoor $PM_{2.5}$ exposure of 75 μg/m^3 appears improbable in the future as the ambient air quality in China is continuously being improved. We should note that the daily allowance of 75 μg/m^3 generally represents the yearly average is much lower, and the assumption of 75 μg/m^3 only indicated an extreme scenario. If we adopt the ratio of the daily standard (75 μg/m^3) to annual standard (35 μg/m^3) for ambient $PM_{2.5}$ concentrations, as established in the GB 3095-2012, the GB/T 18883-2020 guideline for yearly indoor $PM_{2.5}$ concentrations would be close to 35 μg/m^3. Based on this, we recommend that guidelines to maintain the annual indoor $PM_{2.5}$ concentrations be incorporated into future revisions of the policy. For example, in France, Netherlands and Belgium, the annual exposure standard of indoor $PM_{2.5}$ concentrations has already been mandated to fall in the range of 10 μg/m^3 to 15 μg/m^3.

The inclusion of $PM_{2.5}$ in indoor air quality affords a convenient recommendation for residents to protect their health. Recently, the deployment of low-cost sensors has enabled people to investigate individual indoor air quality (Mousavi and Wu, 2021; Zuo et al., 2018). For example, studies based on low-cost sensors have reported that indoor $PM_{2.5}$ concentration ranged in 42–110 μg/m^3 in Beijing (Qi et al., 2017), 17–112 μg/m^3 in Shanghai (Barkjohn et al., 2021), <10 μg/m^3 in California (Mousavi and Wu, 2021). On another aspect, calibrated models have well evaluated indoor $PM_{2.5}$ pollution at a nationwide scale (Du et al., 2018; Hu and Zhao, 2021), which commonly reported higher indoor exposure than ambient $PM_{2.5}$ standard of 35 μg/m^3. Thus, the approaching indoor $PM_{2.5}$ guideline highlights the necessities to mitigate indoor pollution.

Cooking, smoking, heating, sweeping and other human activities have been considered leading drivers of indoor sources (Chen and Zhao, 2011; Hu and Zhao, 2021; Lu et al., 2020). A recent study suggested that cooking and smoking contributed 28.6 μg/m^3 and 14.2 μg/m^3 $PM_{2.5}$ to the air people breathe, respectively (Hu and Zhao, 2021). Therefore, several approaches, such as the use of air purifiers, clean fuel, ventilations, have been suggested to reduce and control indoor $PM_{2.5}$ (Baumgartner et al., 2019; Martins and Da Graca, 2018). Existing studies indicated that $PM_{2.5}$ concentrations air cleaner decreased $PM_{2.5}$ concentrations in the home by >40% (Cooper et al., 2021; Park et al., 2017). During 2005–2015, the reduction of household $PM_{2.5}$ exposure was driven by the decreased use of solid household fuel, primarily due to the rapid urbanization and improved incomes (Zhao et al., 2018). If China can achieve the 60% substitution of solid household fuel, average indoor $PM_{2.5}$ concentrations in living rooms in winter can be decreased by approximately 40% (Meng et al., 2019). Here, our study indicated substantial health benefits by reducing indoor exposure, which can be anticipated by the joint effects of these mitigation strategies.

Some inherent uncertainties exist in our estimation, commonly grouped into three categories: approaches, dose–response curve and data availability. In our research, we majorly followed GBD 2017 approach (Yin et al., 2020a). It should be noted that the GBD 2019 has updated part of the method to evaluate the premature deaths of $PM_{2.5}$ (Murray et al., 2020). For example, the GBD 2019 added the adverse birth outcomes including low birthweight and short gestation. GBD 2019 re-evaluated the RR function using meta-regression, relaxing the log-linear assumption to allow for monotonically changing but nonlinear functions using cubic splines (Murray et al., 2020). Hence, the associated premature death based on GBD 2019 was higher than results using GBD 2017 approach. Such disparities illustrated that our study might underestimate the health benefits by strengthening indoor guideline, which further underpins the importance of improving indoor air quality.

Besides that, the uncertainty raised from dose-response curve may bring some bias in estimating the health outcomes. Most epidemiological studies on air pollution have been implemented in high-income countries with low $PM_{2.5}$ concentration, preventing us from extrapolating the steep relationship at the beginning of the exposure range to locations with high exposure, such as India and China (Murray et al., 2020). To reduce the uncertainty from extrapolation, GBD 2019 included recent studies in China and other higher-exposure settings to include more estimates at high $PM_{2.5}$ concentrations and exclude active smoking studies. In addition, the dose–response curve relied on ambient $PM_{2.5}$ exposure, though a recent study cautioned against using ambient $PM_{2.5}$ as dose metric (Wang et al., 2021). On another aspect, investigations on the dose–response curve between indoor/personal $PM_{2.5}$ and human health effects are required (Dong et al., 2020), promising to minimize the uncertainties when evaluating health implications of air pollution.

Uncertainties stemmed from data, including the infiltration factor, population information, indoor contributions and air quality, should be noted. The infiltration factor used in our study ranged from 0.49 to 0.79 (Hu et al., 2020), accounting for the spatiotemporal discrepancy in population behaviors. However, the infiltration factor was fixed at the provincial level and was not dependent on ambient concentration. The infiltration factor increases when the ambient $PM_{2.5}$ concentration decreases, partly due to an increase in the frequency of open windows. Also, a higher risk of mortality may be associated with smaller-fractioned PM (Yin et al., 2020b), which are more likely to penetrate the building, indicating that we may underestimate the health effects of indoor exposure.

Population structures such as size and aging are known as important factors in estimating deaths associated with air pollution. Our study adopted the population projection in previous studies (Samir and Lutz 2017; Wang et al., 2019; Yue et al., 2020). Given that the policy of third-child policy is being considered, predictions on populations in future may be biased. The RR for stroke and IHR was also generally higher among the elderly, implying that the standardised mortality rate will also increase with aging. Therefore, it is not surprising that an increase in the overall age of the population will result in additional mortalities by 2035 (Fig. 4). Tightening the regulations on indoor air quality will not only have direct health benefits but also considerably decrease the number of premature deaths due to population aging.

Some other data issues also have impacts on our estimations. First, in some less-polluted areas, especially in regions with annual $PM_{2.5}$ concentrations $< 35\ \mu g/m^3$, we assumed that the air quality would be maintained. Changes in the $PM_{2.5}$ concentrations depend on several factors, including energy type, carbon peaking and carbon neutrality goals, which may be difficult to predict at the city or county level. Second, the contributions of ambient $PM_{2.5}$ to indoor $PM_{2.5}$ in our study were assumed under three scenarios: 35%, 50% and 65% (Amato et al., 2014; Hu and Zhao, 2021). Generally, the contribution fractions varied spatially, which can be explained by the different human behaviors among regions. For example, the high frequency of opening windows in South China can elevate higher the contribution of ambient $PM_{2.5}$ to indoor $PM_{2.5}$ exposure. As the ambient exposure is anticipated to decrease in the future significantly, these contributions may be thus altered. Finally, the under-reporting of mortality surveillance may misestimate the $PM_{2.5}$ associated mortality risk (Guo et al., 2015).

Although many studies have estimated the mortality associated with ambient $PM_{2.5}$ exposure, few have assessed mortality due to indoor exposure. Our research revealed that IPOO resulted in 703,533 mortalities, accounting for ~72.9% of the total number of deaths that occurred due to exposure to ambient $PM_{2.5}$; this was comparable to a previously published estimate of 66–87% (Xiang et al., 2019). However, our estimate was also relatively lower than the 81–89% evaluated by Ji et al. (2015), which is attributable to the inclusion of inhalation rate in our study.

Reducing indoor pollution could bring about significant health and economic benefits. When Beijing was used as a case study, the existence of mechanical ventilation was found to achieve annual economic benefits ranging from 200 CNY to 800 CNY per capita by mitigating indoor $PM_{2.5}$ concentrations (Yuan et al., 2018). A recent study evaluated the use of air purification to reduce the indoor exposure to $35\ \mu g/m^3$ and found that it could reduce the number of deaths by 93,200 and cost by 82 billion CNY (Liu et al., 2021). Concurrent with these findings, our study determined that limiting the indoor $PM_{2.5}$ concentrations to 15–35 $\mu g/m^3$ by 2035 can save an additional 1853 billion CNY, further underscoring the necessity for stronger indoor $PM_{2.5}$ guidelines.

5. Conclusion

Overall, our results show that even if the indoor $PM_{2.5}$ concentration guideline of $35\ \mu g/m^3$ was followed, the number of premature deaths due to $PM_{2.5}$ remains high, resulting in a heavy future health burden in China. More strict guidelines regarding indoor $PM_{2.5}$ exposure are therefore required in China to improve public health, especially given the rate of population aging. Strengthening air quality guidelines will also bring significant economic benefits, helping China achieve its long-term goals by 2035.

6. Author statement

ZM Dong and Yang Xie designed the study, performed data collection and analysis and wrote the manuscript. Wanhong Fan, Yichi Zhang, Ying Wang and Peng Yin plotted the figures, analysed the results and particulated the discussion. Peng Yin and Maigeng Zhou designed the study, involved data treatment and discussion.

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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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2022.107082.

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