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Improving Air Quality and Childhood Respiratory Health in Mongolia: The Impact of the Raw Coal Ban and COVID-19 Restrictions—An Interrupted Time-Series Analysis

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Abstract: Background: In May 2019, Ulaanbaatar, Mongolia introduced a city-wide raw coal ban (RCB) to improve ambient air quality. Air pollution exposure particularly affects child health and is associated with acute respiratory disease. We assessed the effects of the RCB on air quality and child respiratory health. Methods: An interrupted time-series analysis was conducted on air quality ($PM_{2.5}$, PM_{10}, SO_2, CO) and child (<5 y) severe acute respiratory disease, adjusting for coinciding co-events (COVID-19) where necessary. The subgroup analysis focussed on peak pollution months (November–February). Results: PM_{10} significantly decreased by -34.3 μg/m^3 (95% CI -62.9, -5.8, $p = 0.02$) and $PM_{2.5}$ by -17.1 μg/m^3 (95% CI -26.3, -7.9, $p < 0.01$), immediately post-intervention. The subgroup analysis showed SO_2 increased by 81.6 μg/m^3 (95% CI 45.2, 117.9, $p < 0.01$) in the first month and by 4.9 μg/m^3 (95% CI 2.6, 7.3, $p < 0.01$) monthly afterwards. CO increased by 56.1 μg/m^3 (95% CI 13.5, 98.7, $p = 0.01$). Child respiratory health showed no significant change after adjusting for the COVID-19 effect. Discussion: The RCB successfully reduced key pollutants (PM), almost instantly. Long-term increases in SO_2 and CO and limited health effects highlight the need for further air quality improvements. Outputs from Mongolia's continuous air quality mitigation efforts provide useful insights for countries facing similar challenges.

Keywords: air quality; air pollution intervention; child health; respiratory health; COVID-19

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1. Introduction

Despite a decade of various air pollution mitigation strategies, including subsidized improved stoves and discounted night-time electricity tariffs, residents of Ulaanbaatar (Mongolia's capital) continue to be exposed to dangerous levels of air pollutants. In particular, winter coal combustion is associated with large increases in PM and SO_2, with an

associated risk of adverse health effects [1,2]. On 15 May 2019, the Government of Mongolia (GoM) implemented a ban on raw coal distribution and consumption in households and small businesses, as a short- to medium-term solution to its ongoing air pollution crisis [3]. To provide an alternative, the GoM heavily invested in subsidizing refined coal briquette production and distribution. The raw coal ban (RCB) aimed to decrease Ulaanbaatar's air pollution by 50% [4]. The effectiveness of the RCB to improve ambient air quality is critically dependent on (i) the efficacy and efficiency of its implementation, (ii) the availability, accessibility, and socio-cultural acceptability of alternative domestic energy sources, and (iii) the impact of unintended or wider negative policy consequences, such as increased air pollution related morbidity and mortality, coal black market trading, and the loss of employment opportunities in coal production and delivery sectors. To determine the RCB policy's impacts on air quality and health, a thorough and independent investigation is required following its introduction.

Whilst exposure to air pollution threatens health across the lifespan, children are particularly at risk due to both their physiology and physical proximity to the pollutants. With key developmental processes occurring during early childhood, alongside their increased respiratory rate relative to body mass and close proximity to cooking and exhaust fumes, children are more vulnerable and susceptible to the adverse effects of air pollution exposure. From early on in the 20th century, it has become clear that exposure to air pollution is a risk factor for developing respiratory morbidity and mortality in vulnerable populations such as young children and elderly [5]. Since then, a large body of evidence has become available on the association between air pollution and child respiratory health, which has been attributed to affecting (i) the (non)specific host defence system against pathogens, (ii) local inflammation of pulmonary tissue, (iii) systemic inflammation through the infiltration of (ultra)fine particles, and (iv) altered prenatal pulmonary development [5,6].

A common adverse health outcome associated with air pollution is severe acute respiratory disease, which is the second leading cause of child death in low- and middle-income countries (LMICs) [7,8]. While short-term exposure to air pollution has consistently been linked to an increased risk of respiratory illness, evidence now also suggests that longer-term exposure may also play a role through persistent inflammation and reduced pulmonary function, further raising the severe acute respiratory disease risk [7,9,10]. Furthermore, some studies suggest that impaired lung function and an increased sensitivity of children result from long-term prenatal exposure [11]. Further evidence and mechanisms of such relationships are still being explored. This clear link between air pollution exposure and child respiratory disease highlights that a reduction in exposure is needed to protect child (respiratory) health.

Coinciding with the initial stages of the RCB was the COVID-19 pandemic, which measures likely affected communicable disease outcomes such as acute respiratory diseases. Social distancing measures likely reduced the transmission of non-COVID-19 respiratory illnesses, potentially influencing the observed effects of the RCB policy on our study outcomes. Additionally, strict lockdown measures may have influenced air quality through reduced population mobility and home confinements.

To determine the effect of the RCB, it is therefore crucial to take such factors into consideration. As a result, it is possible to provide a clear overview of the policy's effects, which is crucial to achieve sustained effectiveness of this air pollution mitigation policy, especially in a country known for a high turnover in government and political agenda [12]. Findings could support health economic evaluations and guide the development of future evidence-based air pollution and health policy interventions. Furthermore, the public dissemination of such insights can in turn be useful to reduce public misinformation on

coal reduction strategies, improve its adoption, and inform air quality interventions in similar settings throughout the world.

The aim of this study is to assess the impact of the RCB on air quality and health in Ulaanbaatar, Mongolia. Specific objectives to achieve this aim are to determine the effects of the RCB on monthly air pollutant concentrations ($PM_{2.5}$, PM_{10}, SO_2, and CO) and hospital-registered childhood severe acute respiratory disease cases (<5 years old) in Ulaanbaatar by comparing trends before and after the RCB was implemented. Additionally, we sought to assess the impact of the COVID-19 restrictions on our study outcomes, which were introduced shortly after the RCB.

The hypothesis is that the successful implementation and adoption of the RCB may have significant environmental benefits, which can be reflected in decreased concentrations of both ambient and indoor air pollutants. Consequently, this can lead to a reduction in air pollution exposure and related adverse child respiratory health events.

2. Materials and Methods

A full description of the study methodology can be found in the published protocol [13]. A summarized description of the study design, outcomes, and statistical analysis methods is provided below.

2.1. Study Design

A quasi-experimental interrupted time-series study design was used for the assessment of the impacts of the RCB intervention on air quality and child severe acute respiratory disease.

2.2. Study Setting

2.2.1. Ulaanbaatar

The capital of Mongolia, Ulaanbaatar, is home to almost 1.5 million individuals, of which just over 10% are aged under five years old. Its population has been experiencing hazardous ambient air pollution levels during the winter months for more than two decades, mainly due to rapid rural–urban migration rates and a lack of affordable housing. Displaced migrants settling around the city centre, in so-called ger districts, have been relying on raw coal for cooking and heating during harsh winter months. These districts are characterized by traditional Mongolian 'ger' tents or rudimentary housing with a lack of infrastructure such as central heating, sewage, or electricity, and are seen as the main source of Ulaanbaatar's air pollution problem due to the burning of raw coal (approx. 1 million tons/year) for heating and cooking [14,15]. The GoM introduced the ban on raw coal in Ulaanbaatar on 15 May 2019 as an effort to reduce its hazardous air pollution concentrations, which predominantly occur during wintertime. Residents and small businesses in the six districts (Bayangol, Bayanzurkh, Chingeltei, Khan-Uul, Songinokhairkhan, and Sukhbaatar) were prohibited to use raw coal. As an alternative, subsidized semi-cooked coal briquettes were promoted. The ban was effective immediately, with strict regulation and enforcement since its introduction.

2.2.2. COVID-19

Shortly following the implementation of the RCB policy, the COVID-19 outbreak was declared a pandemic by the WHO, which resulted in global and nationwide precautionary public health measures. Mongolia's response to this pandemic was prompt and rigorous, which involved early closures of schools and kindergartens, public gatherings, and (international) travel from February 2020 [16]. Such public health measures inevitably affected health behaviours and transmission rates of communicable diseases such as childhood

severe acute respiratory disease. Furthermore, unlike many other countries where travel restrictions were thought to reduce ambient air pollution levels, home confinements (and thus increased stove use) in Mongolia could have negatively affected air quality and countered the benefits of the new RCB policy. Such effects from coinciding co-events ought to be considered.

2.3. Outcome Measures

Child severe acute respiratory disease (<5 years old) was chosen as a suitable health outcome due to its known relationship with air pollution exposure [2]. All registered hospital severe acute respiratory disease cases (counts) in Ulaanbaatar between May 2016 and December 2022 were collected. Severe acute respiratory disease diagnoses were determined through registration under the International Classification of Diseases (ICD)-10 codes J12–J18, including pneumonia caused by viruses, bacteria, and unknown organisms. Whilst this ICD code specifically captures pneumonia, adherence to official pneumonia diagnostic guidelines, including the use of CT scans, could not be guaranteed in this LMIC setting, resulting in the use of an alternative label of this health outcome, i.e., 'severe acute respiratory disease'. Registrations did not differentiate between admission status, nor did it include children diagnosed at primary health centres or private practices.

Particulate matter (in both the PM_{10} and $PM_{2.5}$ mass fractions), sulphur dioxide (SO_2), and carbon monoxide (CO) were chosen as representative air pollutants for assessing air quality, due to their known association with public health. Monthly temperature and humidity levels were also collected due to their potential confounding role.

2.4. Data Collection

Monthly counts of child severe acute respiratory disease cases registered in hospitals in Ulaanbaatar between May 2016 and December 2021 were collected from the national statistics office (National Center for Health Development Mongolia).

Air pollution and meteorological (temperature and humidity) data were routinely collected at the 12 weather stations monitoring air quality operated by the National Agency for Meteorology and Environmental Monitoring (NAMEM) and the Air Pollution Reduction Department (APRD), located across Ulaanbaatar, in the city centre and surrounding ger districts (see Appendix A for map of locations). Weekly air pollution and meteorological data from May 2016 to December 2021 were obtained from a publicly available air quality database (agaar.mn), run by the GoM. These data were subsequently aggregated to monthly averages to align with the temporal resolution of the health data.

2.5. Statistical Analysis

2.5.1. Descriptive Statistics

An initial descriptive analysis was conducted on both air pollution and severe acute respiratory disease data, presenting data prior to (May 2016–April 2019) and after (May 2019–December 2021) the introduction of the RCB intervention. A visual inspection assessed seasonal patterns, peak (maximum monthly average) levels, and trends, which are also described.

2.5.2. Interrupted Time-Series Analysis

Prior to the statistical analysis, an impact model was proposed based on five key factors (outcome, environmental, data collection, circumstantial, and policy factors) that were deemed to influence the policy impact assessment, which were identified through the literature and qualitative research [13]. Adjusting for seasonality is expected to be necessary for both air pollution and severe acute respiratory disease. Furthermore, due to the high enforcement of policy regulations and public awareness, the intervention effects

are deemed to be sustainable over time. The resulting proposed impact model therefore assumes, after adjusting for seasonal patterns and autocorrelation, that there should be an immediate decrease in both air pollution and severe acute respiratory disease levels upon the implementation of the RCB, followed by a stable trend downwards due to increased public awareness (e.g., trough media sources) and uptake over time as suggested in our recent mixed-methods study assessing RCB adoption amongst target populations (contact authors for details).

A segmented regression ITS analysis was conducted to assess the impacts of the RCB on air pollution and childhood severe acute respiratory disease trends using monthly aggregated outcome data. The data were evaluated for stationarity through the Augmented Dickey Fullers test, followed by assessments of white noise using Ljung–Box Q and Bartlett's test [17–19]. Further autocorrelation was identified through Durban–Watson tests and the inspection of (partial) autocorrelation plot patterns. Non-stationary variables were differenced or log transformed where necessary. An autoregressive integrated moving average (ARIMA) model was applied to adjust for the identified autocorrelation [17,18]. A residual autocorrelation after fitting the ARIMA was further assessed through the steps described above and adjusted for using adjustments in auto-regressive, integrated, or moving average components. Seasonal effects were controlled for using monthly dummy variables and/or applying seasonal ARIMA terms (SARIMA) determined by residual checks for the presence of autocorrelation. The coefficient of other covariates, including temperature, humidity, and COVID-19 were assessed for significant values ($p < 0.05$) within the ITS model output, determining the need for adjustment. A subsequent subgroup analysis was conducted on air pollution data to solely assess the effect on peak pollution months (November–February). The sensitivity analysis included lagged variables and the impact of COVID-19 pandemic-related public health restrictions in Mongolia.

Changes in outcome trends are expressed as immediate (first month following RCB) and gradual effects (subsequent monthly changes), which are also termed as level and slope changes, respectively.

3. Results

3.1. Descriptive Statistics

Air pollution data were aggregated into monthly means and visually inspected to assess for patterns and trends prior to and after the introduction of the RCB, hereafter described as the pre- and post-intervention periods, respectively. Seasonal variation patterns in air pollution levels are shown in Figure 1, in which visible reductions are shown in PM_{10} and $PM_{2.5}$ ($\mu g/m^3$) peak levels in the post-intervention period, compared to the pre-intervention period. Peak levels in the pre-intervention period ranged between 218.0 and 235.5 $\mu g/m^3$ for PM_{10}, compared to peak levels between 105.0 and 141.5 $\mu g/m^3$ in the post-intervention period (Table 1). A visible rise in average SO_2 levels in peak pollution months is seen since the introduction of the RCB, with pre-intervention peak concentrations ranging from 49.4 to 84.4 $\mu g/m^3$ and post-intervention peak concentrations ranging from 108.5 to 157.5 $\mu g/m^3$. CO does not show apparent changes in the post-intervention period.

Descriptive statistics of the severe acute respiratory disease data show a visible seasonal pattern of childhood severe acute respiratory disease cases, with yearly peaks in late winter. There is also a clear reduction in severe acute respiratory disease cases evident in the latter part of the post-intervention period (Figure 2).

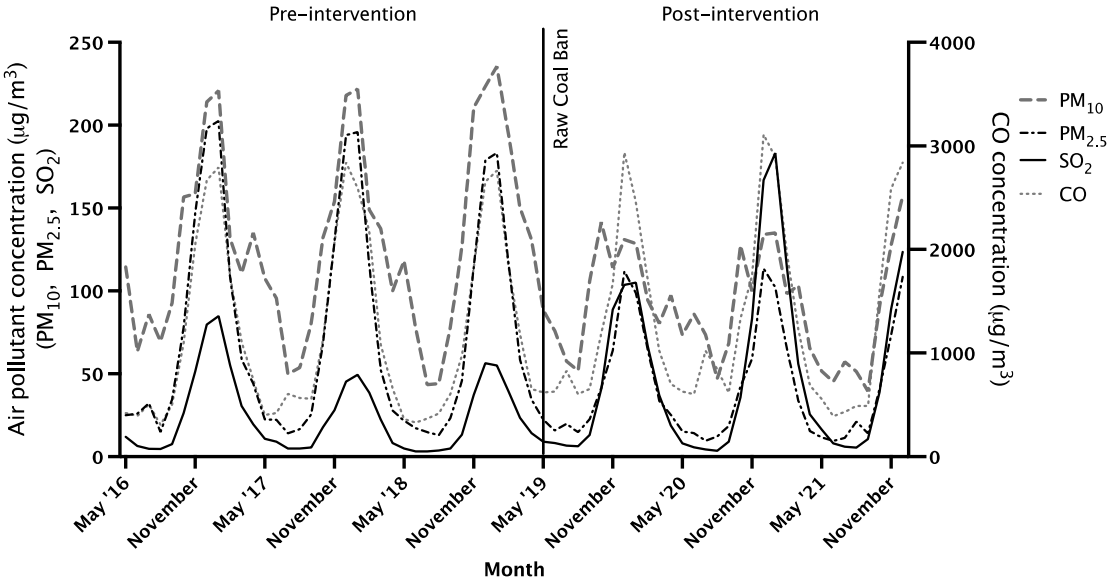


Figure 1. Monthly average air pollution concentrations (µg/m^3) for PM_{10}, $PM_{2.5}$, SO_2 (left y-axis), and CO (right y-axis) between May 2016 and December 2021. Dashed vertical line indicates introduction of the raw coal ban (May 2019).

Table 1. Descriptive statistics of pre- and post-intervention average air pollution concentrations (µg/m^3). Overall pre- and post-intervention averages (median, interquartile range (IQR)) are presented for each air pollutant (PM_{10}, $PM_{2.5}$, SO_2, and CO).

Variable (µg/m^3)	Pre-Intervention Period (2016–2019)	Post-Intervention Period (2019–2021)
	Median Overall (IQR)	Median Overall (IQR)
PM_{10}	127.3 (80.2–170.4)	89.4 (81–125.5)
$PM_{2.5}$	45.9 (22.1–126.2)	27.1 (15.9–64.1)
SO_2	16.5 (6.1–63.1)	30.3 (7.3–89.5)
CO	974.9 (445.8–1965.0)	1024.0 (649.9–1807.0)

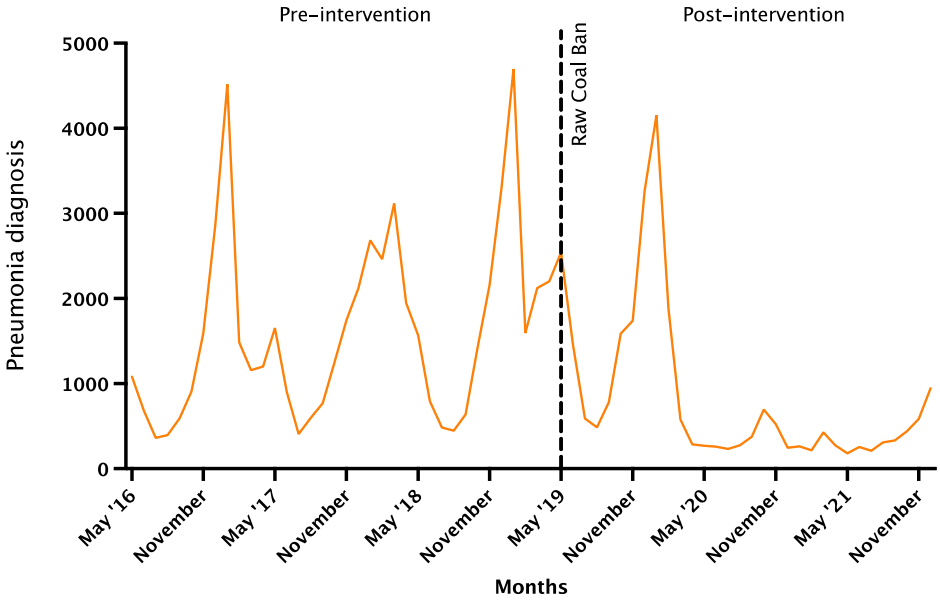


Figure 2. Monthly child (<5 years) severe acute respiratory disease cases registered in the secondary health facilities in Ulaanbaatar. Dashed vertical line indicates introduction of the raw coal ban (May 2019).

3.2. Interrupted Time-Series Analysis

An interrupted time-series analysis was conducted after the visual inspection of the descriptive data. Both PM_{10} and $PM_{2.5}$ showed significant decreased levels of −34.3 μg/m^3 (95% CI −62.9, −5.8, $p = 0.02$) and −17.1 μg/m^3 (95% CI −26.3, −7.9, $p < 0.01$), respectively, in the immediate post-intervention period (Table 2). During the following months, no further PM decreasing trends were found. SO_2 did not show an immediate level change, yet was found to have an increasing slope of 1.1 μg/m^3 per month (95% CI 0.1, 2.1, $p = 0.03$) in the post-intervention period. CO did not show any significant changes in level (88.1 (95% CI −135.1, 311.2), $p = 0.44$) or slope (4.5 (95% CI −5.7, 14.7), $p = 0.39$). These findings were adjusted for non-stationarity, seasonality, and autocorrelation.

Table 2. ITS results assessing raw coal ban intervention effects on air pollutants (PM_{10}, $PM_{2.5}$, SO_2, and CO) in μg/m^3 and childhood severe acute respiratory disease admissions (<5 years old) in Ulaanbaatar, Mongolia between May 2016 and December 2021. Bold results indicate statistically significant changes.

Outcome	Level Change (95% CI, *p*-Value)	Slope Change (95% CI, *p*-Value)
$PM_{2.5}$	−17.1 (−26.3, −7.9), **$p < 0.01$**	−0.3 (−1.1, 0.5), $p = 0.51$
PM_{10}	−34.3 (−62.9, −5.8), **$p = 0.02$**	−0.3 (−1.7, 1.1), $p = 0.68$
SO_2	5.1 (−12.0, 22.2), $p = 0.56$	**1.1 (0.1, 2.1), $p = 0.03$**
CO	88.1 (−135.1, 311.2), $p = 0.44$	4.5 (−5.7, 14.7), $p = 0.39$
Child severe acute respiratory disease (adjusted COVID-19)	−55.4 (−926.1, 815.4), $p = 0.90$	33.4 (−143.4, 210.2), $p = 0.711$
Child severe acute respiratory disease (unadjusted COVID-19)	8.9 (−850.4, 868.1), **$p = 0.02$**	**−62.7 (−120.4, −5.0), $p = 0.03$**

We found COVID-19 to be a coinciding co-event significantly impacting child severe acute respiratory disease results. Prior to adjusting for this, an immediate level change of 8.9 (−850.4, 868.1, $p = 0.02$) was found, and subsequent monthly decreases of 62.7 (−120.4, −5.0, $p = 0.03$) were found. Once the effect of COVID-19 restrictions was adjusted for, no significant level (−55.4 (95% CI −926.1, 815.4, $p = 0.90$) or slope (33.4 (95% CI −143.4, 210.2, $p = 0.71$) changes were observed following the RCB intervention (Table 2 and Figure 3).

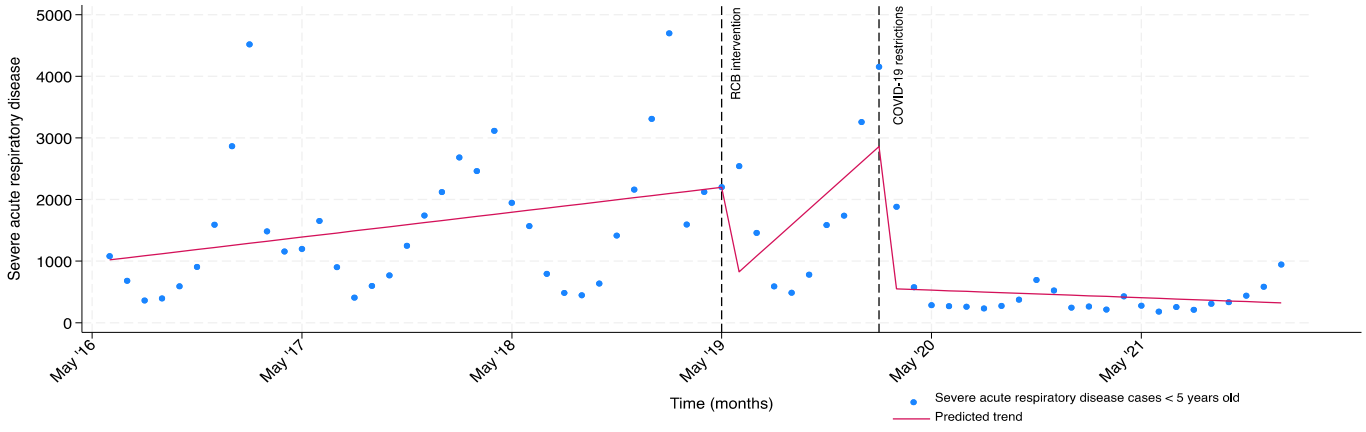


Figure 3. Interrupted time-series analysis results on the effects of the RCB on childhood severe acute respiratory disease (<5 y). Trendline indicates predicted trends without adjustment for seasonality, temperature, or humidity for improved visualisation.

The subgroup analysis using peak pollution months (November–February) was conducted to reflect changes in winter pollution months only. PM_{10} and $PM_{2.5}$ similarly showed a significant immediate decrease of −106.2 μg/m^3 (95% CI −130.3, −82.1, $p < 0.01$) and −45.3 μg/m^3 (95% CI −70.7, −19.8, $p = 0.001$), respectively. SO_2 was found to have a

significant level increase of 81.6 μg/m^3 (95% CI 45.2, 117.9, $p < 0.01$), followed by a slope increase of 4.9 μg/m^3 (95% CI 2.6, 7.3, $p < 0.01$) per month. Furthermore, the assessment of CO in the peak pollution months revealed a significant slope increase of 56.1 μg/m^3 (95% CI 13.5, 98.7, $p = 0.01$) per month in the post-intervention period (Table 3).

Table 3. Subgroup and sensitivity analysis ITS results assessing raw coal ban intervention effects on air pollutants (PM_{10}, $PM_{2.5}$, SO_2, and CO) in μg/m^3 and childhood severe acute respiratory disease admissions (<5 years old) in Ulaanbaatar, Mongolia between May 2016 and December 2021. Air pollutants were assessed during peak pollution months only (November–February). Bold results indicate a statistically significant change.

Outcome	Level Change (95% CI, *p*-Value)	Slope Change (95% CI, *p*-Value)
$PM_{2.5}$ peak months	−45.3 (−70.7, −19.8), **$p = 0.001$**	−0.1 (−3.0, 2.8), $p = 0.93$
PM_{10} peak months	−106.2 (−130.3, −82.1), **$p < 0.01$**	1.5 (−2.4, 5.4), $p = 0.46$
SO_2 peak months	**81.6 (45.2, 117.9), $p < 0.01$**	**4.9 (2.6, 7.3), $p < 0.01$**
CO peak months	−85.8 (−565.7, 394.0), $p = 0.73$	**56.1 (13.5, 98.7), $p = 0.01$**

ITS ARIMA models and adjustments used can be found in Appendix B.

4. Discussion

Air pollution interventions that aim to improve air quality have the potential to reduce emissions and consequent negative health effects. However, the extent and longevity of these improvements are highly dependent on the effectiveness of their implementation and adoption. Furthermore, the careful consideration and assessment of the (unintended) consequences of such interventions should be included in early policy monitoring efforts. Robust study methodologies are needed to accurately assess and determine the air pollution intervention's (side)effects, which in turn can provide local insights and insights for others facing similar challenges throughout the world. Timely and periodic assessments of the intervention effects are furthermore advised to keep policymakers informed on the impact of coinciding co-events, such as COVID-19 and natural disasters, as well as provide timely information on the effectiveness and unintended consequences.

Evidence on the effectiveness of raw coal bans in other settings have been encouraging. A ban on coal sale and distribution in Dublin in 1990 resulted in a substantial decrease in air pollution concentrations and related respiratory (15.5%) and cardiovascular (10.3%) death rates within the first year of its introduction [20]. Furthermore, intervention assessments in a coal ban zone in northern China have shown declines in PM of up to 60% during peak pollution in wintertime [21]. Similar to Ulaanbaatar, many cities in northern China heavily rely on coal for heating in the harsh winters, with annual average $PM_{2.5}$ and SO_2 concentrations recorded at approximately 45 and 20 μg/m^3, respectively [22].While studies have reported promising reductions in air pollution levels following such policies, they have also highlighted potential unintended consequences associated with the introduction of coal bans [21,23].

In Ulaanbaatar, initial reports characterising air pollution since the RCB introduction suggest notable reductions in ambient PM_{10}, $PM_{2.5}$, and indoor CO levels [24,25]. In the present study, similar encouraging trends in reductions in air pollutant (PM) concentrations were observed, especially in the peak pollution months. Such reductions could have huge implications on air pollution-related public health. Whilst we found a declining trend in childhood severe acute respiratory disease cases since 2019, it was determined to be heavily impacted by the effect of the COVID-19 restrictions. Public health measures introduced during the COVID-19 pandemic, such as social distancing and hygienic practices, are known to impact spread of other communicable diseases [26]. The impact of COVID-19 restrictions has not only been linked to effects on health; additionally, cities throughout

the world have reported on effects on air quality during lockdown measures [27,28]. The extent of the COVID-19 restriction's impact on air quality in Ulaanbaatar has been a topic of debate, due to the overlap with the RCB [29]. Our study reinforces the hypothesis that declines in air pollution were already ongoing prior to the COVID-19 restrictions. A potential explanation for the limited effect of COVID-19 restrictions likely lies in the source of Ulaanbaatar's air pollution. Other countries reported significant declines in air pollution during lockdowns, largely driven by reduced traffic-related emissions [27]. Ulaanbaatar's air pollution primarily originates from indoor cooking and heating, which likely increased during home confinements, offsetting potential further lockdown effects.

Links between PM and adverse health are well known and have been widely published, making it plausible to suggest that consequent health improvements are to be expected. Specifically, in Mongolia, much research has been conducted on the impact of air pollution on maternal and child health [30–32]. Reducing air pollution exposure in such a vulnerable and susceptible population could have long-term positive effects on health across the lifespan. Whether the observed reductions are enough for such effects is, however, yet to be determined. Despite showing significant reductions in PM in the peak pollution months, air quality is still far above WHO recommended guidelines (e.g., PM_{10} average annual mean 15 $\mu g/m^3$). This highlights that vulnerable populations continue to be exposed to hazardous air until further measures are taken.

Similar to other studies on coal ban policies, there were also unintended (unexpected) findings. Increases in SO_2 and CO levels are an unexpected finding, which require further investigation and longer-term monitoring to identify the cause and likely adverse health effects. These significant increases are identified to arise in the months following the ban on raw coal and transition to briquettes, possibly due to an unintended consequence of this policy and/or the effects of altered fuel use behaviour. The increases in SO_2 could be linked to the composition of the promoted coal briquettes as well as improper fuel use practices. The sulphur content of briquettes has been reported to be more than double the amount of the traditional raw coal (0.42%) [33]. This, alongside stoking practices, could significantly alter the pollution profile and both indoor and ambient air pollution exposure. SO_2 has known adverse effects on human health, including respiratory and cardiovascular disease. The effects of SO_2 are also thought to be synergistic in combination with exposure to other air pollutants [34]. Concerningly, alongside SO_2 increases, our recent publication on the impact of coal briquettes on indoor CO levels following the RCB showed that despite significant reductions in average indoor CO levels, hazardous exposure to CO persists [25]. An increase in CO poisoning cases was observed following the introduction of the RCB, which is also suggested to be linked to stoking practices [35–37]. In response to public concerns about these negative health effects from briquette use, the GoM launched an initiative to promote better fuel practices through (social) media education, encouraging frequent chimney sweeping and providing CO alarms [37].

Our current study highlights that despite remarkable improvements being made in certain air pollution levels, the effects on acute child respiratory health are limited [2,31]. Despite the visible reductions in absolute severe acute respiratory disease cases in the period following the RCB, adjusting for the COVID-19 effect showed this reduction to be most likely to be explained by early restrictions on social interaction and (pre)schools being implemented throughout the capital, which requires further investigation [16].

It should be noted that the overall implementation of the RCB has been successful in reducing key air pollutants (i.e., PM) and the cessation of raw coal use. In our recent mixed-methods study (contact authors for details) assessing facilitators and barriers to the adoption of the air pollution interventions, there was notable high uptake and support of the RCB, despite widespread safety concerns of the fuel alternative [38]. Furthermore,

there were strict regulations on the transport of raw coal into the city parameters and heavy fines for unlawful use in place. Apart from policy efficacy, this study highlights the need to assess the public understanding and adoption of air pollution interventions. The unexpected rise identified in SO_2 and CO, along with the rise in unintended health consequences (CO poisoning), highlights the need for the early assessment of (i) alternative fuel pollution profiles, (ii) public understanding of the policy, and (iii) public awareness of health consequences.

To our knowledge, this study is the first to formally assess the effects of the RCB on air quality trends and health. While previous reports address initial changes in air quality following the RCB policy, they did not assess or account for trend changes over the years. The current study uses an ITS analysis method, which is considered the most appropriate approach for this kind of natural experiment. Our study's findings could be strengthened by lengthening the study period, to include more years after the COVID-19 pandemic, as well as including other health outcomes. Health outcomes such as all-cause mortality or cardiovascular disease are commonly used as a representative parameter to assess air pollution and public health. Adding such outcomes to the RCB impact analysis could provide important insights into the effects of this RCB intervention on population health levels.

Insights gained from this study could enhance the effectiveness of promising air pollution mitigation strategies such as the RCB. This, in turn, could improve policy sustainability and longer-term uptake, which subsequently could improve public health. Demonstrating improvements in key air pollutants could encourage global policymakers facing similar challenges to consider implementing such short- to medium-term air pollution mitigation strategies whilst continuing efforts towards cleaner longer-term solutions.

In conclusion, Mongolia has demonstrated how air quality can be rapidly improved through policy change. Despite these efforts, air quality remains a threat in Ulaanbaatar and worldwide. Vulnerable populations, such as children and pregnant women, are still at risk. Further assessments of the impact of the observed rapid reductions in particulate matter are deemed necessary to fully understand the health benefits of this air pollution intervention, including pregnancy outcomes, overall mortality, and cardiovascular disease.

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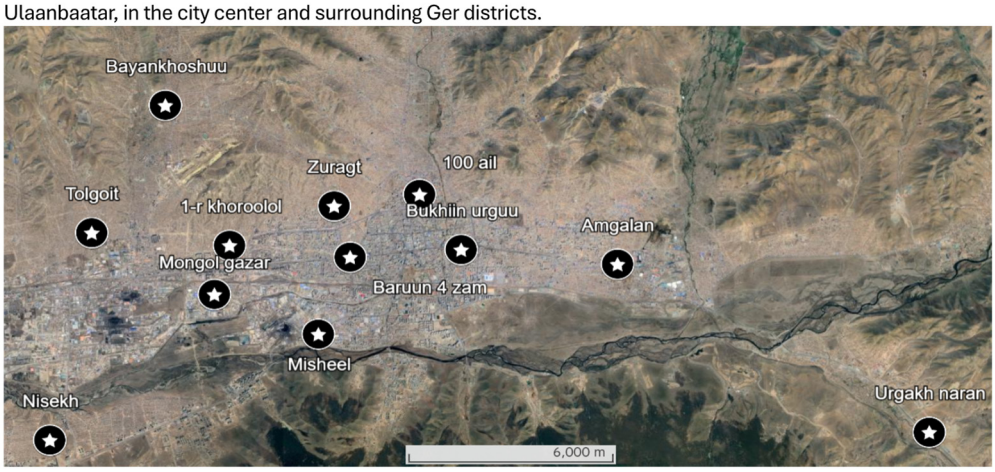
Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Improving Air Quality and Childhood Respiratory Health in Mongolia: The Impact of the Raw Coal Ban and COVID-19 Restrictions—An Interrupted Time-Series Analysis

APPENDIX A

Map of the 12 weather stations monitoring air quality operated by the National Agency for Meteorology and Environmental Monitoring (NAMEM) and the Air Pollution Reduction Department (APRD), located across Ulaanbaatar, in the city center and surrounding Ger districts.



Station	Name	Latitude	Longitude
UB03	1-r khoroolol	47°55'7.68 "N	106°50'52.08"E
UB05	100 ail	47°55'58.8"N	106°55'17.04"E
APRD03	Amgalan	47°54'48.6"N	106°59'52.8"E
UB02	Baruun 4 zam	47°54'55.8"N	106°53'40.2" E
APRD05	Bayankhoshuu	47°57'28.08"N	106°49'22.8"E
UB04	Bukhiin urguu	47°55'3.36"N	106°56'15"E
UB01	Misheel	47°53'38.4"N	106°52'55.92"E
UB07	Mongol gazar	47°54'18.36"N	106°50'30.84"E
APRD04	Nisekh	47°51'51.84"N	106°46'41.88"E
APRD01	Tolgoit	47°55'20.28"N	106°47'39.84"E
UB08	Urgakh naran	47°51'59.4"N	107°7'4.8"E
APRD06	Zuragt	47°55'47.28"N	106°53'17.88"E

Station(s)	Equipment Name	Manufacturer	Air Pollutant	Detection Principle
UB01-05, UB07-08	AF22M/e	Envea, France	SO_2	UV Fluorescence gas monitor
UB01-05, UB07-08	CO12M/e	Envea, France	CO	Non-dispersive InfraRed gas monitor
UB01-05, UB07-08	MP101M	Envea, France	PM10/PM2.5	Particulate analyzer
APRD01-05	APSA370	Horiba, Japan	SO_2	UV Fluorescence gas monitor
APRD01-05	CO12e	Horiba, Japan	CO	Non-dispersive InfraRed gas monitor
APRD01-04	EDM180	Grimm, Germany	PM10/PM2.5	Light scattering method
APRD05	BAM	Horiba, Japan	PM10/PM2.5	Beta attenuation monitor

Figure A1. Air pollution (weather) station map.

Appendix B

Improving Air Quality and Childhood Respiratory Health in Mongolia: The Impact of the Raw Coal Ban and COVID-19 Restrictions—An Interrupted Time-Series Analysis

APPENDIX B

Outcome variable	Model	Covariates	Seasonality adjustment	Final model
PM25	ARIMA, SARIMA	Temperature, Humidity	SARIMA	arima pm25 Time RCBperiod interaction Temp RelHum, arima(3,0,0) sarima(1,0,0,12)
PM10	ARIMA, SARIMA	Temperature, Humidity	SARIMA	arima pm10 Time RCBperiod interaction Temp RelHum, arima(1,0,0) sarima(1,0,0,12)
SO	ARIMA, SARIMA	Temperature, Humidity	SARIMA	arima SO Time RCBperiod interaction Temp RelHum, arima(2,0,0) sarima(1,0,0,12)
CO	ARIMA, SARIMA	Temperature, Humidity	SARIMA	arima CO Time RCBperiod interaction Temp RelHum, arima(1,0,0) sarima(1,0,0,12)
PM25 peak	ARIMA	Temperature, Humidity	None	arima pm25 Time RCBperiod interaction Temp RelHum, ar(2)
PM10 peak	ARIMA	None	None	arima pm10 Time RCBperiod interaction, ar(2)
SO peak	ARIMA	Temperature, Humidity	None	arima SO Time RCBperiod interaction Temp RelHum, ar(3)
CO peak	ARIMA	Temperature, Humidity	None	arima CO Time RCBperiod interaction Temp RelHum, arima(2,0,0)
Pneumonia	ARIMA	Temperature, COVID	SARIMA	arima pneu Time RCBperiod interaction Temp COVIDperiod Covidinteract, arima(1,0,0) sarima(1,0,0,12)
Software used : STATA SE 18.5 All models included diagnostic checks as listed in table below				

Diagnostic check	Test type	Adjustment/action
Stationarity	Augmented Dickey Fuller	Differencing or log transformation
White noise	Ljung-Box Q Bartlett	ARIMA, SARIMA
Autocorrelation	Durban-Watson ACF/PCF plots	

Figure A2. ITS models.

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