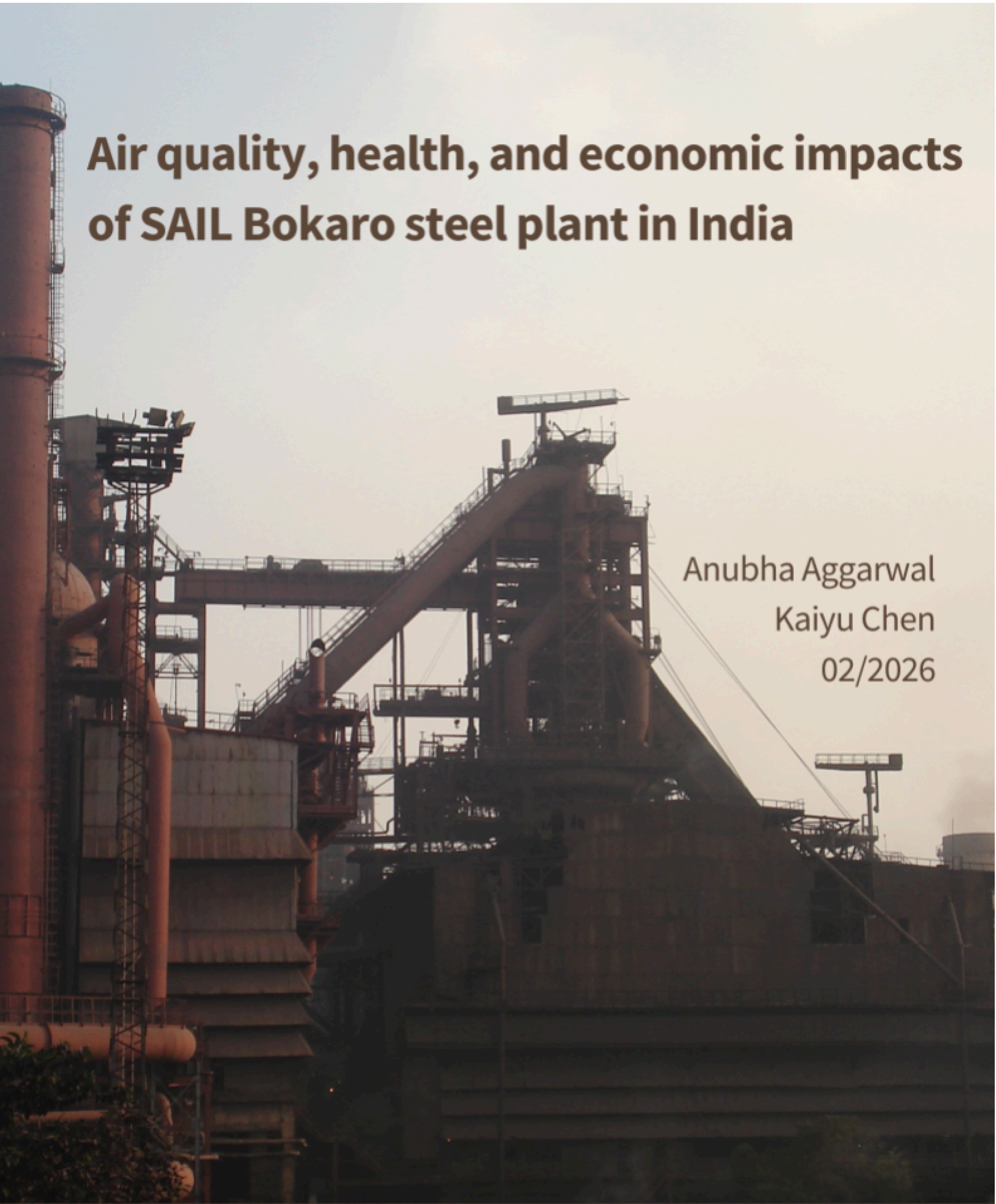
Air quality, health, and economic impacts of SAIL Bokaro steel plant in India



Anubha Aggarwal
Kaiyu Chen
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CREA

Health Impact Assessment
CREA HIA

Air quality, health, and economic impacts of SAIL Bokaro steel plant in India

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Authors
Anubha Aggarwal; Kaiyu Chen

Editor / Designer
Jonathan Seidman

Contributors
Jamie Kelly; Lauri Myllyvirta; Nandikesh Sivalingam

Cover photo
SuLTan0203

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Key findings

CORRIGENDUM, 27 February 2026 – *In the initial report published on 26 February 2026, the following sentence on page six of the introduction stated that, 'The steel industry is classified as one of the 17 highly polluting industries by India's Central Pollution Control Board (CPCB), with a capacity of 150 million tonnes of steel per year and plans to more than double this number by 2030.' This sentence should read, 'The steel industry is classified as one of the 17 highly polluting industries by India's Central Pollution Control Board (CPCB), with a capacity of 150 million tonnes of steel per year and plans to add another 100 MT by 2030'. The report has been updated. We apologise for any inconvenience.*

This report assesses how poorly regulated stack emissions from the Steel Authority of India Limited's (SAIL) Bokaro Steel Limited (hereafter referred to as BSL) plant have affected air quality, public health, and India's economy during the facility's operations in the financial year 2023. The plant's technology configuration is representative of most integrated steel plants in India, therefore offering broader relevance for the overall sector.

- Air pollutant emissions from the Bokaro steel plant severely affect child health, leading to an estimated 273 (84–475) low birthweight births and 284 (137-301) preterm births each year. The emissions also severely compromise the respiratory health of children, our estimates suggesting 25 (5–59) new cases of asthma in children for each year of operation of the plant.
- In adults, the emissions from the plant — which uses highly polluting reactor fuels including coal and coke and lacks adequate air pollution control measures in several of its stacks — are linked to an estimated 168 (112-246) deaths due to exposure to $PM_{2.5}$ and NO_2 as well as 290 (173-406) asthma-related emergency room visits each year.

- Air pollution from the Bokaro steel plant can be linked to 123,000 (104,000-141,000) days of work absences due to air pollution-related health issues. These absences represent lost productivity, disrupted workflows, and reduced economic output across multiple sectors.
- The annual total cost due to health impacts from air pollution caused by the Bokaro steel plant is estimated at USD 79 (50-116) million, or INR 6.4 (4.0-9.5) billion, in 2023.
- There are no national standards for SO_2 emissions from facilities like sinter plant, mill zone and refractory material plant in India, despite them being recognised as sources of SO_2 emissions.

Introduction

Air pollution has a detrimental impact on the global environment, public health, and economy. Exposure to air pollutants, such as fine particulates ($PM_{2.5}$), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2), leads to negative impacts on nearly all the major systems and organs of the human body, including the respiratory, cardiovascular, and reproductive systems, as well as the brain, heart, and lungs. Health outcomes range from asthma in adults and children, preterm and underweight births in pregnant women, work absences, and even death through diseases including ischaemic heart disease, chronic obstructive pulmonary disease, lung cancer, lower respiratory infections, and diabetes (Lelieveld et al., 2019; World Health Organization, 2021).

Globally each year, the impacts of exposure to air pollution include 2 million paediatric asthma cases (Anenberg et al., 2022), 1 billion days of work absences (Organisation for Economic Co-operation and Development, 2016), and over 6 million deaths (Lelieveld et al., 2019). As a result of these health consequences, air pollution costs the global economy USD 8 trillion (World Bank, 2022).

Across India, air pollutant levels regularly breach guideline levels set by the World Health Organization (WHO) (Jaganathan et.al, 2025), to the extent that it is consistently ranked as one of the most polluted countries in the world (IQAir 2025). A study published in 2021 suggested that industries are responsible for 21 to 38% of $PM_{2.5}$ and 23 to 37% of PM_{10} pollution in India (Ganguly et.al, 2021).

The steel industry is classified as one of the 17 highly polluting industries in India (CPCB). India currently has a capacity of almost 200 million tonnes of steel per year (MTPA) and plans to add another 100 MT by 2030 (Ministry of Steel, 2017). In early 2025, Global Energy Monitor (GEM) reported that 113 MTPA of 152 MTPA iron worldwide is produced through emissions intensive blast furnaces (BF); and 135 MTPA of the 155 MTPA crude steel capacity uses Basic-Oxygen Furnace (BOF); India also accounts for 57% of all coal-based BOF steelmaking capacity under development globally. (Astrid-Grigsby-Schulte et. al., 2025).

Environmental, health, and economic impacts from steel plants in India have been previously established (CREA, 2022). The sector was found to be least transparent and most 'shy of public scrutiny' in an assessment in a study that scored 'green-ness' of sectors based on sector-specific key pollution indicators (CSE, 2012).

Steel Authority of India Limited (SAIL) alone accounts for 13% of the total crude steel capacity in India, with India's government holding a 65% equity in the company as of

December 2025. The company operates five integrated steel plants: Bhilai Steel plant, Bokaro Steel Plant, Durgapur Steel Plant, Rourkela Steel Plant, and IISCO Steel Plant. It also operates three special steel plants (Salem Steel Plant in Tamil Nadu, Visvesvaraya Iron & Steel Plant in Karnataka, Alloy Steel Plant in West Bengal) and Ferro Alloys Plant at Chandrapur, Maharashtra.

The SAIL BSL steel plant, located in Bokaro, Jharkhand, is one of the oldest steel plants in India. The plant has a capacity of 5.25 MTPA and produces crude steel using the BF-BOF route. Extensive use of coal and metallurgical coke in this process renders this route highly polluting and emission intensive.

Bokaro was selected as the focus for this study for multiple reasons:

- First, of all SAIL's integrated steel plants, BSL had the most consistently available environmental emissions data, enabling a robust and comparative analysis.
- Second, BSL is located in a region that is home to several other industries such as, power plants, coal washeries, cement plants, and others, and the plant's operations are expected to significantly contribute to regional air-quality stresses. Media reports on local monitoring data (Jamwal, 2025), state-level air-quality plans have flagged the Bokaro district for air-quality concerns (MoHFA 2024), noting that the district's average air quality index (AQI) reading is above 200. There have also been community complaints (ToI, 2025) and documented non-compliance with 'pollution control measures' (ToI 2013) at BSL.
- Third, SAIL has announced a planned expansion of the plant from 5.25 MTPA to 7.5 MTPA, with an investment of INR 20 crores (Economic Times, 2025). This expansion is expected to substantially increase the plant's fuel consumption and emissions, making an assessment of its current environmental performance timely and policy-relevant.

Moreover, BSL's technology configuration — coke ovens, sinter plant, blast furnaces, BOF converters, and reheating furnaces — is representative of most integrated steel plants in India. Therefore, insights from Bokaro steel plant offer broader relevance for understanding the environmental, health and economic impact of India's steel sector.

Scope of study and methodology

In this study, we perform a health impact assessment (HIA) of the air pollution from the Bokaro steel plant. To achieve this, stack emissions from different facilities within the Bokaro steel plant — sinter plant, coke oven, refractory material plant, blast furnace (BF) and steel melting shop (SMS) — from April 2023 to March 2024 have been used to understand the health and economic impact of the industry in its vicinity.

Next, we simulate pollutant concentrations in the surrounding atmosphere by using an industry-standard air pollution model (Scire et al., 2000).

Finally, we estimate health outcomes and economic costs by combining pollutant exposure with CREA's detailed, globally implementable HIA framework (Myllyvirta, 2020), which is updated continuously based on the latest science. The general HIA approach and specific functions and data sources are all widely used by scientists and governments worldwide (Eionet Portal, 2021; EPA, 2011; Zhang et al., 2019), and are based on scientific information that has been established through the use of scientific research.

It's important to note that only $PM_{2.5}$ and NO_2-associated health impacts are calculated. Health endpoints for both pollutants are calculated based on estimations from multi-pollutant models and are additive.

For a detailed description of this methodology, please refer to the Annexure at the end of the report.

Results

Pollutant emissions

Here, we present the emissions of toxic pollutants from the Bokaro steel plant. The total annual emissions of Total Suspended Particulate Matter (hereinafter referred to as PM), NO_X and SO_2 from all sources of the Bokaro steel plant have been calculated using the monitored stack emission results and flue gas flow rate as provided in the six monthly compliance reports for April 2023 to March 2024 of BSL (Bokaro Steel Limited, 2024). The aforementioned reports are hereinafter referred to as 'compliance reports'.

Table 1 gives total annual emissions of PM, $NO_{X,}$ and SO_2 from all sources of Bokaro steel plant.

Table 1 — Total emission of pollutants from Bokaro steel plant

Pollutant	Total (thousand tonnes per year) (approx.)
PM	34.7
NO_X	19.6
SO_2	47.7

Source: CREA analysis of BSL compliance reports, 2025

In Figure 1, we further break down the annual total pollutant emissions or PM, NO_X and SO_2 for the Bokaro steel plant from different plant processes. Emission of PM, NO_X and SO_2 from each stack from all facilities are summarized in this figure.

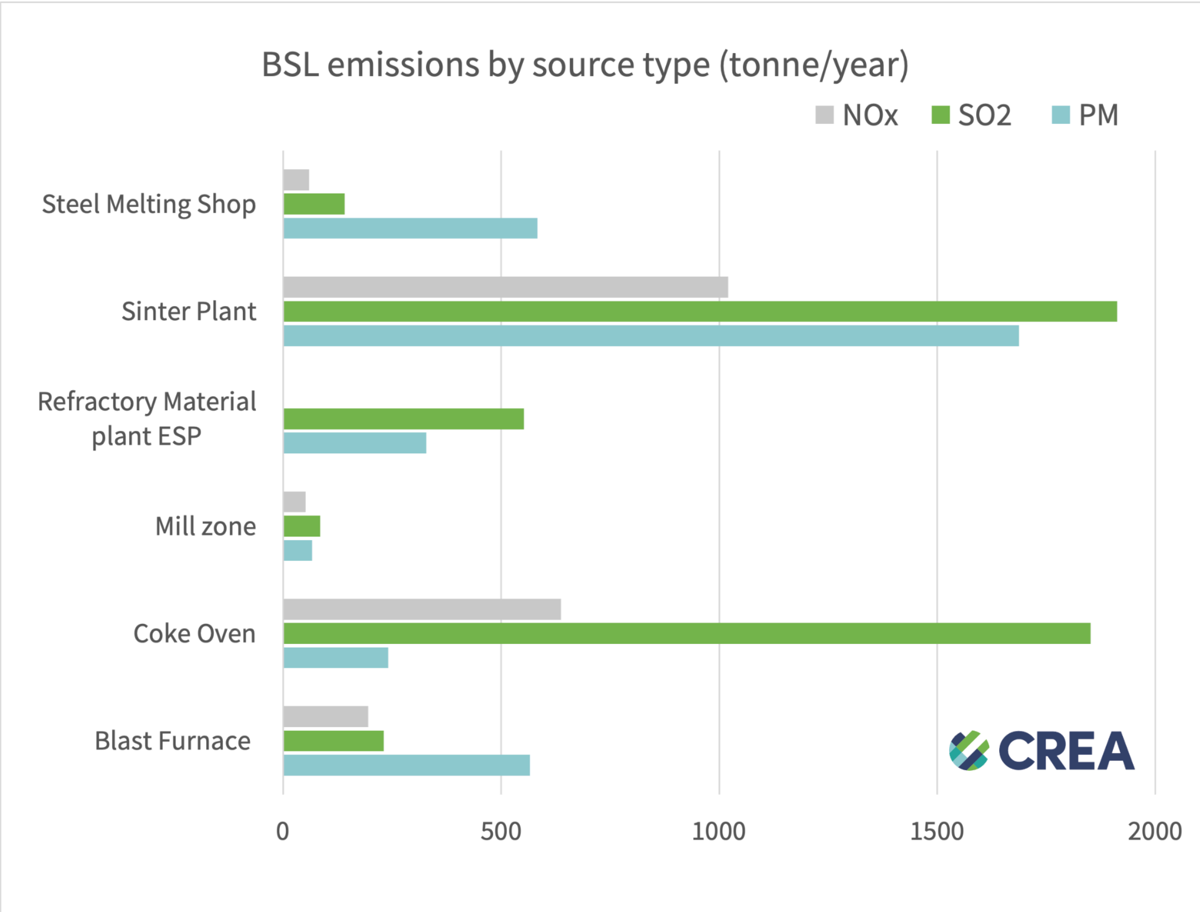

Figure 1 — BSL emissions by source type (tonne/year)

These figures are likely an underestimation of the true pollutant emissions from this steel plant, as noting that there are some facilities and stacks for which we do not have any data available, meaning these estimations only account for available data.

From this study, we have also been able to quantify that the sinter plant is the highest-emitting zone in the BSL steel plant,contributing 49% of total PM emissions, 40% of total SO_2 emissions, and 52% of total NO_X emissions. Table 2 lists the percentage share of different facilities in annual air pollutant emissions from the plant.

Table 2 — Percentage share of different facilities in BSL plant in total PM, SO_2 and NO_X pollution

Plant units	PM	SO_2	NO_X
Blast Furnace	16.%	5%	10%
Coke Oven	7%	39%	32%
Mill zone	2%	2%	3%
Refractory Material plant	9%	12%	0%
Sinter Plant	49%	40%	52%
Steel Melting Shop	17%	3%	3%

Source: CREA analysis of BSL compliance reports, 2025

Pollutant concentrations

In this study, we simulated how the Bokaro steel plant contributes to the ground-level concentrations of atmospheric pollutants, including $PM_{2.5}$, NO_2 and SO_2 (as shown in the figures below) — in the immediate vicinity of the plant, BSL increases annual mean pollution concentrations by more than 1.2, 0.6, and 1.5 µg/m^3 , respectively . This suggests that the steel plant is damaging for local communities.

Air pollution also has long-range impacts — $PM_{2.5}$ persists in the atmosphere for one to two weeks, meaning that it doesn't only affect local communities, but also the wider region. For instance, in cities nearby, such as Ranchi, the Bokaro steel plant leads to increases in $PM_{2.5}$, NO_2, and SO_2 of 0.15, 0.05, and 0.2 µg/m^3, respectively. Overall, we find that the steel plants degrade air quality in both the local area, as well as in downwind regions.

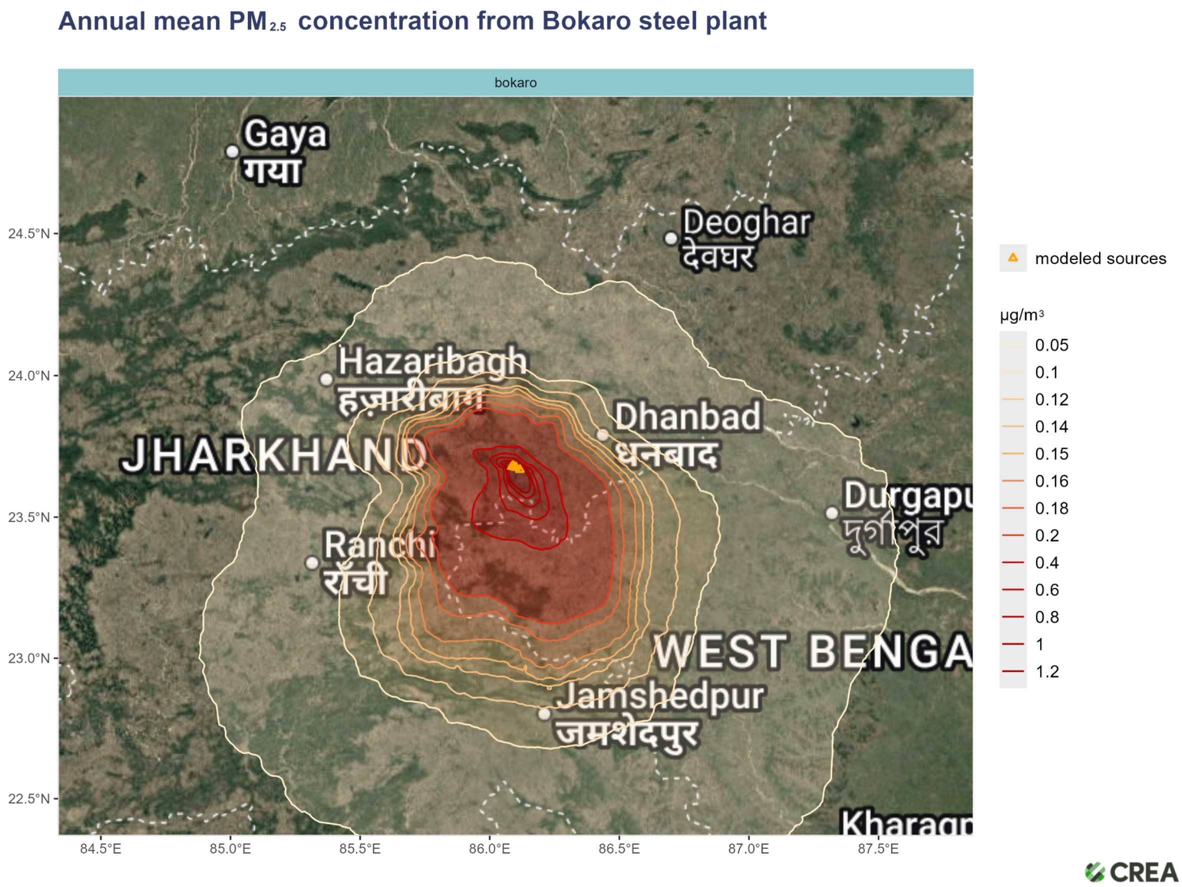

Figure 2 — Annual mean $PM_{2.5}$ concentration from Bokaro steel plant

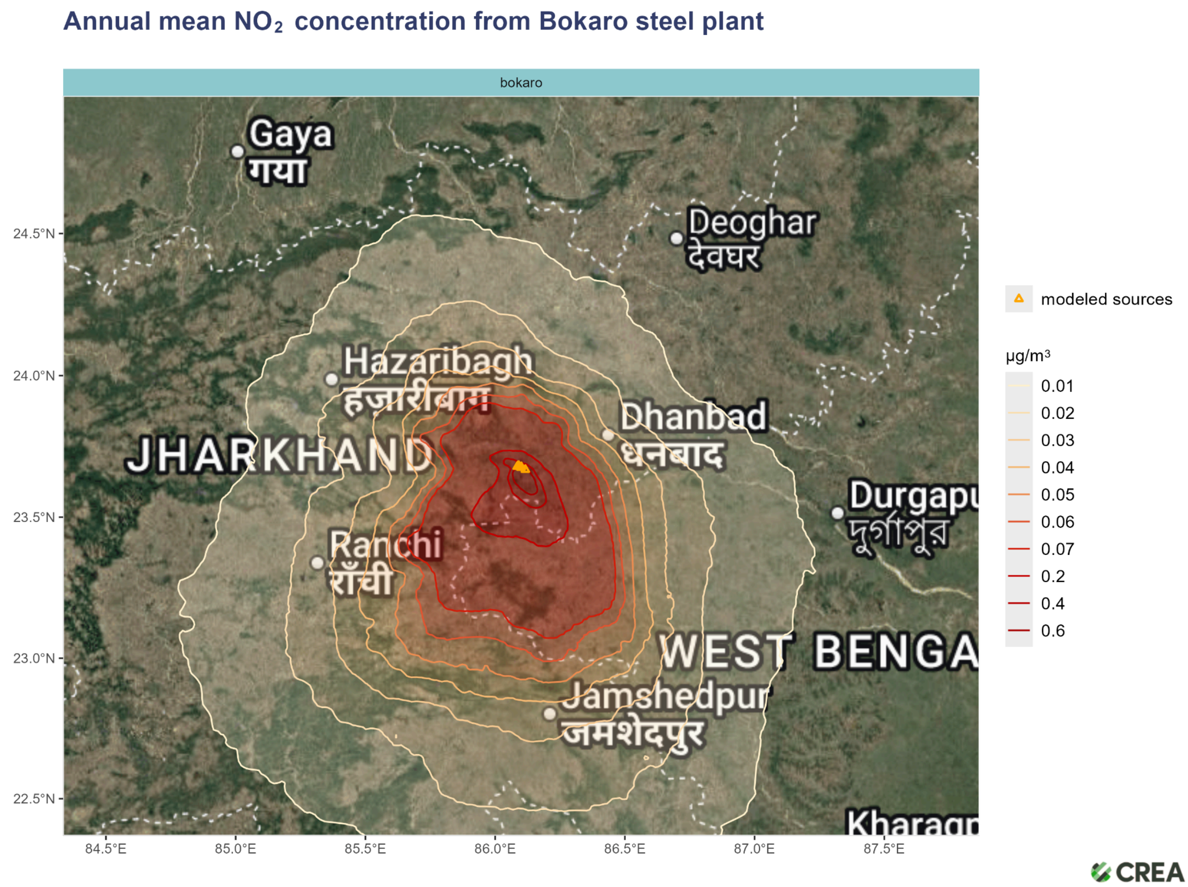

Figure 3 — Annual mean NO_2 concentration from Bokaro steel plant

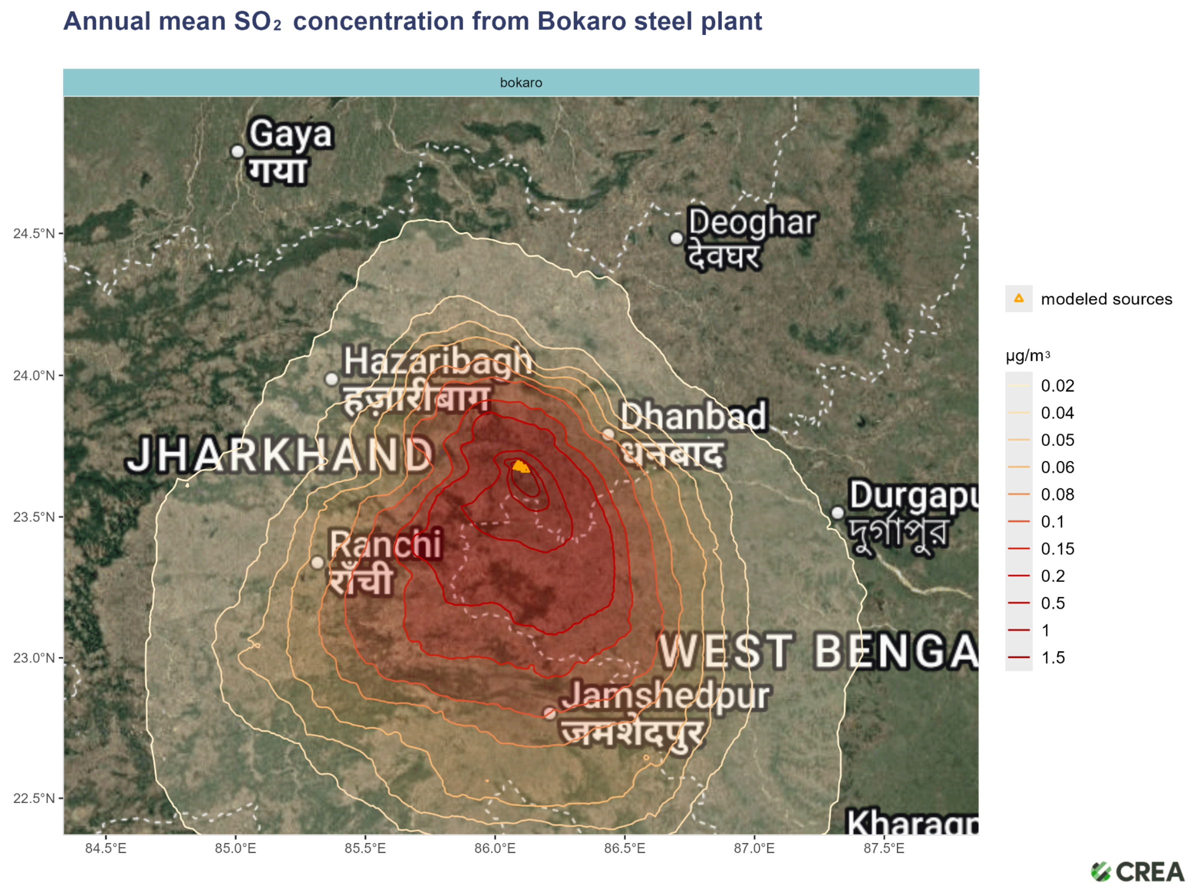

Figure 4 — Annual mean SO_2 concentration from Bokaro steel plant

Health impacts

Table 3 shows the estimated impacts of air pollution from the Bokaro steel plant on human mortality and morbidity outcomes for the year 2023.

The impacts of air pollution on human health begin before birth. Both pregnant women and newborns are at risk due to emissions. Exposure to pollutants can lead to adverse birth outcomes, including low birth weight, a risk factor for long-term health issues. CREA finds that pollution from the Bokaro steel plant leads to **273 (95% confidence interval: 84-475) low birthweight births,** and **284 (137-301) preterm births each year** (Table 3).

Air pollution from steel production also damages the respiratory system. CREA estimates that emissions from the Bokaro steel plant lead to **290 (173-406) asthma-related emergency room visits each year**. For patients and healthcare systems, these emergency visits represent a significant strain, increasing the demand for medical resources such as hospital beds, oxygen therapy, and medications. The burden extends beyond healthcare infrastructure, as frequent asthma episodes can disrupt daily life, leading to school absences for children and productivity losses for parents who must take time off work to provide care. Additionally, the economic strain is felt both at the individual level — through medical expenses and lost wages — and at the societal level, as higher healthcare costs and reduced workforce productivity place pressure on public health systems and economies.

Children are particularly vulnerable to the impacts of air pollution on respiratory health. We estimate that emissions from the Bokaro steel plant lead to **25 (5—59) new cases of asthma in children each year** (Table 3). The impact on children's health underscores the importance of stricter emissions standards to protect the youngest and most vulnerable members of society.

The impact of air pollution extends beyond direct health outcomes, imposing a significant economic burden on workforce productivity. Each year, air pollution from the Bokaro steel plant causes **123,000 (104,000-141,000) days of work absences due to pollution-related health issues** (Table 3).

Emissions from the Bokaro steel plant also contribute to premature deaths, one of the most severe consequences of toxic emissions from steel production. Each year, air pollution from the Bokaro steel plant is linked to **148 (103-201) and 20 (9-45) deaths due to $PM_{2.5}$ and NO_2**, respectively. Deaths caused by $PM_{2.5}$ occur through lung cancer, chronic obstructive pulmonary disease (COPD), and ischemic heart disease, stroke, and diabetes.

Table 3 — Annual health impacts due to air pollution from the Bokaro steel plant

Cause of death	Pollutant	Age group	Values (95% confidence interval in parentheses)
All-cause mortality	$PM_{2.5}$	Adult	148 (103-201)
All-cause mortality	NO_2	Adult	20 (9-45)
Lower respiratory infection mortality	$PM_{2.5}$	Children	5 (2-10)
Asthma emergency room visits	$PM_{2.5}$	Adult	290 (173-406)
Low birthweight births	$PM_{2.5}$	Children	273 (84-475)
New cases of asthma in children	NO_2	Children	25 (5-59)
Number of children suffering from asthma	NO_2	Children	135 (34-279)
Preterm births	$PM_{2.5}$	Children	284 (137-301)
Work absence (sick leave days)	$PM_{2.5}$	Adult	123,000 (104,000-141,000)
Years lived with disability	$PM_{2.5}$	Adult	206 (83-372)
Years of life lost	$PM_{2.5}$	Adult	4,090(2,705-5,856)
Years of life lost	NO_2	Adult	489 (216-1,103)

Source: CREA, 2025

Economic impacts

Many of the health impacts covered in this report have an economic cost to society. For example, work absences lead to losses in productivity that not only affect individual employers but also have cascading impacts on national economies. Increased absenteeism strains businesses, reduces workforce efficiency, and drives up operational costs. The associated healthcare costs compound the financial burden, creating a dual pressure on both the private and public sectors.

Many of the health impacts are associated with increased medical expenses. The largest share of the total economic burden is driven by the welfare costs associated with excess mortality, quantified using the Value of Statistical Life (VSL) approach. Table 4 shows the total cost due to health impacts from air pollution caused by the Bokaro Steel Plant. Air pollution from the plant is estimated to cost society USD 72 million, which is equivalent to INR 5.8 billion in 2023.

Table 4 — Annual economic cost of air pollution from the Bokaro steel plant

Currency	Pollutant	USD (million)	INR (billion)
USD (million)	$PM_{2.5}$	71 (47-98)	5.8 (3.8-8.1)
USD (million)	NO_2	8 (3-18)	0.6 (0.2-1.4)
Total		**79 (50-116)**	**6.4 (4.0-9.5)**

Source: CREA, 2025

Conclusion

Scientific evidence proves the detrimental effects on public health and economy due to Bokaro Steel Plant operations: This health impact assessment has found clear scientific evidence that the Bokaro Steel Plant has severely damaged the environment, public health, and the economy in its vicinity. In our annual estimates using the limited data available for stack emissions, pollution from the **Bokaro steel plant caused approximately 168 (112-246) deaths and a loss of USD 79 (50-116) million in 2023 alone.**

These deaths and economic cost of air pollution need to be seen from the perspective that these estimates are: 1) based on manual monitoring carried out once every quarter from each stack and therefore do not provide a year-long emission profile, which could skew the results, possibly leading to under-reporting (e.g. by excluding spikes in emissions); 2) the monitoring results do not account for fugitive dust emissions and several other facilities in the plant that are not reported on by the proponent, and lastly; 3) the results represent a small fraction of the overall impact of pollution from steel plants — the Bokaro Steel Plant accounts for only 28% (approximately) of SAIL's total crude steel capacity of 19 MTPA (as in September 2025) (Economic Times, 2025) and 2.66% of India's total steel capacity.

The estimated pollution increments from the Bokaro Steel Plant are significant because they demonstrate both strong local impacts and long-range pollution transport. An increase of 1.2 $\mu g/m^3$ in $PM_{2.5}$ in the plant's immediate vicinity is substantial in public-health terms. The additional NO_2 load (0.6 $\mu g/m^3$) further exacerbates risks of asthma, cardiovascular disease, and secondary particulate formation.

The fact that pollutants travel downwind and elevate $PM_{2.5}$ and NO_2 levels — even by 0.15 and 0.02 µg/m^3, respectively — in cities like Ranchi underscores that the plant's emissions are not confined to industrial zones — they contribute to regional air quality degradation affecting large populations. When adding similar contributions from all other upwind industrial facilities, the burden on urban air quality can become very significant. These findings highlight the need for tighter emission controls, robust monitoring, and regional airshed-based regulatory strategies rather than plant-specific compliance alone.

Stacks are not always equipped with the best available air pollution control devices (APCD): A study conducted by the Central Pollution Control Board (CPCB, 2012) shows that electrostatic precipitators (ESP) are more efficient at collecting dust as compared to multi-cyclone dust collectors. Most of the sinter plants in India were installed before the year 2000 and have multi-cyclones for dust collection. These sinters are far more polluting than the newer ones with ESPs. As reported in the compliance reports for Bokaro Steel Plant, only two of the six ducts for sinter stacks have ESPs installed and the rest only have cyclones.

The May 2024 compliance report (Bokaro Steel Limited, 2025) states that air pollution control devices in sinter are 'being considered' to be refurbished or replaced to achieve PM limit of 30 mg/Nm3, but there is no clear deadline mentioned by when this will be done. Table 5 lists the APCDs in the sinter plant of the Bokaro steel plant.

More importantly, the best available air pollution control technology includes control devices for SO_2 and NO_x emissions, of which there is no mention in the six-monthly compliance reports (April 2014–March 2020; April 2023–March 2024) and annual environment statement reports (March 2014–19, March 2023–24) assessed by CREA for this study (Bokaro Steel Limited, 2025).

BSL in its compliance report for April 2023 to September 2024 (Bokaro Steel Limited, 2025) has stated that the coke oven gas (COG) is desulfurised, without giving any details on how this is being done provided that the coke oven does not have any desulfurisation mechanism. Therefore, it is safe to presume that the plant does not have any APCDs in place for control of SO_2 and NO_x pollutants — both of which make the largest contribution to $PM_{2.5}$ exposure and health impacts associated with the plant.

Table 5 — APCDs in sinter plant of Bokaro steel plant

Sinter	Duct	APCD for PM	APCD for SO_2	APCD for NO_x
Sinter plant-1	Duct-A	Cyclone	None (Not reported)	None (Not reported)
	Duct-B	ESP		
Sinter plant-2	Duct-A	Cyclone		
	Duct-B	Cyclone		
Sinter plant-3	Duct-A	Cyclone		
	Duct-B	ESP		

Source: Compiled by authors from six-monthly compliance reports of BSL

Critical emission sources operating without emission limits: The air emissions from the sinter plant have the largest share in the Bokaro plant's total emissions. Sintering is the process of amalgamation of iron ore fines in the presence of coke oven breeze. Coke oven breeze has high trace elements such as SO_2. Combustion of a blend of iron ore fine and iron bearing waste using coke breeze generates high amounts of PM as well as SO_2. However, **India does not have any national standards for** SO_2 **for sintering plants**. China, US, Japan, meanwhile, all have and enforce such standards.

There are no standards specified for SO_2 and NO_X emissions from the mill zone. Bokaro Steel Plant has reported SO_2 and NO_X emissions from its mill zone during the entire study period. These emissions are possibly from the reheating furnaces in the mill zone which typically uses Coke Oven Gas (COG), Blast Furnace Gas (BFG), mixed gases, or fuel oil in absence of gases.

Similarly, BSP's Refractory Material Plant too has reported SO_2 emissions during the entire monitoring period — however, there are again no standards specified by the Ministry of Environment, Forest and Climate Change| (MoEFCC) or CPCB for the same.

Lack of monitoring and data transparency: In 2014, the Central Pollution Control Board (CPCB) mandated installation of Continuous Emission Monitoring Systems (CEMS) in 17 categories of highly polluting industries including integrated steel plants (CPCB, 2014). It has been over a decade and yet, CEMS calibration and its regulation remains a major challenge in its implementation. An investigative report in 2020 found out that the CEMS data was hardly available in the public domain, several industries were found offline, meaning that they did not relay data to the main server and there was therefore almost no historical data available for any meaningful analysis (Aggarwal & Singh, 2020), and not much has changed since then (Mallaya, Kumar, & Elango, 2024).

CEMS data is still not used for regulatory purposes due to several challenges, including uncertified sensors, lack of timely calibration, unreliable data, and interruptions or no data transmission (Sudarshan, 2022) (Verma, 2022).

Therefore, manual monitoring of stack emissions is used for regulatory purposes in India. The stack emission monitoring results in these industries are either self-monitored or monitored by National Accreditation Board for Testing and Calibration Laboratories (NABL)- certified laboratories that are contracted by the entity. More often than not, these reports are not available in the public domain. The lack of data transparency, and inconsistent data reporting– whether in frequency, measuring units, or emission sources – renders it difficult for any stakeholders including State Pollution Control Boards (SPCB) to take legal action against the polluters.

In the case of Bokaro Steel Plant, the stack emissions reported by the plant in its compliance reports are consistently well below the MoEFCC-prescribed limit or standard. On paper, not a single parameter exceeds the limit. In the case of other SAIL plants as well, the measured $PM_{2.5}$ is far below the standard as shown in Table 6. Such uniform compliance raises questions about the credibility of the monitoring process — for example, given the variability within the small number of reported readings, it is possible or even likely that a complete set of continuously monitored hourly data would show periods of non-compliance.

Table 6 — Stack emission monitoring results from other SAIL plants

Plant name	Facility	Monitoring period	Number of readings	Parameter	PM standard*	Measured range mg/Nm3	Source
IISCO steel plant	BF stove	Nov 2022 to Feb 2023	3	PM	50	4.86 – 19.62	IISCO Steel Plant, 2023
Bhilai Steel Plant	BF stove	October 2024 to March 2025	48	PM	50	17.42-22.28	Bhilai Steel Plant, 2025
			48	SO_2	250	20.96-144.10	
Durgapur Steel Plant	Sinter plant	October 2022 to March 2023	6	PM	150 mg/Nm3	56 – 116	Durgapur Steel Plant, 2023
	Coke oven	October 2023 to March 2024	4 (from 4 different coke ovens)	SO_2	800	208 – 278	Durgapur Steel Plant, 2024
				NO_X	500	153 – 209	

Source: Authors' compilation from various 'six-monthly environmental compliance reports' by each plant.

(*) As per MoEF emission standards, 2012 and as per six-monthly compliance reports of BSL for April 2023 to March 2024

(#)State Pollution Control Boards (SPCBs) have the authority to prescribe stricter emission standards to a plant. However, there is no such information in the compliance reports, environmental clearances, or any other documents accessed during our research.

The emissions from an old, technology-constrained plant are so low that they fall far below even relatively relaxed standards, which begs a broader policy question: why is industry given such a wide amount of wiggle room if such low emissions are possible?

Annexure: Methodology

Stack emission standards

MoEFCC revised the emission or discharge of pollutants from integrated iron and steel industries vide notification G.S.R 277(E) dated 31 March, 2012 (MoEFCC, 2012). Table 7 shows stack emission standards for integrated iron and steel plants.

Table 7 — Emission standards for integrated iron and steel plant

Facility	Process	SO_2 (mg/Nm^3)	NO_X (mg/Nm^3)	PM (mg/Nm^3)
Coke oven	Coke oven	800	500	50
Sinter Plant	Sintering			150
Steel melting shop (SMS)	Normal Blown (NB) converters			50
	Bottom lance (BL) converters			300
	Other converters (new)			50
Blast furnace (BF)	Stove in existing units	250	150	50
	Stove in new units	200	150	30
	Space dedusting/other stacks in old units			100
	Space dedusting/other stacks in new units			50
Rolling mills	Rolling mills			150
Refractory Material Plant (RFP)	Refractory unit			150

Source: Compiled by authors based on emission standards notified by MoEFCC in 2012

Table 8 shows the range of stack emissions from different facilities as reported by the plant during the study period. It is to be noted that as per the last environmental clearance dated 17 March, 2021 and amendment thereofs (MoEFCC, 2021; Parivesh, 2022), the particulate matter emissions shall be less than 30 mg/Nm^3 in new units and in all old units – it shall be achieved by Dec 2023 except for coke oven chimneys which shall be less than 50 mg/Nm^3.

However, in the compliance reports of BSL, the emission limits are as per the aforementioned notification.

Table 8 — Measured flue gas concentrations, reported by Bokaro Steel Plant

Facility	Flue gas concentrations (mg/Nm^3) (April 2023 to March 2024)		
	PM	SO_2	NO_x
Sinter plant	39 – 99		
Coke oven	17 – 49	85 – 296	49 – 109
SMS BL converter	39 – 260		
SMS NB converter	8 – 19		
SMS other converter (Ladle furnace)	22 – 33		
Mill Zone	22 – 40	32 – 60	20 – 30
RFP	1 – 96	56 – 127	

Source: Compiled by authors based on the compliance reports by Bokaro Steel Plant for FY 2023

Atmospheric modeling

For this study, we simulated air pollutant concentrations using the CALPUFF air dispersion model, version 7 (Scire et al., 2000). CALPUFF, which is evaluated by the US Environmental Protection Agency (US EPA) (US EPA, 2023), has been a widely used industry standard model for assessing the long-range air quality impacts of point sources. Due to its capability of capturing the complex chemical processes and atmospheric transport of pollutants, this modeling system is approved for use by regulators, such as the Maryland Department of the Environment (TRC Environmental Corporation, 2024), and in academic research (Zhang et al., 2020).

The model has been evaluated extensively by the US Environmental Protection Agency, is open-source, and fully documented. The CALPUFF model has been applied in many regions around the world, including the United States (Rzeszutek, 2019), Europe (Holnicki et al., 2016), Central America (Hernández-Garcés et al., 2020), South America (Arregocés et al., 2023), the Middle East (Ghannam & El-Fadel, 2013), Asia (Zhou et al., 2003; Jittra et al., 2015), and Africa (Affum et al., 2016).

CALPUFF calculates the atmospheric transport, dispersion, chemical transformation, and deposition of the pollutants, and the resulting incremental ground-level concentrations attributed to the studied emission sources.

- Chemical transformations of SO_2 and NO_2 to PM2.5 are calculated using ISORROPIA. Background concentrations of oxidants (ozone, ammonia, and hydrogen peroxide) are taken from a global atmospheric chemistry model.
- Meteorological input data for the year 2023 are generated from the Weather Research Forecasting (WRF) model (Skamarock et al., 2008), version 4.2.2. WRF was set up with 33 vertical levels and 1 nested grid. The mother nest has a grid resolution of 9 km and spans 720 km in both the north-south and east-west directions. The inner nest has a grid resolution of 3 km, spans 270 km in both the north-south and east-west directions and is centered over the Bokaro steel plant.

  Mother and inner domains use a two-way nesting technique, which ensures dynamic interaction between them. WRF simulations use initial and lateral boundary conditions from the National Centers for Environmental Prediction (NCEP) Final Analyses (FNL) dataset to produce three-dimensional, hourly meteorological data covering the full calendar year of 2023.
- For the assessment of annual average pollutant concentrations, emissions are assumed constant throughout the year. Emissions from each facility were modelled as separate buoyant point sources, taking into account the stack height and thermal plume rise from the stacks.

Health and economic impact assessment

We calculate the corresponding public health and economic impacts of the air pollution from the Bokaro steel plant for the year 2023.

CREA has developed a detailed globally implementable health impact assessment (HIA) framework (Myllyvirta, 2020) and updated it continuously based on the latest science. This framework includes as complete a set of health outcomes as possible without obvious overlaps. Health outcomes covered in this framework are those which have been identified in the peer-reviewed academic literature from meta-analyses covering multiple different populations, and in which incidence data is available at the national level from global datasets.

For each health outcome, we use a concentration-response relationship that has already been used in academic peer-reviewed literature to quantify the health burden from air pollution at the global level. This indicates that the evidence is mature enough to be applied across varying geographies and exposure levels. We estimate the number of cases for each health outcome following a standard epidemiological calculation:

$$\Delta case = Pop * \sum_{age} [Frac_{age} * Incidence_{age} * \left(\frac{RR_{c,age}}{RR_{c_{base},age}} - 1\right),$$

Where:

Pop is the total population in the grid cell;

age is the specific age group for which the epidemiological studies have established a health risk;

$Frac_{age}$ is the fraction of the population belonging to the specific age group;

$Incidence_{age}$ is the baseline rate of occurrence of the health outcome for the population within the population belonging to the specific age group;

c is the pollutant concentration from vehicles with c_{base} referring to the baseline concentration or current ambient concentration; and,

$RR_{c,\ age}$ is the function giving the risk ratio of the health outcome at the given concentration for the given age group compared with clean air. In the case of a log-linear, non-age specific concentration-response function the RR function becomes:

$$RR(c) = RR_0^{\frac{C - C_0}{\Delta C_0}},\ where\ c > c_0,\ 1\ otherwise$$

Where:

RR_0 is the risk ratio calculated in epidemiological research;

Δc_0 is the concentration change that RR_0 refers to; and,

c_0 is the no-harm threshold concentration — in general, the lowest concentration found in study data.

We use national-level population data for the year 2020 from the Gridded Population of the World v4 from the Center for International Earth Science Information Network (CIESIN, 2017) and scale to different years using changes in population and death rates from the World Population Prospect dataset of the UN (UNPD, 2019).

Table 9 shows the health outcomes included in this study and the relative risk values, as well as sources of incidence data, used for each. Deaths associated with PM2.5 pollution were estimated using the risk ratio developed by Burnett et al. (2022).

Health impact modelling projects the effects of pollutant exposure during the study year. Some health impacts are immediate, such as exacerbation of asthma symptoms and lost working days, whereas other chronic impacts may have a latency of several years. Concentration-response relationships for emergency room visits for asthma and work absences were based on studies that evaluated daily variations in pollutant concentrations and health outcomes; these relationships were applied to changes in annual average concentrations.

Table 9 — Input parameters and data used to estimate physical health impacts

Health outcome	Age group	Pollutant	Relative risk			Incidence
			Value	Threshold	Reference	
New cases of asthma	1–18	NO_2	1.26 (1.10–1.37) per 10 ppb	2 ppb	Khreis et al. (2017)	Achakulwisut et al. (2019)

People suffering from asthma	1–18	NO_2	1.26 (1.10–1.37) per 10 ppb	2 ppb	Khreis et al. (2017)	Achakulwisut et al. (2019)
Asthma ER visits	0–17	$PM_{2.5}$	1.025 (1.013–1.037) per 10 μg/m^3	6 μg/m^3	Zheng et al. (2015)	Anenberg et al. (2018)
Asthma ER visits	18–99	$PM_{2.5}$	1.023 (1.015–1.031) per 10 μg/m^3	6 μg/m^3	Zheng et al. (2015)	Anenberg et al. (2018)
Preterm birth	Infant	$PM_{2.5}$	1.15 (1.07–1.16) per 10 μg/m3	8.8 μg/m^3	Sapkota et al. (2012)	Chawanpaiboon et al. (2018)
Work absence	20–65	$PM_{2.5}$	1.046 (1.039–1.053) per 10 μg/m^3	0.0	WHO (2013)	EEA (2014)
Deaths	0–4	$PM_{2.5}$	Burnett et al. (2022)	0 μg/m^3	Burnett et al. (2022)	IHME (2020)
Deaths	25–99	$PM_{2.5}$	Burnett et al. (2022)	0 μg/m^3	Burnett et al. (2022)	IHME (2020)
Years lived with disability	25–99	$PM_{2.5}$	IHME (2020)	2.4 μg/m^3	Burnett et al. (2018)	IHME (2020)
Deaths	25–99	NO_2	1.02 (1.01–1.04)	4.5 μg/m^3	Huangfu & Atkinson (2020); Stieb et al. (2021)	IHME (2020)

			per 10 µg/m^3			

Note: Numeric values in the column ‘Concentration-response function’ refer to odds ratio (OR) corresponding to the increase in concentrations given in the column ‘concentration change’. Literature references indicate the use of a non-linear concentration-response function. No-harm threshold refers to a concentration below which the health impact is not quantified, generally because the studies on which the function is based did not include people with lower exposure levels. Data on concentration-response relationships do not exist for all geographies, so a global risk model is applied. National incidence data is applied to the model to estimate the health outcomes. $PM_{2.5}$ deaths in 25–99 year-olds are from non-communicable diseases, disaggregated by cause, and from lower respiratory infections. $PM_{2.5}$ deaths in 0–4 years old are due to lower respiratory infections. Years lived with disability (YLDs) attributed to $PM_{2.5}$ exposure are associated with diabetes, stroke and chronic respiratory disease.

This study calculates the economic costs of health impacts resulting from air pollution, following a similar methodology to Myllyvirta (2020). The analysis accounts for respiratory and cardiovascular diseases, including their complications, which significantly reduce quality of life, lower economic productivity, and increase healthcare costs. The health impacts with their valuations are summarized in Table 10.

Table 10 — Health impact costs included in this study and their economic valuation

Health outcome	Valuation at world average GDP/GNI per capita (2017 int. USD)	Reference
Work absence (sick leave days)	85	EEA (2014)
Number of children suffering from asthma due to pollution exposure (increased prevalence)	1,077	Brandt et al. (2012)
Deaths (adults)	2,637,000	Viscusi & Masterman (2017)
Deaths of children under 5	5,273,000	OECD (2012)*
Preterm births	107,700	Trasande et al. (2016)
Years lived with disability	28,480	Birchby (2019)

*The deaths of young children are valued at twice the valuation of adult deaths, following OECD's recommendations (2012)

The valuation for adult deaths (Viscusi and Masterman, 2017) is based on labour market data, and we multiply it by two to estimate the value for children, following the recommendation of OECD (2012). The economic cost of disability is assessed using disability valuations from the UK's Department for Environment, Food & Rural Affairs (Birchby et al., 2019). 'Disability weights' calculated by the Global Burden of Disease (GBD) allows comparison of economic costs across different illnesses. Disabilities considered include diabetes, chronic obstructive pulmonary disease (COPD), and stroke.

The original studies referenced in Table 10 are based on different countries, time periods, and currencies. To ensure comparability, all valuations are converted into current local currencies based on differences in GDP per capita. This approach ensures that future economic costs are expressed in terms of the present-day currency value (2023), allowing for consistent comparison over time.

Data limitations and assumptions

The point sources of air pollution considered in this study are sinter plant, coke oven, refractory material plant, blast furnace (BF) and steel melting shop (SMS). The Bokaro steel plant depends on the grid for its electricity needs and also has a captive power plant in its premises. However, due to paucity of data in the public domain, we could not establish a material balance between the steel plant and the power plant. We also do not have air emission data from the power plant. Therefore, the study does not account for the emissions from the captive power plant.

Emission data is obtained from the Environmental Clearance (EC) six-monthly compliance reports from April 2023 to March 2024 (Financial Year 2023). Limitations and assumptions considered for emissions are discussed as follows:

1) Emission readings are not consistently available for all facilities during the study period. For example:
- Monitoring readings for stack emissions from the Steel Melting Shop (SMS) are not available for May 2023. There is no information available if these facilities were under shutdown mode or under repair or have simply not been reported on.
- Stack emissions reported from the mill zone are either from hot-strip mill (HSM) or cold-rolling mill (CRM) in different monitoring periods. There is no information on if the other mill at the time of reporting were not operating or not reported on.
- SO_2 and NO_X readings are only available for Blast Furnace 2, 4, and 5 for February and March 2024.

2) Production for each facility (tonnes per hour), number of operating days, flue gas temperature (degree Celsius) and exit velocity (m/s) are all design parameters obtained from various documents procured from Ministry of Environment, Forest and Climate Change (MoEFCC) Parivesh portal for Bokaro Steel Plant. Actual or in operation details are not provided in the compliance reports or any other documents available in public domain.

3) It was assumed because of lack of information that facilities which are not reported on are in shut-down mode during that period.

4) Coordinates for different facilities were taken based on demarcations in the layout map (toposheet) for the plant. However, stacks are not marked in the layout plan, and approximate latitude and longitude were considered based on the plant layout.

5) The number of hours of operation are not reported anywhere. Therefore, an average number of hours are considered for different facilities based on literature review and expert interviews.

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