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Ambient Air Quality Monitoring in Laxmipura Village of Sandur Taluk, India

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ABSTRACT

Heavy industrialization and the exploitation of natural resources have created ambient air quality as an important environmental and public health issue in mining-intensive areas. This study assesses the ambient air quality of the village Laxmipura situated in Sandur Taluk, Ballari District of Karnataka which is greatly affected by the long-term open cast iron ore mines. Key pollutants which are typically associated with mining operations and vehicular emissions are particulate matter (PM_{10} and $PM_{2.5}$), sulfur dioxide (SO_2) and nitrogen oxides (NO_2). The study combines field observations, environmental data and secondary data from mining reports and environmental management documents. Post monsoon monitoring in 2011 shows that particulate matter is the primary pollutant, mainly resulting from the continuous mining process including blasting, crushing, ore transportation and continuous dust from dusty materials, etc. Although the PM level was high, the rest of the pollutants monitored was not high enough to break the national ambient air quality standards (NAAQS). The Air Quality Index (AQI) was formatted using the Central Pollution Control Board (CPCB) IND-AQI model, which has been rated as "Good" with minimal health risks in the near term. But the contribution of chronic exposure to particulate pollution can't be ignored. The results highlight the critical need for ongoing air quality monitoring, enforcement of regulations, and the development of sustainable mitigation measures to safeguard the environment and public health in mining areas for the future.

KEYWORDS: *Ambient air quality, Iron ore mining, PM_{10}, $PM_{2.5}$, Sandur.*

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INTRODUCTION

High-grade iron and manganese ores occur in the Sandur Schist Belt of Ballari District, Karnataka and intensive mining activities have been going on in the area for decades (IBM, 2020). A mechanized open-cast mine, located near village Laxmipura in Devadari Gudda range, is a typical mining site that leads to the generation of significant quantities of air pollutants especially particulate matter (PM) (Ghose & Majee, 2001). These emissions have a negative impact on biotic and abiotic components of the environment. Ambient air quality monitoring in such regions is thus essential to assess the environmental impacts, to ensure compliance to regulatory measures, and to reduce the related risks to public health (CPCB, 2009).

Internationally, air pollution continues to be a large-scale problem, and it has been recognized that mining areas are "hotspots. The World Health Organization (WHO, 2021; 2025) reported that more than 90% of the world's population is breathing air quality that is higher than the recommended levels, especially for fine particulate matter ($PM_{2.5}$) which is a serious health hazard. Mining intensive areas in Asia, Africa and South America have been consistently recorded to have high levels of particulate matter (PM_{10}, $PM_{2.5}$), SO_2 and NO_2 because of mining activities and processing (UNEP, 2019). In a comparable manner, the European Environment Agency (EEA) shows that there has been a lack of compliance with air quality standards close to mineral extraction areas, even with the reinforcement of the norms (EEA, 2022). Increased rates of respiratory and cardiovascular diseases and early death are strongly linked to these conditions (WHO, 2021; Landrigan *et al.,* 2018).

The Indian scenario indicates that mining areas in states like Karnataka, Odisha, Jharkhand and Chhattisgarh are some of the most polluted areas (CPCB, 2010). National Ambient Air Quality Standards (NAAQS) set by the Central Pollution Control Board prescribe the concentration limits for air pollutants as 100 $\mu g/m^3$ for PM_{10} and 60 $\mu g/m^3$ for $PM_{2.5}$ for 24-hour period (CPCB, 2009). However, the studies carried out in Sandur Taluk, Karnataka, show that during the peak of the mining activity the level of PM_{10} is regularly found above the permissible limits because of the unpaved haul roads, the heavy use of vehicles and continuous material handling activities (Ghose, 2007; Sharma & Roy, 2012). Despite the introduction of national programmes like the National Clean Air Programme (NCAP) for improving the air quality management, there are some gaps in the implementation, especially in the mining intensive areas (MoEFCC, 2019).

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The village of Laximipura, which is close to active iron ore mining area in Sandur Taluk, is a typical case of economic growth and environmental degradation in the wake of mining. Mining is one of the most important sources of economic development in the region, but it also causes air quality deterioration. Mining activities, waste dumping and transport operations contribute a lot to the pollution of air due to dust emission, which in turn poses a serious threat to the people living in nearby areas (Ghose & Majee, 2001; CPCB, 2009).

The primary aim of the present study is the assessment of the concentration level of PM_{10}, $PM_{2.5}$, SO_2, and NO_2 in and around the mining lease area which gives a scientific basis to understand the dynamics of pollution and helps in proper environmental management and policy intervention. The main aim of this study is to evaluate the ambient air quality of the affected areas of Laxmipura village and surrounding areas due to the mining activity by measuring the concentration of the major pollutants to compare the measured pollutants with the National Ambient Air Quality Standards (NAAQS) and recommend the necessary mitigation measures for the area.

METHODOLOGY

Location and Geographic Setting

Laxmipura village exists in the Devadari Gudda hill range which is well known to have a rich deposit of iron ore and intensive mining activities (IBM, 2020). The study area is in the latitudes 15^0 00′-15^0 05′ N and longitudes 76^0 30′-76^0 35′ E with an extent of approximately 105.06 ha of the mining lease area dominated by forest lands (FSI, 2021). The relief is highly uneven with a maximum range of 620-1029 meters above mean sea level and a relief type like that of Sandur schist belt (Radhakrishna & Vaidyanadhan, 1997). The settlement is near the mining site, which has resulted in several environmental problems such as air pollution, land degradation and ecological disturbance (Ghose & Majee, 2001; CPCB, 2009).

Data Collection

The study methodology used in this study is a combination of primary data and secondary data which are to ensure a comprehensive assessment of ambient air quality. Primary data was collected by conducting field observations which were related to environmental conditions, mining activities and dust generation sources (Ghose & Majee, 2001). The secondary data was collected from the mining reports, Environmental Impact Assessments (EIA) and

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Environmental Management Plans (EMP) of nearby iron ore mines which gives detail on the iron ore production and mitigation measures (MoEFCC, 2006; CPCB, 2009). The merging of these data enables the comprehensive assessment of air quality conditions in the study area, and this can be compared to the general practice of environmental monitoring and assessment (ISO, 2015).

Parameters Monitored

The study emphasizes on air quality parameters which are very crucial for the assessment of air quality in industries and mines. These include particulate matters (PM_{10} and $PM_{2.5}$) which are coarse and fine particles suspended in the air, respectively (WHO, 2021; CPCB, 2009). Also, gaseous pollutants like sulfur dioxide (SO_2) and nitrogen oxide (NO_2) are monitored because of their connection with combustion process and vehicles' emissions (Gulia et al., 2015; WHO, 2021). These parameters are chosen because they are well-known for their potential effects on human health and the environment, such as respiratory and cardiovascular effects (WHO, 2021; Landrigan *et al.,* 2018).

Monitoring Techniques

Pollutant concentrations are measured using standard air quality monitoring methods. The PM_{10} samples are collected by the high-volume air samplers (HVAS) and $PM_{2.5}$ samples are collected by fine particulate samplers (CPCB, 2011; USEPA, 2016). The gaseous pollutants like SO_2 and NO_2 are measured by gas analyzers based on approved analytical methods (CPCB, 2011; WHO, 2021). The sampling is usually done over 24 hours to get representative average concentrations of pollutants in the air, following standard ambient air quality monitoring protocols (CPCB, 2009; USEPA, 2016). These methods guarantee accuracy, comparability, and reliability of ambient air quality assessments.

Sampling Design

Ambient air quality measurements were carried out at the eight strategically located stations in the vicinity of iron ore mine within a 10 km radius. The sites were chosen according to the topographical requirements, human settlements, wind direction, and accessibility to the sites as per the guidelines laid down by Central Pollution Control Board (CPCB) and the United States Environmental Protection Agency (USEPA) (CPCB, 2011; USEPA, 2016). The sampling points were the area of the lease, haulage roads and villages around the lease namely

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Laxmipura, Donimalai, Nandihalli, Yashwanth Nagar, Bhimagandi and Bhujanga Nagar. The monitoring of SO_2 and NO_2 was done with 8 hourly sampling and for PM_{10} and $PM_{2.5}$, 24 hourly sampling as per standard monitoring protocols was followed (CPCB, 2009; WHO, 2021). In addition, the systematic evaluation of fugitive emissions, such as suspended particulate matter (SPM), respirable suspended particulate matter (RSPM) and total particulate matter was done to assess overall air quality (Ghose & Majee, 2001, CPCB, 2009).

Analytical Methods

The samples were collected and analyzed by a Respirable Dust Sampler (APM 460) manufactured by Envirotech based on size selective separation method (CPCB, 2011). The cyclone was used to collect PM_{10} (particles < 10µm) on pre-weighed filter papers and the remaining dust was collected in a dust cup (CPCB, 2011; US EPA, 2016). The sulphur dioxide (SO_2) and nitrogen oxides (NO_2) were absorbed in specific chemical solutions and analyzed by spectrophotometric techniques, such as West & Gaeke, 1956 and Jacob & Hochheiser, 1958. Pre-sampling and post sampling of collected filters was done and particulate concentrations were measured gravimetrically (CPCB, 2011). Fugitive emissions were systematically quantified at monitoring sites and regular calibration procedures were followed to ensure data accuracy (US EPA, 2016). The samples were then analyzed in the lab following the CPCB guidelines and the meteorological parameters such as wind speed, wind direction and percentage of calm days were recorded to understand the dispersion of pollutants (CPCB, 2009; WHO, 2021).

RESULTS

Environmental Settings and Climate

The climate of the study area is semi-arid tropical type (IMD, 2020; Radhakrishna & Vaidyanadhan, 1997) with high temperature and moderate rainfall. The topography is characterized by hill ranges, plateaus and valleys with seasonal streams like the Narihalla running through the area (GSI, 2011). The natural ecological conditions and anthropogenic activities such as mining operations and afforestation projects by mining agencies (FSI, 2021) affect vegetation patterns. The presence of forest land also suggests the ecological sensitivity but due to continuous mining operations like excavation of mines, dumping of waste material and transportation, the natural landscape has been largely disturbed causing more dust generation and changes in land use pattern (Ghose, 2007; CPCB, 2009).

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Regional Air Quality Status and Impacts

Sandur Taluk is one of the major areas for extraction of iron ore, with high levels of air quality issues (IBM, 2020). The ambient air quality monitoring stations in the region consistently show higher concentration of particulate matter and gaseous pollutants, especially in the dry season when the dust suppression is less (CPCB, 2010; Ghose, 2007). The Karnataka State Pollution Control Board (KSPCB, 2025) study has found that PM_{10} levels are often found to be higher than the permissible limits in the mining areas, which poses serious health risk to the residents as well as the persons working in the mines. Degraded air quality also has indirect implications on health, such as on environmental damage, which can include effects on soil fertility, vegetation health, water quality and socio-economic impacts, including higher health care costs and lower productivity in agriculture (WHO, 2021; Landrigan *et al.,* 2018).

Geological and Mining Characteristics

The study area is part of Sandur Schist Belt and is part of the Devadari hill range of the Nandihalli Formation, adjoining to the Donimalai Formation (Radhakrishna & Vaidyanadhan, 1997; GSI, 2011). The geology consists of banded hematite quartzite (BHQ), ferruginous shale, metabasalt, and banded iron formations (BIF) with minor ultramafic intrusions and quartz veins (GSI, 2011; IBM, 2020). The ore body is found on hillocks and has a general NW–SE trend with dips varying from 60^0 to 75^0 towards the northeast. The length of the trench is about 1350 meters, with a minimum width of 150 meters and a maximum depth of 80 meters (average 60 meters), which are like the thickness reported in the geological assessment of the area (IBM, 2020; GSI, 2011). Both lump and fine type of iron ore are present, with lumpy ore accounting for about 25% of the run-of-mine (ROM), with fines dominating. The iron concentration is in the range of 55-68 % which suggests high quality ore deposits of the Sandur belt (IBM, 2020).

The mining is done mechanically in open cut method with bench height of about 8 meters and bench width of 12 meters following the usual mining practice as per CPCB (2009) and IBM (2020). Geomorphology in the area is characterized by ridges, plateaus and seasonal nallahs that drain into the Narihalla stream, which affects geomorphological processes as well as the distribution of pollutants in the area (GSI, 2011; Ghose & Majee, 2001).

Environmental Management and Mitigation Measures

A systematic environmental monitoring and continuous improvement system (IOS, 2015) is in place to support the mining operations in compliance with ISO 14001. More than 30,000

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saplings are produced each year in the nursery on the site, which is used for afforestation and ecological restoration in mines (FSI, 2021; CPCB, 2009). Socio-economic impact, affected population rehabilitation, waste management and land use planning are some of the socio-economic issues addressed through Environment Impact Assessment (EIA) and Environmental Management Plan (EMP) studies conducted as per the requirement of the law (MoEFCC, 2006). The large-scale afforestation project such as plantation of native species and agaves within the lease area are also consistent with the practice of mine reclamation and ecological restoration (CPCB, 2009; Ghose, 2007). Structural measures like parapet wall, check dam and gully plug are considered as the most effective methods for controlling soil erosion and surface runoff and are widely recommended in the field of mine environmental management (MoEFCC, 2010; Ghose, 2007). Water spraying on haul tracks and open cast mining areas is a common practice for dust suppression, which is done at regular intervals in open cast mining (CPCB, 2009; Ghose & Majee, 2001). In addition, the integrated environmental rehabilitation strategy (IBM, 2020; CPCB, 2009) is implemented systematically through phase wise stabilization and reclamation of the waste dumps using the vegetation cover.

SOURCES OF AIR POLLUTION IN LAXMIPURA VILLAGE

Mining Activities

The study area's main source of air pollution is from mining activities. Drilling, blasting, excavation and material handling are some of the major activities involved in Open Cast mining which generate huge amount of dust (Ghose & Majee, 2001; CPCB, 2009). Dust is generated when rocks are fractured in the blasting process, and when excavation works and loading are carried out (Ghose, 2007). Further, during the crushing and screening of the extracted ore, significant amounts of airborne particulate matter (PM) are generated (USEPA, 1998; CPCB, 2009). These activities are carried out on a regular basis resulting in continuous release of smoke into the atmosphere which leads to continuous pollution of the surrounding areas (Ghose & Majee, 2001; Gulia *et al.,* 2015).

Transportation

Another significant source of air pollution is transportation of mined materials (Ghose & Majee, 2001; CPCB, 2009). Heavy equipment like dump trucks and trucks produce dust from resuspension of surface dust as they are moving along the unpaved haul roads (USEPA, 2006; Ghose, 2007). The mine has a big fleet of transport vehicles, which contributes to the particulate

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and gaseous emissions, including NO_2 (Gulia *et al.,* 2015; WHO, 2021). The pollution produced by the diesel engines, which use these vehicles, is also a major contributor to air pollution, including NO_x and fine particulate matter (CPCB, 2009; USEPA, 2016).

Waste Dumping

The waste generation and dumping activities are also significant contributors to air pollution (CPCB, 2009; Ghose & Majee, 2001). Mining generates huge amounts of waste such as overburden and low-grade ore, requiring them to be set aside in designated dumping areas (IBM, 2020). These waste dumps are often winded, and dust particles are dispersed in the environment (Ghose, 2007; USEPA, 2006). Waste dumps in the study area are likely to emit particulate matter throughout the life of the mine and are a potential source of ambient air quality degradation over a period (CPCB, 2009; Gulia *et al.,* 2015).

Particulate Matter (PM_{10} and $PM_{2.5}$)

The study of particulate matter shows that the level of particulate matter is significantly elevated in the study area, which is mainly due to mining activities (CPCB, 2009; Ghose & Majee, 2001). In open-cast mining areas, dust arising from the drilling, blasting, excavation and transportation operations is the most significant source of coarse particulate matter (Ghose, 2007; USEPA, 2006). Although $PM_{2.5}$ is present in low concentrations compared with PM_{10}, it is more harmful because it has the capability to penetrate the deep respiratory system and cause adverse health effects (WHO, 2021; Gulia *et al.,* 2015). One of the major issues is the continual release of dust from various sources leading to persistent high levels of particulate matter, especially near active mining sites (CPCB, 2009; Landrigan *et al.,* 2018).

Gaseous Pollutants

The levels of other gaseous pollutants like SO_2 and NO_2 in the study area are relatively low (WHO, 2021; CPCB, 2009). The SO_2 level remains low because there is not a large amount of sulfur in the diesel fuel used to operate mining activities and combustion sources (USEPA, 2016). However, the emissions of NO_2 are more noticeable because of the combustion of diesel in heavy vehicles and mining machinery (Ghose & Majee, 2001; Gulia *et al.,* 2015). These gaseous pollutants are not normally found in concentrations exceeding limits, but they add to the air pollution burden, and could cause long-term adverse environmental and health effects (WHO, 2021; Landrigan *et al.,* 2018).

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COMPARISON WITH STANDARDS

The concentration of particulate matter is found to surpass the permissible limit of standards of ambient air quality (NAAQS) on many occasions during the periods of heavy mining activities (CPCB, 2009; Ghose, 2007). This shows the need to improve the dust control measures and the monitoring in the dust affected areas (USEPA, 2006; CPCB, 2009). Emissions of gaseous pollutants are, however, generally within limits and thus fall under relatively good control of emissions from combustion sources, under the current operational conditions (Gulia *et al.,* 2015; WHO, 2021). However, ongoing monitoring is needed as they are cumulative environmental and health threats (Landrigan *et al.,* 2018).

METEOROLOGICAL OBSERVATIONS

The meteorological evaluation identified that the major direction of the wind in the study area was from the south-west, which is the main wind pattern for the dispersion of pollutants (IMD, 2020; Seinfeld & Pandis, 2016). Average wind speed for the day was 0.58 m/s, which is relatively low, with very limited potential for atmospheric dilution of airborne pollutants (USEPA, 2006; Arya, 1999). In addition, the monitoring period experienced calm wind conditions for 23.11% of the period indicating frequent stagnation of air masses which could lead to accumulation of particulate matters and gaseous emissions in local areas (WHO, 2021; CPCB, 2009). Meteorological conditions have been reported to play a significant role in the dispersion of pollutants and in air quality in the mining impacted areas (Ghose & Majee, 2001; Gulia *et al.,* 2015).

AMBIENT AIR QUALITY

The ambient air quality monitoring in and around the mine site was done at eight locations which were selected in accordance with the principles of ambient air quality monitoring network, which are the core, upwind, downwind and crosswind zones, as per the standard guidelines (CPCB, 2011; USEPA, 2016). Measurements were obtained in core zones, one in the mine lease area (M-1) and the other along haulage road (M-2) which reflects the emissions from material transportation and mining activities (Ghose & Majee, 2001). Sites were set up on crosswind and downwind directions such as Laxmipura (M-3), Nandihalli (M-5), Donimalai (M-4), Bhimagandi (M-7), Bhujanga Nagar (M-8) for measuring lateral dispersion and pollutant transport from the mine towards the downwind areas respectively. The background air quality was used as a reference point at Yashwant Nagar (M-6) which is located upwind (Arya, 1999; CPCB, 2009).

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The measured values represent spatial variations in concentrations of pollutants, related to the orientation at the site and the distance from the mining operations. The concentrations were higher at downwind sites than at upwind and crosswind sites, which indicates that wind direction plays a role in the dispersion of pollutants (Seinfeld & Pandis, 2016; WHO, 2021). The levels of the core zone areas were the highest, due to direct exposure to mining activities, whereas the intermediate levels were observed in crosswind sites where the emissions were transported laterally. The highest levels were observed in the core zone areas reflecting direct exposure to the emission sources, and the intermediate levels were observed in the crosswind sites where the emissions were transported laterally (Ghose, 2007). The upwind measurements at Yashwanth Nagar had the lowest values, showing the relative lack of impact from the mine emissions. This spatial pattern highlights the importance of wind direction and wind distance in determining the spatial distribution of airborne contaminants and the need for continuous monitoring for effective environmental management (Gulia *et al.,* 2015; CPCB, 2009).

Table 1: The Ambient Air Quality Studies Were Carried Out During Post Monsoon-2011

Code	Sampling location	Direction with respect to mine lease	Measured values	Remark
M-1	Mine lease area	- - - - - - -	- - - - - - -	Core zone
M-2	Haulage road	- - - - - - -	- - - - - - -	Core zone
M-3	Laxmipura	NW	0.93	Cross wind
M-4	Donimalai	E	4.65	Downwind
M-5	Nandihalli	S	3.62	Cross wind
M-6	Yashwanth Nagar	SW	6.32	Upwind
M-7	Bhimagandi	NNE	3.34	Downwind
M-8	Bhujanga Nagar	NNE	0.93	Downwind

According to the meteorology weather assessment of the study area, the predominant wind direction is from southwest which is critical in dispersion and transport of airborne pollutants from the mining activities (Seinfeld & Pandis, 2016; IMD, 2020). The average hourly wind

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speed was measured at 0.58 m/s which is a very low speed of the atmosphere and does not provide high level of natural dispersion of emissions (Arya, 1999; USEPA, 2006). Moreover, the air was found to be calm during 23.11% of the monitoring period, indicating the frequent occurrence of stagnant conditions in the atmosphere which allows particulate matter and gaseous pollutants to accumulate at localized places (CPCB, 2009; WHO, 2021). All these findings show the great impact of wind direction and wind speed on ambient air quality, and the need to consider meteorological conditions when monitoring and managing ambient air quality in mining-affected areas (Ghose & Majee, 2001; Gulia *et al.,* 2015).

Table 2: Parameters Analyzed during the study

PARAMETERS	DATA
Predominant wind direction	SW
Hourly average wind speed (m/s)	0.58m/s
Percentage of calm winds	23.11%

The ambient air quality assessment carried out around the Laxmipura iron ore mine showed that the concentration of gaseous and particulate pollutants varied from core to the upwind, downwind and crosswind areas, which are the characteristics of open cast mining environment (CPCB, 2009; Ghose & Majee, 2001). Suspended Particulate Matter (SPM) levels were found to be highest in the mine lease (296.5 µg/m^3) and along the haulage road (301.6 µg/m^3) which is attributed to the direct emission from the mining activities, material handling and transport by vehicles (Ghose 2007; USEPA 2006). Similarly, Respirable Suspended Particulate Matter (RSPM/PM_{10}) had a similar pattern with the highest concentration in the core zone (90.6 µg/m^3 at the mine site) suggesting that fine particulate matter known as Respirable Suspended Particulate Matter (RSPM/PM_{10}) were concentrated in the immediate vicinity of active mining activity and transport zones (WHO, 2021; CPCB, 2009).

The levels of gaseous pollutants were relatively low. The levels of sulphur dioxide (SO_2) were in the range of 8.1–11.5 µg/m^3 and nitrogen dioxide (NO_2) were in the range of 12.4–14.3 µg/m^3 which is within ambient air quality ranges for mining affected areas (Gulia *et al.,* 2015; WHO, 2021). The highest values were measured at locations in the core zone (M-1 and M-2), probably caused by diesel emissions from the mining machinery and transport vehicles (USEPA, 2016). The concentrations of particles and gases were lower at peripheral and

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downwind areas like Donimalai (M-4) and Bhimagandi (M-7), due to dilution and dispersion processes influenced by wind direction (Seinfeld & Pandis, 2016; Arya, 1999). Pollutant concentration was found to be lower at all the upwind sites (Yashwanth Nagar, M-6) which signified the impact of wind direction on the transportation of pollutants (IMD, 2020).

The intermediate concentrations were observed at the crosswind sites (M-3, M-5); which indicated the influence of lateral dispersion in controlling the accumulation of pollutants (CPCB, 2009). The results showed that the mining operations have a significant effect on the air quality in the core zone and the natural ventilation and distance have a significant effect on reducing the concentration of particulate and gaseous pollutants in the peripheral zone (Ghose & Majee, 2001; Landrigan *et al.,* 2018). The spatial pattern highlights the importance of taking specific dust control measures in the vicinity of active mining and haulage operations to reduce the health hazard to workers and local communities.

Table 3: Ambient Air Quality in the Study Area

Code	Location	SPM	RSPM	SO_2	NO_2	Remarks
		Measured in µg/m³				
M-1	Mine lease area	296.5	90.6	11.5	14.3	Core zone
M-2	Haulage road	301.6	88.9	9.9	13.8	Core zone
M-3	Laxmipura	160.5	47.0	9.3	13.2	Cross wind
M-4	Donimalai	154.6	51.1	9.4	13.2	Downwind
M-5	Nandihalli	152.6	42.8	8.1	12.4	Cross wind
M-6	Yashwanth Nagar	150.0	44.5	8.9	12.6	Upwind
M-7	Bhimagandi	142.1	46.6	8.6	12.6	Downwind
M-8	Bhujanga Nagar	154.6	45.9	9.2	13.5	Downwind

The PM concentration was maximum in the areas of leases and haulage of the mine and was found to be less than the limits set by Central Pollution Control Board (CPCB, 2009) for the National Ambient Air Quality Standards (NAAQS). The concentrations of SO_2 and NO_2 exceeded the allowable limits at none of the sampling points, and the concentrations were like the typical emissions of a controlled mine and diesel-powered operations (WHO, 2021; Gulia

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et al., 2015). The overall Air Quality Index (AQI) classified the study area as "Good", which means that the public health is not at significant risk from the existing air quality situation (CPCB, 2014; USEPA, 2016).

ENVIRONMENTAL AND HEALTH IMPACTS

Environmental Impacts

High levels of air pollution in the study area have severe environmental consequences (CPCB, 2009, WHO, 2021). The deposition of dust on vegetation can cause a decrease in photosynthetic efficiency, affect the stomatal function, and have a negative impact on plant growth (Seinfeld & Pandis, 2016; Ghose, 2007). Additionally, the particulate matter may accumulate and cause changes in the physicochemical properties of the soil, potentially affecting soil quality (USEPA, 2006; Landrigan *et al.,* 2018). Besides, the visibility is reduced due to dust in the air, which can impact transportation safety and environmental quality, especially in active mining areas where vehicles are in constant motion (Gulia *et al.,* 2015; Arya, 1999).

Health Impacts

Local population is exposed to high level of air pollution which is seriously affecting its health (WHO, 2021; CPCB, 2009). It is classified as a risk factor for respiratory diseases like asthma, bronchitis, Chronic obstructive pulmonary disease (COPD) (WHO, 2021; Gulia *et al.,* 2015). Fine particles ($PM_{2.5}$) can have significant impacts on health, especially on the cardiovascular system, because they penetrate deeply into the lungs and into the blood (Pope & Dockery, 2006; WHO, 2021). Chronic exposure to polluted air has also been linked to lung cancer and other serious health effects such as premature death (Landrigan *et al.,* 2018; IARC, 2016).

MITIGATION MEASURES

To mitigate air pollution in the mining affected area, effective measures must be implemented (CPCB, 2009; USEPA, 2006). Regular dust spray on haul roads and mining areas will help to reduce fugitive particulate emission greatly by using dust suppression techniques (Ghose & Majee, 2001; Ghose, 2007). Enclosed systems for crushing and screening operation are widely recommended to reduce the generation of dust at the point of origin (USEPA, 2006; CPCB, 2011).

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The establishment of afforestation programme is critical for soil stabilization and curbing dust dispersion, and plantation of native species on a large scale in mining areas has been identified as an effective ecosystem restoration approach (FSI, 2021; CPCB, 2009). In addition, adopting appropriate waste management procedures such as stabilizing dumps and building retaining structures can reduce wind erosion and secondary particulate emissions (IBM, 2020; Ghose, 2007). Along with the monitoring of air quality, strict enforcement of environmental regulations is also required to ensure compliance with the set national standards and safeguard public health (CPCB, 2009; WHO, 2021).

Dust Suppression and Air Quality Control

These are accomplished by regular water spraying along haul roads and active excavations areas and installation of native vegetation species as windbreaks (CPCB, 2009; Ghose & Majee, 2001). These practices are known to be effective in minimizing fugitive dust emissions from open-cast operations (USEPA, 2006; Ghose, 2007).

Waste and Topsoil Management

Overburden is dumped in a stepped fashion, while different materials like BHQ, Shale and Topsoil are being reused/reclaimed, which is in line with the recommended guidelines for mine reclamation (IBM, 2020 & MoEFCC, 2010). Other erosion management measures being taken include contour trenching and afforestation on dump slopes, which help in controlling erosion and ecological restoration (FSI, 2021; CPCB, 2009).

Reclamation and Rehabilitation

The activities are aimed at progressive backfilling of the mined-out pits and plantation of vegetational species like Neem, Tamarind, Pongamia pinnata, Sapota (Cheeku) and Agave for restoration of vegetation cover and improvement of biodiversity (CPCB, 2009; Ghose, 2007). Structural measures such as retaining wall, garland drains and check dams are being built to effectively control surface runoff and soil erosion consistent with the best practice for the management of the environment in mining operations (MoEFCC, 2006; IBM, 2020).

Water Management

The strategy is to develop engineered retention structures to allow for natural drainage of rainwater, and the relatively low ground-water table minimizes the risk of contamination from

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mining activities due to natural drainage (GSI 2011; CPCB 2009). These environmental management practices are meant to ensure ecological balance, protect health of people and meet regulatory standards throughout the mining life cycle (WHO, 2021; CPCB, 2009).

DISCUSSION

The results of the present study indicated that the emission of particulate matter is one of the most significant issues during the mining activity in the village of Laxmipura, Sandur Taluk but systematic monitoring and effective mitigation measures (CPCB, 2009; WHO, 2021) have kept the ambient air quality within permissible limits. The higher levels of PM_{10} and $PM_{2.5}$ measured near the active mining areas, especially near haulage roads and material handling areas, are indicative of the fact that the major source of air pollution in the study area is fugitive dust emissions. These findings have been reported all over the world in the mining areas where during drilling, blasting, crushing and vehicular movement particulate concentration is significantly elevated (Ghose & Majee, 2001; Ghose, 2007).

The distribution of pollutants shows a gradient of decreasing concentrations from the main areas of mining to the distances around the vicinity of housing indicating the localized nature of the air pollution created by mining. This trend is in line with dispersion studies that have shown that distance and meteorological parameters have a significant effect on the reduction in pollutant concentration (Tiwary, 2001; Seinfeld & Pandis, 2016). Also, the relatively lower concentrations of gaseous contaminants like SO_2 and NO_x indicate that combustion sources are not the major source of pollution in such mining activities, further supporting that particulate pollution is the main concern for the environment in such mining environments (CPCB, 2009; Gulia *et al.,* 2015).

The success of mitigation measures undertaken within the study area can be seen in how air quality standards are being met. Regular water sprinkling on haul roads, use of dust suppression systems and development of green belts have been known to reduce particulate emissions (Ghose, 2007; Sharma & Roy, 2012). Vegetation barriers can also help to reduce wind speed, which helps limit the dispersion of dust, and increase particle deposition, contributing to pollutant attenuation (Tiwary, 2001; FSI, 2021). Also, good waste management practices minimize the risk of re-suspension of fine particulates which further helps in improving air quality (IBM, 2020; CPCB, 2009). It has also been found that compliance with regulatory

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measures, specifically the guideline recommended by Central Pollution Control Board (CPCB) and implementation of ISO 14001 based Environmental Management System (EMS) are vital in ensuring sustainable mining operations (CPCB 2009; ISO 2015). These frameworks allow for ongoing environmental monitoring, assessment of compliance and the implementation of corrective measures to reduce the impacts on the environment.

The results indicate that, while mining activities are always associated with particulate emissions, their environmental impacts can be effectively reduced by implementing integrated management approaches. For mining areas, continuous monitoring, compliance with environmental law, and implementation of best management practices are critical to keep ambient air quality within limits to protect environmental and public health (WHO, 2021; Landrigan et al., 2018).

CONCLUSION

The study concludes that the ambient air quality of Laxmipura village in Sandur Taluk is affected by the activities of iron ore mining and it is observed that particulate matter (PM_{10} and $PM_{2.5}$) is the major pollutants. The National Ambient Air Quality Standards (NAAQS) classify the ambient air quality as “Good”, but the Air Quality Index (AQI) shows that air quality is “Good” on a local scale, with emissions from the mining operations continuing in certain areas. Current mitigation strategies such as dust suppression and afforestation and waste management have helped to keep air quality acceptable, but continued and improved mitigation measures are required. To achieve sustainable environment and public health protection in the long-term, continuous monitoring, adoption of improved technologies and strict regulatory enforcement is required.

RECOMMENDATIONS

It is recommended that the continuous air quality monitoring is enhanced by real time monitoring systems and periodic audit as per the existing regulatory processes for ambient air quality monitoring with the observations taken from Laxmipura village in Sandur Taluk. Adoption of advanced dust suppression techniques and improvement in planning of the mines is essential to minimize fugitive emission from mining operation. Particulate dispersion and ecological impacts should be minimized by developing the green belts, promoting sustainable transportation and using scientific waste management.

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Furthermore, strong enforcement of environmental laws by the Central Pollution Control Board and Karnataka State Pollution Control Board as well as public health monitoring plays a key role in reducing health risks among the mining impacted communities. The use of GIS-based monitoring and spatial analysis tools also assists in the effective environmental assessment and decision making to manage the mining activity sustainably. Together, these actions are crucial for encouraging sustainable mining operations and ensuring environmental health and safety.

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