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Editorial Note

This is a brief introduction to a timely and intellectually relevant conversation in this AYIKA publication. It centres on ten articles that cover unique aspects of development challenges in Africa, with particular attention to South Africa and Nigeria. These contributions, taken together, not only identify persistent challenges in environmental protection and economic growth but also advance policy recommendations in response to Africa's changing circumstances across various fronts. To be clear, the needs of Africa are multifaceted and interconnected in several ways; the challenges are similar across the board, although the manifestations may differ geographically. These articles address the connections in the needs and choices of Africa while projecting a better future. Motswaledi's article illuminates this in this volume, concluding that equitable and inclusive energy provision should be prioritised as a fundamental social justice intervention to redress historical inequalities, promote human dignity, and advance socio-economic transformation in post-apartheid South Africa. Such insight applies to all of Africa.

Collectively, these contributions demonstrate that Africa's development challenges cannot be understood in isolated compartments. Governance affects environmental management; energy affects social justice; infrastructure affects economic growth, etc. The major strength of this collection is therefore its interdisciplinary character. It brings together governance, economics, environmental studies, development studies, public policy, agriculture and social justice. More importantly, the articles consistently return to a central question: how can African societies build institutions and development pathways that improve human welfare without undermining the environmental and social foundations of the future? This collection does not claim to offer simple answers. Instead, it provides evidence, cases and critical perspectives that can help scholars, policymakers and practitioners ask better questions. New and better research questions are a right way in the right direction.

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TABLE OF CONTENT

1. Critical Analysis Of Energy Provision As An Instrument For Advancing Social Justice <i>Thabang R. Motswaledi</i>	5
2. The Development Of An Emissions Inventory Of Selected Air Pollutants Within The Phalaborwa Town, South Africa <i>Phumudzo O Thivhafuni, Shadung J Moja</i>	27
3. Beyond The Climate Crisis: Protecting African Children From Rising Violence <i>Douglas Nyathi, Victor H Mlambo</i>	48
4. Transforming Rural Agricultural Marketing Through Neuromarketing: A Review Of Consumer Preferences, Brand Trust And Loyalty <i>Olaitan Ayotunde Shemfe</i>	73
5. Investigating The Nexus Of Economic Growth, Energy Consumption And Carbon Emissions In South Africa: Evidence From Cointegration And Causality Analysis <i>Badienzele Isaiah Mutombo, Strinivasan Soondrasan Pillay</i>	94
6. Building Resilient Livelihoods In Informal Settlements: Assessing Hemp-Based Strategies Through The Sustainable Livelihoods Framework And Institutional Theory In Ethekewini Municipality <i>Tshililo Ruddy Farisani</i>	113
7. Using Qualitative Meta-Analysis In The Last Decade To Affirm The Dictum That Intrinsic Development Hinges On Established Functional Local Autonomy (Using Nigeria's Realpolitik Environment As Lessons For Africa) <i>Ikemefuna Taire Paul Okudolo</i>	135
8. Political Corruption And Its Impact On Public Governance In Post-Apartheid South Africa <i>Sandiso Mahlala, Xolisile Ngumbela, Phumudzo P. Ramolai, Makhura B. Rapanyane, Mahlatse Sevhake</i>	151

9. Entrenching Sustainable Development Goal Sixteen Within A Developmental
Local Government In South Africa

Kaizer R. Makole, Kabelo B. Moeti

178

10. Climate Change Adaptation And National Water Policies On Flooding Risk
Management: Analytical Experience From Osun State, Nigeria

Luqman Olawale Alako, Bolanle Waliu Shiyabade, Kazeem Oyedele Lamidi

201

THE DEVELOPMENT OF AN EMISSIONS INVENTORY OF SELECTED AIR POLLUTANTS WITHIN THE PHALABORWA TOWN, SOUTH AFRICA

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Abstract

Resolving the neglect of secondary industrial and mining nodes within South Africa, this study establishes a 2015 high-resolution baseline emissions inventory for the Phalaborwa region. Utilizing a hybrid top-down and bottom-up approach across point, mobile, and area sources, mass emission loads were quantified for six criteria pollutants: sulphur dioxide (SO₂), nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), and PM₁₀ and PM_{2.5}. The integrated inventory revealed a total regional atmospheric burden dominated by severe sectoral splits. The industrial sector is the main driver of gaseous pollutants, dictating 77.05% of SO₂ (4,650.70 t/a) and 77.22% of NO_x (2,004.65 t/a) emissions due to pyrometallurgical processing. Transport sector dominated the regional footprint for CO (50.93% or 1,940.25 t/a) and NMVOC (51.89% or 267.45 t/a), reflecting expanding mining freight corridors. Crucially, the mining and minerals processing sector emerged as the principal source of particulate mass loading, accounting for 87.10% of total PM₁₀ (1,337.02 t/a) and 73.37% of PM_{2.5} (402.32 t/a) across the basin. This baseline inventory transforms localized environmental management from a passive compliance exercise into a data-driven atmospheric strategy, providing a transferable blueprint for secondary industrial nodes across the region.

Keywords: *Emission inventory; SO₂; CO; NO_x; PM₁₀; PM_{2.5}; NMVOC; air quality management*

1. Introduction

Atmospheric pollution in South Africa's industrialized and urban corridors represents an escalating national priority, public health crisis, and regulatory challenge (Altieri & Keen, 2021). Developing a comprehensive emissions inventory is a fundamental prerequisite for effective local governance, allowing authorities to identify sources, quantify baseline levels, execute predictive dispersion modeling, and frame targeted mitigation strategies (Mues et al., 2022; Sahu et al., 2024).

Despite its necessity, baseline emission data remains severely fragmented or absent across many understudied domestic industrial zones. To address this empirical deficit, this study develops a high-resolution emissions inventory for Phalaborwa region using 2015 base year. Tracking six pollutants [sulphur dioxide (SO₂), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), carbon monoxide (CO), and particulate matter (PM₁₀ and PM_{2.5})], the methodology applies a hybrid framework integrating top-down macro-statics and bottom-up point-source tracking across five socio-economic sectors: industrial, mining, transport, waste, and residential activities. Ultimately, this baseline inventory establishes the empirical foundation necessary to design air quality management plans within the study area.

2. Literature To contextualize the empirical necessity of this inventory, it is critical to evaluate the frameworks governing air quality management across international, national, and sub-national scales. Globally, literature extensively documents transboundary pollutant transport, source apportionment, and the resulting public health exposure risks (Mao et al., 2023; World Health Organisation, 2021). However, South Africa's domestic research landscape mirrors its national regulatory focus, dedicating the bulk of academic funding and monitoring infrastructure to major urban-industrial basins and designated priority areas (Standard et al., 2022). Consequently, secondary industrial hubs are systemically omitted from mainstream scientific literature.

In Limpopo Province, atmospheric research is severely constrained and largely restricted to localised, compliance driven Environmental Impact Assessments. This deficit is highly pronounced within the Phalaborwa Local municipality. Despite being formally designated as an air pollution hotspot due to extensive localised mining and metallurgical operations, the municipality lacks a comprehensive Air Quality management Plan (Ba-Phalaborwa Local Municipality, 2026; Mopani District Municipality, 2024). This regulatory vacuum creates a profound knowledge gap regarding

localised emission source strengths and spatial pollutant distributions.

Compounding this deficit is the historical vulnerability of continuous monitoring infrastructure in the region. Prior to the execution of this inventory, localised automated continuous monitoring and passive sampling of nitrogen dioxide (NO₂), SO₂, benzene (C₆H₆), ozone (O₃), and PM₁₀ revealed persistent, severe degradation in local air quality, with PM₁₀, SO₂, and O₃ concentrations exceeding the National Ambient Air Quality Standards of 2009 (Moja & Thivhafuni, 2017). These baseline exceedances confirm sustained industrial and transboundary stress, demonstrating the critical applicability of multi-sector source inventory presented in this work.

3. Methodology

Emissions inventories are systematically compiled using either top-down macro-scale evaluations or bottom-up tracking. This study primarily used a bottom-up approach (van der Gon, 2012; Brook et al., 2008; Thunis et al., 2016), leveraging spatial profiles, process-specific activity rates, and localized source-configurations

across six consecutive phases. Primary activity data was collected through targeted field campaigns using sector-customized questionnaires deployed across mining, heavy industrial, brickworks, wastewater, and commercial sectors. Comprehensive site visits were conducted across Phalaborwa's industrial and mining corridors to validate questionnaire inputs and map geographic coordinates. These field surveys verified visible fugitive sources and localized stack heights, providing accurate parameters for subsequent quantification modeling.

3.1 Stationary and Point Source Quantification

Mass emission rates for point and stationary sources were quantified using a specialized Microsoft Excel® atmospheric emissions database developed for the Department of Economic Development Environment and Tourism (LEDET, 2013). Emissions were estimated by combining activity data with source-specific emission factors using the standard empirical mass-balance framework (EEA, 2009; Zhao et al., 2015):

$$E_p = \sum_{k=1}^m \left[A_k \times EF_{k,p} \times \left(1 - \frac{ER_{k,p}}{100} \right) \right]$$

where E_p represents the total annual mass emission rate of pollutant p discharged into the atmosphere. (t/a), A_k denotes the annual operational

activity rate or fuel throughput for process line k . $EF_{k,p}$ is the uncontrolled emission factor assigned to process or fuel type k for pollutant p ,

representing the mass generated per unit of activity before abatement. $ER_{k,p}$ is the overall engineering reduction or control efficiency for pollutant p achieved by integrated emission abatement technologies.

Because localized, source-specific emission factors for secondary South African industrial hubs are heavily constrained in peer-reviewed literature, the underlying emission factor inputs ($EF_{k,p}$) embedded within the LEDET database were primarily adapted from the United States Environmental Protection Agency (US EPA) AP-42 compilation frameworks (USEPA, 1996, 2010, 2016). Where applicable, default AP-42 factors for solid bituminous coal combustion were adjusted to align with the unique fuel properties characteristic of South African coal, specifically accounting for the high ash content and localized sulphur fractions typical of regional low-grade utility feeds.

3.2. Mobile Source Quantification and Fuel balancing

Transport emissions for 2015 baseline were calculated using the Computer Programme to Calculate Emissions from Road Transport (COPERT IV) methodology (EEA, 2012), with activity data, including daily vehicle kilometers traveled (VKT), average speed distributions, and diurnal start-cycle frequencies sourced from Roads Agency Limpopo (RAL, 2013) and the South African National Roads Agency Limited (SANRAL, 2012).

A top-down and bottom-up fuel reconciliation protocol was employed to minimize uncertainty, validating calculated fuel consumption against actual 2015 sales records for Phalaborwa region. Tailpipe pollutant loads were estimated by adjusting vehicle mileage to align with fuel sales data ensuring regional emission constraints and localized sectoral distribution via the following expression:

$$FC_{i,f} = \frac{N_{i,f} \times S_{i,f} \times VKT_{i,f}}{\eta_{i,f}}$$

Where $FC_{i,f}$ represents the calculated fuel consumption for the vehicle category i utilizing fuel specification f . $N_{i,f}$ is the total number of registered vehicles assigned to category i , $S_{i,f}$ represents the fractional fuel share allocation parameter assigned to vehicle class i , defining the percentage

of the fleet operating on a specific fuel type f . $VKT_{i,f}$ is the average annual vehicle kilometers traveled per vehicle within category i using fuel type f , derived from regional traffic counts and spatial transit metrics. $\eta_{i,f}$ is the category-specific operational fuel efficiency, expressed as the total

distance travelled per unit of fuel consumed (km/L or km/tonne).

In the second phase of the mobile tracking loop, the total bottom-up modeled fuel consumption summed across all vehicle categories ($\sum FC_{i,f}$) was validated against actual, top-down fuel sales records for the Phalaborwa region during the 2015 base year. Discrepancies between modeled and reported fuel distributions were corrected by adjusting the vehicle mileage ($VKT_{i,f}$) attributes until the calculated fuel consumption converged with actual sales statistics.

3.3 Quantification of Uncertainties in Inventory

The compilation of a localized atmospheric emissions inventory inherently involves varying degrees of statistical uncertainty. In accordance with the guidelines established by the Intergovernmental Panel on Climate Change (IPCC, 2006) and the

European Environment Agency (EEA, 2019), uncertainties within this inventory were systematically classified into two primary vectors: parameters governing activity data (AD) and parameters governing emission factors (EF). To quantify the combined effect of these individual variances on the total regional mass emissions, an empirical Tier 1 error propagation framework was deployed. This mathematical approach assumes that the underlying uncertainties are independent, symmetrically distributed around the mean (Zhao et al., 2015).

When estimating emissions from an individual source category where the total mass load (E) is derived as a product of multiplication parameters ($E = A \times EF$), the relative uncertainty (U_{total}) of the sector was calculated using the square root of the sum of squares of the relative uncertainties of the inputs:

$$U_{total,j} = \sqrt{U_{A,j}^2 + U_{EF,j}^2}$$

Where $U_{total,j}$ represents the percentage uncertainty of pollutant emissions for source category j, while $U_{A,j}$ and $U_{EF,j}$ represent the percentage uncertainties associated with the activity rate and emission factor, respectively.

To determine the cumulative uncertainty of the integrated regional inventory across all n independent source sectors (Industrial, Mining, Transport, Waste, and Residential), the absolute uncertainties of each individual category were aggregated using the standard error propagation equation for addition:

$$U_{regional} = \frac{\sqrt{\sum_{j=1}^n (E_j \times U_{total,j})^2}}{\sum_{j=1}^n E_j}$$

Where $U_{regional}$ is the final percentage uncertainty assigned to the total regional mass emission for a specific pollutant, and E_j represents the absolute annual mass emission rate (t/a) quantified for sector j .

Table 1: Assigned Input Uncertainties (%) and Resulting Propagated Total Error by Sector and Pollutant Type

Source Sector	Parameter Type	SO ₂	NO _x	CO	NMVOCS	PM ₁₀	PM2.5
Industrial	Activity Data (UAD)	± 10%	± 10%	± 15%	± 20%	± 15%	± 15%
	Emission Factor (EF)	± 25%	± 30%	± 40%	± 50%	± 45%	± 50%
Mining	Activity Data (UAD)	± 15%	± 15%	± 20%	± 25%	± 25%	± 25%
	Emission Factor (EF)	± 35%	± 35%	± 45%	± 50%	± 65%	± 70%
Road Transport	Activity Data (UAD)	± 12%	± 12%	± 12%	± 15%	± 20%	± 20%
	Emission Factor (EF)	± 20%	± 25%	± 35%	± 40%	± 40%	± 45%
Residential	Activity Data (UAD)	± 40%	± 40%	± 40%	± 45%	± 45%	± 45%
	Emission Factor (EF)	± 50%	± 50%	± 60%	± 70%	± 75%	± 80%
Waste	Activity Data (UAD)	N/A	N/A	N/A	± 50%	± 50%	± 50%
	Emission Factor (EF)	N/A	N/A	N/A	± 80%	± 85%	± 90%
Propagated Total	Regional Airshed (Uregional)	± 26.8%	± 31.4%	± 37.1%	± 43.9%	± 58.6%	± 61.2%

As compiled in Table 1, the lowest calculated regional uncertainties were observed for SO₂ ($\pm 26.8\%$) and NO_x ($\pm 31.4\%$). This higher data confidence is directly attributable to the fact that these pollutants are overwhelmingly generated by centralized, highly regulated industrial point sources, which maintain precise material throughput data and continuous emissions tracking.

Conversely, the highest uncertainties occurred within the particulate matter core fractions, with PM₁₀ and PM_{2.5} exhibiting regional error boundaries of $\pm 58.6\%$ and $\pm 61.2\%$, respectively driven by the dynamic and micro-climatic variability of fugitive mining dust emissions.

3.4 Quality Assurance and Quality Control (QA/QC)

Rigorous Quality Assurance and Quality Control (QA/QC) protocols were integrated into every phase of data collection and compilation to ensure data integrity. Structural QC operations included systemic double-entry verification of raw questionnaire

data, arithmetic completeness checks on the LEDET calculator outputs, and outlier detection for activity rates. Comprehensive QA was maintained by documenting all data sources, processing methods, and underlying assumptions, ensuring the transparency, reproducibility, and reliability of the final localized inventory.

4. Results and discussion

4.1 Industrial sector Emissions

4.1.1 Fuel combustion-based industrial emissions

Atmospheric emissions stemming from industrial fuel combustion, predominantly driven by bituminous coal and heavy fuel oil (HFO), were quantified using process-specific consumption rates. Industrial combustion generated an annual mass load of 35.86 tonnes per annum (t/a) for PM₁₀, 202.75 t/a for SO₂, 383.80 t/a for NO_x, 221.62 t/a for CO, and 33.94 t/a for NMVOCs. The detailed disaggregation by fuel category is presented in Table 2.

Table 2: Fuel combustion-based emissions from industrial sources in Phalaborwa (t/a)

Fuel Use d	Consumptio n Rate	TSP	SO2	NOx	CO	PM1 0	NMVOC s	PM2. 5
Coal	7,800,000 kg	23.5 0	170.5 9	32.79	176.4 6	22.18	16.83	20.47

HF O	16,448,015l L	13.6 8	32.16	351.0 1	45,16	13.68	17.11	13.68
Total		37.1 9	202.7 5	383.8 0	221,6 2	35.86	33.94	34.16

Stoichiometric evaluation reveals that solid coal combustion acts as the primary driver for SO₂ (84.1%), CO (79.6%), PM₁₀ (61.8%), and PM_{2.5} (59.9%) profiles within the combustion subcategory, linked directly to low-efficiency thermal constraints and fuel sulphur content. Conversely, for liquid HFO use dominates localised industrial NO_x formation (91.5%), which is highly indicative of high-temperature combustion zones within local boilers.

4.1.2 Process-Related Non-Combustion Industrial Emissions Non-combustion process emissions tracked across nine industrial facilities contributed an additional mass load of 110.56 t/a PM₁₀, 89.45 t/a PM_{2.5}, 4,447.95 t/a SO₂, 1,620.85 t/a NO_x, 91.97 t/a CO, and 64.23 t/a NMVOCs (see Table 3).

Table 3: Non-combustion industrial process emissions by subcategory (t/a)

Source Category	PM10	PM2.5	SO2	NMVOCs	NOx	CO
Chemical Products	25.92	19.44	1,836.00	50.40	3.56	19.62
Metallic Products	57.16	43.97	2,286.52	6.60	1,552.20	0.04
Small Boilers	27.48	26.03	325.43	7.23	65.09	72.32
Total	110.56	89.45	4,447.95	64.23	1,620.85	91.97

Metallurgical processes represent the main driver of non-combustion point emissions, yielding the majority of particulate and gaseous loads (PM₁₀, PM_{2.5}, SO₂, and NO_x). Chemical processes drive regional point source NMVOC (50.40 t/a), while small-scale utility boilers are the main source of

CO (72.32 t/a). Integrating both combustion and process channels yields a total industrial footprint of 146.42 t/a for PM₁₀, 123.61 t/a for PM_{2.5}, 4,650.70 t/a for SO₂, 98.17 t/a for NMVOC, 2,004.65 t/a for NO_x, and 313 t/a for CO.

4.2 Road transport Emissions

The on-road transportation sector within Phalaborwa tacking grid showed heavy concentrations of combustion gases. CO was the primary mass pollutant emitted at 1,940.25 t/a, followed by NO_x (326.61 tpa) and NMVOCs (267.45 tpa). Sulphur and particulates fractions remained low due to low fleet-wide emission factors (Table 4)

Table 4: Transport Emissions Across Vehicle Categories (t/a)

Category	Fuel	Consumption (tpa)	NOx	SO2	CO	NMVO C	PM10	PM2.5
Motor-cycles	Gasoline	702.16	4.66	0.70	349.47	92.26	1.90	1.54
Passenger cars	Gasoline	8,192.03	71.52	8.19	693.86	82.33	0.30	0.25
	Diesel 50	4,977.06	64.50	0.50	16.57	3.48	8.46	5.47
LDV	Gasoline	5,523.48	73.02	5.52	841.23	80.59	0.17	0.11
	Diesel 500	3,356.02	50.04	3.36	24.83	5.17	5.71	5.10
HDV	Diesel 500	959.16	32.01	0.96	7.27	1.84	1.15	0.90
Buses	Diesel 500	924.98	30.87	0.92	7.01	1.78	1.11	0.87
Total			326.61	20.16	1940.25	267.45	18.79	14.25

Figure 1 outlines the percent contribution of emissions from transport sector by fuel type. Evaluated across fuel specifications, gasoline vehicles dominate the CO and NMVOC profiles, while diesel accounts for the primary share of transport-derived SO₂, PM₁₀ and PM_{2.5}. For the regional fleet configuration, NO_x emissions are driven predominantly by diesel (comprising Diesel 500 ppm and Diesel 50 ppm classes), which contribute a combined 177.42 t/a (54.3%) of total mobile NO_x. Outstripping gasoline combustion outputs.

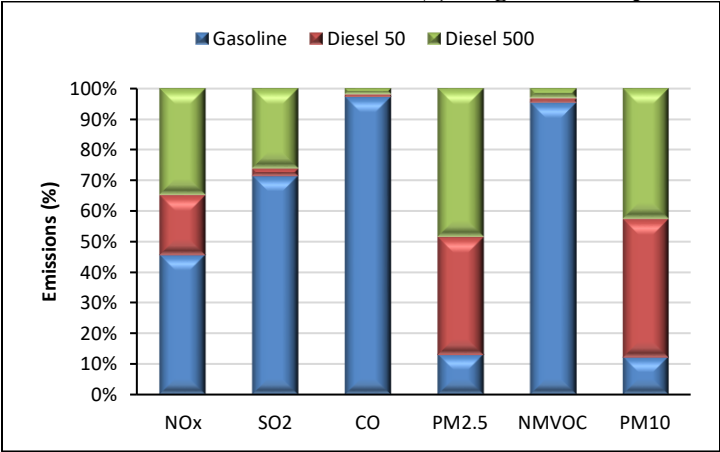


Figure 1: Percent contribution of transport Sector emissions by fuel type.

Light-duty vehicles (LDVs) and passenger cars dominate the transport footprint. LDVs account for the highest CO (44.6%) and SO₂ (44.1%) shares, whereas passenger vehicles emit the largest fractional shares of NO_x (41.7%), PM₁₀ (46.6%), and PM_{2.5} (40.2%). Motorcycles yield a highly disproportionate NMVOC load (34.5%), largely due to gasoline combustion, reflecting high

hydrocarbon passing rates inherent to small-capacity gasoline engines.

4.3 Residential Sector Emissions

Using domestic energy profiles, residential fuel use for the 2015 base year generated 143.86 t/a CO, 31.86 t/a PM₁₀, 9.01 t/a NMVOCs, 8.04 t/a PM_{2.5}, 2.58 t/a NO_x, and 0.03 t/a SO₂ (Table 5).

Table 5: Emissions from domestic fuel consumption in the residential sector (t/a)

Fuel Type	NOx	SO2	NMVO C	CO	PM10	PM2,5
Paraffin	0.0923	0.0021	0.0327	0.6203	0.2072	0.1275
LPG	0.0016	0.0003	0.0014	0.0034	0.0019	0.0003
Wood	2.4817	0.0165	8.9756	143.1127	31.6419	7.9001
Dung	0.0088	0.0136	0.0008	0.1239	0.0094	0.0094
Total	2.5844	0.0326	9.0106	143.8603	31.8604	8.0373

Solid wood combustion is the dominant driver residential pollution, accounting for over 99% of CO, PM₁₀, and NMVOCs, alongside 98% of PM_{2.5}, and 96% of NO_x. Animal dung contributes a minor absolute footprint but represents a key source of localized residential SO₂ due to high organic sulphur content.

4.4 Mining and Quarrying Emissions
 Fugitive mining and quarrying activities represent a major source of coarse and fine dust within Phalaborwa region. Mechanical extraction. Open cast handling, and wind erosion generated a mechanical fugitive burden of 8,342.90 t/a TSP, 1,159.60 t/a PM₁₀, and 238.57 t/a PM_{2.5} (Table 6).

Table 6: Fugitive Dust Emissions from Extraction activities by ore type (t/a)

Mineral/Metal	Production Capacity (t/a)	TSP	PM10	PM2,5
Non-metallic Ore	19 499 118	4 634,80	672,84	141,21
Metallic Ore	16 796 303	3 708,10	486,77	97,35
Total	36 295 421	8 342,90	1 159,60	238,57

In addition to fugitive mechanical dust, thermal operations within the mining sector generate substantial fuel combustion emissions, as shown in Table 7

Table 7: Fuel combustion-based emissions from mining and processing activities (t/a)

Activity Type	TSP	PM10	PM2,5	SO2	NOx	CO	NMVO Cs
Drying & Calcining	144,63	136,47	125,97	1 049,76	201,79	1 085,92	103,58
Clamp Kilns	43,39	40,94	37,79	314,93	60,54	325,78	31,07
Total Emissions	188,02	177,41	163,76	1 364,69	262,33	1 411,70	134,65

Stoichiometric tracking shows that CO at 1,411.69 tpa (11%), SO2 at 1,364.69 (10%) operate as the dominant gas species emitted via thermal fuel

combustion in mining processing, driven by high process temperatures, while thermal NOx remains lower at 262.33 t/a.

When coupling raw mining extractions with downstream thermal processing and product manufacturing, the total integrated mining footprint expands significantly, as shown in table 8.

Table 8: Integrated totals for the mining and minerals processing sector (t/a)

Source Category	Annual Emissions (tonnes)						
	TSP	PM10	PM2,5	SO2	NOx	CO	NMVOCs
Mineral Processing	4,822.82	850.25	304.97	1,364.69	262.32	1,411.69	134.65
Metallic Ore	3,708.10	486.77	97.35	N/A	N/A	N/A	N/A
Total Emissions	8,530.92	1,337.02	402.32	1,364.69	262.32	1,411.69	134.65

Note: N/A denotes not applicable

Figure shows the distribution of these emissions from the mining and quarrying sector.

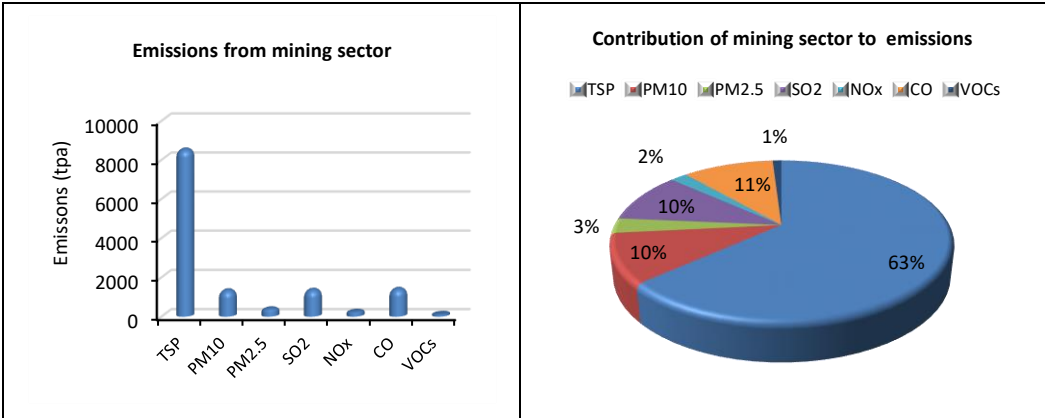


Figure 2: Emissions from mining and quarrying sector.

Total integrated sector metrics indicate that TSP is the primary pollutant at 8,530.92 t/a (63%), followed by thermal combustion gases including CO at 1,411.69 t/a (11%), and SO2 at 1,364.69 (10%) as well as particulates, PM10 at 1,337.02 t/a (10%). Finer

fragments (PM2.5), NOx and NMVOCs yield minor fractional loads at 402.32 t/a (3%), 262.32 t/a (2%) and 134.65 t/a (1%) respectively. Non-metallic mineral mining and processing serve as the primary

sectoral drivers over metallic paths due to higher handling capacities.

4.5 Waste sector Emissions

Atmospheric loads tracking solid waste landfilling alongside wastewater treatment and discharge categories, are detailed in

Table .

Table 9: Emissions from waste and wastewater sectors (t/a)

Waste Sector	NMVOC	TSP	PM10	PM2,5
Solid Waste Disposal	6,042	1,848	0,890	0,139
Wastewater Treatment	0,137	n/a	n/a	n/a
Total	6,179	1,848	0,89	0,139

As outlined in Table 9 and Figure 3, volatile organic compounds dominate the total waste sector emissions, accounting for approximately 85.7% of mass load (6.18 t/a), drive by anaerobic degradation pathways. Fugitive dust

from landfill operations contributes minor coarse shares (PM10 at 0.89 tpa (12%) and PM2.5 at 0.139 tpa (2%)).

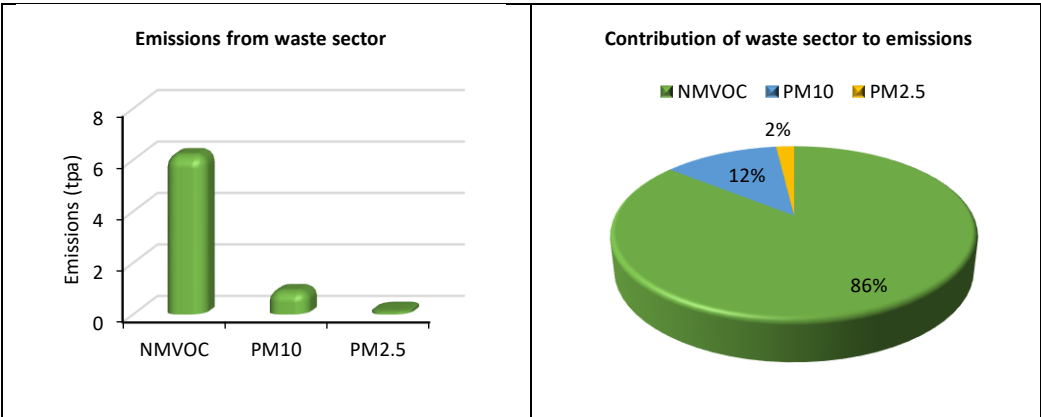


Figure 3: Emissions from waste sector, 2015.

4.6 Consolidated Regional Inventory and Sectoral balance

To establish a clear perspective on regional source distributions, Table

provides the final consolidated baseline atmospheric emissions inventory for the Phalaborwa region.

Table 10: Consolidated Baseline emissions Inventory for Phalaborwa Region (t/a)

Source Sector	Annual Emissions (Tonnes)					
	PM10	PM2,5	SO2	NMVO Cs	NOx	CO
Industrial	146.42	123.61	4,650.70	98.17	2,004.65	313.59
Road Transport	18.79	14.25	20.16	267.45	326.61	1,940.25
Residential	31.86	8.04	0.03	9.01	2.58	143.86
Mining	1,337.02	402.32	1,364.69	134.65	262.32	1,411.69
Waste	0.89	0.14	n/a	6.18	N/A	N/A
Total Emissions	1,534.98	548.35	6,035.58	515.46	2,596.17	3,809.39

Note: N/A denotes not applicable

The integrated inventory indicates that the industrial sector is the largest source of regional SO₂ (77.05%) and NO_x (77.22%) emissions, primarily driven by pyrometallurgical point processing and HFO industrial boilers. Mobile road transport dominates CO (50.93%) and NMVOCs (51.89%) due to widespread urban and commercial freight corridors. Conversely, the mining and quarrying sector is the principal source of particulate mass

4.7. Evaluation of Inventory Uncertainties and Their Policy and Compliance Implications

The calculated error boundaries compiled via the Tier 1 propagation framework, ranging from relatively constrained bounds for gaseous species

loading, accounting for 87.10% of PM10 and 73.37% of PM2.5 across the airshed. This baseline inventory provides an empirical foundation for future localized atmospheric impact assessments and supports the development of targeted source-specific emission reduction strategies across the region governance, compliance verification, and future air quality management strategies within the Phalaborwa airshed

(±26.8%) for SO₂ and (±31.4%) for NO_x to highly volatile variances for particulate fractions (±58.6% for PM10) and (±61.2%) for PM2.5), carry profound implications for atmospheric.

4.7.1. Gaseous Uncertainty and the Point-Source Compliance Paradigm

The lower relative uncertainty boundaries observed for SO₂ and NO_x reflect the centralized, heavily regulated nature of their primary emitting channels. Because the industrial sector dictates an overwhelming 77.05% of absolute regional SO₂ and 77.22% of NO_x mass loads, the activity data metrics are rooted in precise industrial logging. Large-scale pyrometallurgical operations and chemical fertilizer plants in Phalaborwa keep continuous, verifiable records of bituminous coal tonnage, heavy fuel oil (HFO) volumetric throughput, and raw mineral compositions as part of standard corporate material-balancing and fiscal accounting. This commercial oversight significantly constrains the variance of the Activity Data (UAD) parameter.

However, the remaining $\pm 25\%$ to $\pm 30\%$ uncertainty in industrial gaseous emission factors (UEF) introduces an explicit barrier to regulatory enforcement. These variances exist because point-source quantifications frequently rely on US EPA AP-42 default metrics, which assume optimized thermal efficiencies and uniform combustion conditions. In reality, sub-continental boiler systems often operate with varying maintenance schedules, fluctuating feed-material sulphur contents, and localized modifications that alter stoichiometric air-to-fuel ratios. When local environmental management officers utilize these unadjusted

baseline metrics to verify compliance with local standards or to issue Atmospheric Emission Licenses (AELs), the underlying statistical variance can lead to over- or under-estimating a facility's true mass contribution. This variance compromises the legal defensibility of municipal enforcement actions.

4.7.2. Particulate Uncertainty and the Fugitive Dust Dilemma

The pronounced error boundaries governing the particulate matter core fractions ($\pm 58.6\%$ for PM₁₀ and $\pm 61.2\%$ for PM_{2.5}) represent a critical vulnerability for regional environmental planning. This high level of uncertainty is driven by the mining sector's dominance over the particulate footprint, accounting for 87.10% of total PM₁₀ and 73.37% of PM_{2.5} across the airshed. Unlike stationary industrial chimneys, which release pollutants through distinct, metered points, mining-derived particulate matter is overwhelmingly fugitive. Dust entrainment by heavy hauling vehicles on unpaved roads, mechanical fracturing during blasting and crushing, and wind erosion over expansive Tailings Storage Facilities (TSFs) are inherently dynamic processes.

The empirical formulas used to estimate these fugitive emissions rely heavily on variables that are highly unstable over space and time. For instance, wind erosion equations are governed by local meteorological

parameters, changing wind fields, surface roughness lengths, and soil moisture thresholds, all of which fluctuate hourly within the semi-arid Phalaborwa climate. Furthermore, the material properties of local ore bodies, such as silt loading percentages on haul roads and the moisture content of processed magnetite, vary across different extraction blocks within the open-cast pits. Consequently, calculating a single annual mass emission rate for mining particulates carries an unavoidable margin of error. This makes it challenging to determine whether a sudden spike in ambient PM₁₀ concentrations recorded downwind is driven by a genuine increase in production capacity or is simply a function of changing microclimatic parameters accelerating wind-induced erosion.

4.7.3. Impacts on Air Quality Compliance, Modeling, and Municipal Strategy

For the Ba-Phalaborwa Local Municipality and LEDET, these particulate error boundaries create significant challenges for regulatory compliance and strategic planning under the National Environmental Management: Air Quality Act (AQA). When local authorities attempt to project the future status of the airshed or draft an active Air Quality Management Plan (AQMP), the inventory's internal variance scales up when fed into atmospheric dispersion models (such as AERMOD or

CALPUFF). A $\pm 58.6\%$ uncertainty input for particulate matter means that the modeled downwind ambient concentration plumes will feature broad, overlapping confidence intervals.

This mathematical uncertainty directly impacts the local compliance framework by undermining source apportionment defensibility: If a municipality issues an administrative non-compliance notice to a mining operation based on a modeled violation of the 24-hour PM standard ($75\text{g}/\text{m}^3$), the facility's legal team can easily challenge the notice by pointing out that the inventory's underlying uncertainty boundary encompasses the compliance target itself.

Furthermore, high inventory uncertainty expands the theoretical geographical boundaries of pollutant impact zones, complicating urban and industrial zoning adjacent to the Phalaborwa industrial corridor. Long-term planning and residential zoning rely on clear boundaries of exclusion zones, and broad margins potentially stalls local infrastructure development or inadvertently exposing new residential settlements to unquantified particulate hotspots.

Finally, while the residential biofuel and waste management sectors exhibit massive localized uncertainties (exceeding $\pm 80\%$) due to highly fragmented data on community wood scavenging and landfill volumes), their low fractional contribution to the total

regional mass balance prevents them from driving the overall airshed metrics. However, because these are low-level, ground-release sources situated directly within high-density communities, their real-world health impact is highly disproportionate to their mass footprint. The broad uncertainty surrounding these low-level inputs prevents municipal health officers from assessing local exposure dynamics.

To resolve these systematic compliance challenges, future environmental policy must move away from generic international defaults. Local authorities must mandate facility-specific source testing, enforce continuous point-source monitoring, and institute site-specific silt and moisture assessments across all active mining operations. Transitioning from generic emission factors to direct, localized measurements is the only viable pathway to shrink these error boundaries, provide legally defensible source apportionment, and safeguard the public health and ecological integrity of the Phalaborwa region.

5. Conclusion and Policy

Recommendations

5.1. Conclusion

This study established a comprehensive baseline atmospheric emissions inventory for the Phalaborwa region, Limpopo Province, for the 2015 base year. By deploying a hybrid verification framework across

five primary socio-economic sectors, this research successfully resolved a critical administrative knowledge vacuum, providing the first unified, source-specific mass-apportionment dataset for this secondary South African industrial hub.

The integrated inventory revealed distinct, sector-dominant chemical signatures across the airshed. The industrial sector represents the definitive driver of regional gaseous configurations, dictating 77.05% of absolute SO₂ (4,650.70 t/a) and 77.22% of NO_x (2,004.65 t/a) loads, due to intensive pyrometallurgical processing and high-temperature heavy fuel oil boiler operations. Mobile road transport dominates the regional footprint for CO (50.93% or 1,940.25 t/a) and NMVOC (51.89% or 267.45 t/a), reflecting heavy commercial freight corridors supporting regional mining logic. Crucially, the mining and minerals processing sector emerged as the absolute principal source of particulate matter loading, accounting for an overwhelming 87.10% of total PM₁₀ (1,337.02 t/a) and 73.37% of PM_{2.5} (402.32 t/a) across the basin.

The Tier 1 error propagation analysis bounded these metrics within clear statistical confidence margins, highlighting low variances for centralized industrial gases but severe uncertainty boundaries for particulate fractions ($\pm 58.6\%$ for PM₁₀) this variance stems from the dynamic micro-climatic and fugitive nature of

open-cast mining operations, which historically complicated local compliance monitoring.

5.2. Policy Recommendations

To translate these empirical findings into target-directed environmental governance under the AQA, the following local policy actions are recommended:

- **Promulgation of a Localized AQMP:** LEDET must prioritize immediate regulatory funding to develop and implement a dedicated AQMP for the Ba-Phalaborwa Local Municipality to set mandatory emission caps on primary point sources.
- **Mandatory Flue-gas Abatement Retrofits:** Industrial AELs must mandate the installation of modern flue-gas desulphurization (FGD) systems and selective catalytic reduction (SCR) technologies.
- **Targeted Fugitive Dust Suppression Protocols:** Environmental inspectors must enforce mandatory site-specific dust management plans in mines, requiring chemical stabilizers on open-cast haul roads, the deployment of windbreaks around active tailings storage facilities (TSFs).
- **Establishment of Commercial Freight Corridors:** Traffic planning must implement designated heavy-vehicle freight corridors to divert

heavy-duty diesel mining trucks away from high-density urban zones.

- **Subsidized Domestic Energy Transitions:** Local government must accelerate rural electrification and subsidize liquid petroleum gas (LPG) infrastructure in adjacent informal settlements to phase out solid biomass reliance.
- **Rehabilitation of Monitoring Networks:** The dysfunctional continuous automated air quality monitoring infrastructure within Phalaborwa must be systematically rehabilitated to track future airshed variations.

6. Methodological Limitations and Assumptions

The study has several methodological limitations and assumptions, including the use of international emission factors that may not fully reflect South African conditions, a single base year (2015), incomplete activity data for some sources, and reliance on secondary data. Consequently, the results should be interpreted as the best available estimates to support air quality management, environmental compliance, environmental crime detection, and future inventory refinement.

Author contributions

The manuscript is based on unpublished findings from a master's research study completed in 2017. The first author was responsible for the

study's conceptualisation, data collection, data analysis, and write up of the write-up of the manuscript. The second author supervised the research and contributed to the review, revision, and preparation of the manuscript. Both authors have reviewed and approved the final version of the manuscript.

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Ethical statement

Ethical approval for the research protocol was obtained from the University of South Africa (UNISA) Research Ethics Committee prior to the commencement of the study. Permission to access the required data was granted by the Limpopo Department of Economic Development, Environment and Tourism (LEDET) and other relevant institutions that provided activity data for the emissions inventory. The research was conducted in accordance with accepted ethical principles of

scientific integrity, confidentiality, and responsible data management.

Informed Consent Statement

The study did not involve the collection of personal or sensitive information from human participants. Primary activity data were obtained through sector-specific questionnaires administered to institutional representatives during site visits, supplemented by published emission factors and other secondary datasets. The site visits were conducted to verify emission sources and collect technical information for emissions estimation. Consequently, individual informed consent was not required.

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Conflicts of Interest

The authors declare no conflicts of interest.

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