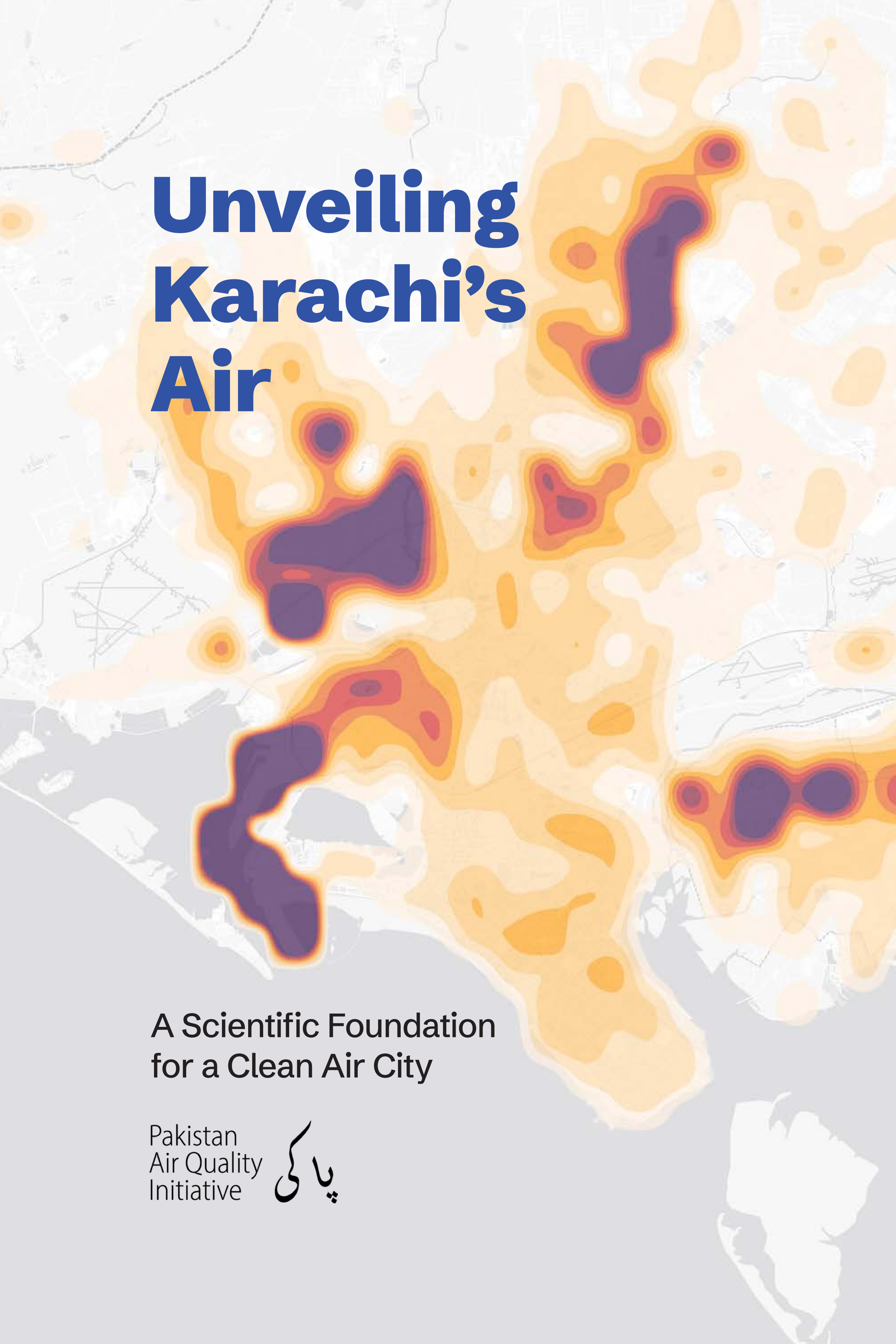

Unveiling Karachi's Air

A Scientific Foundation for a Clean Air City

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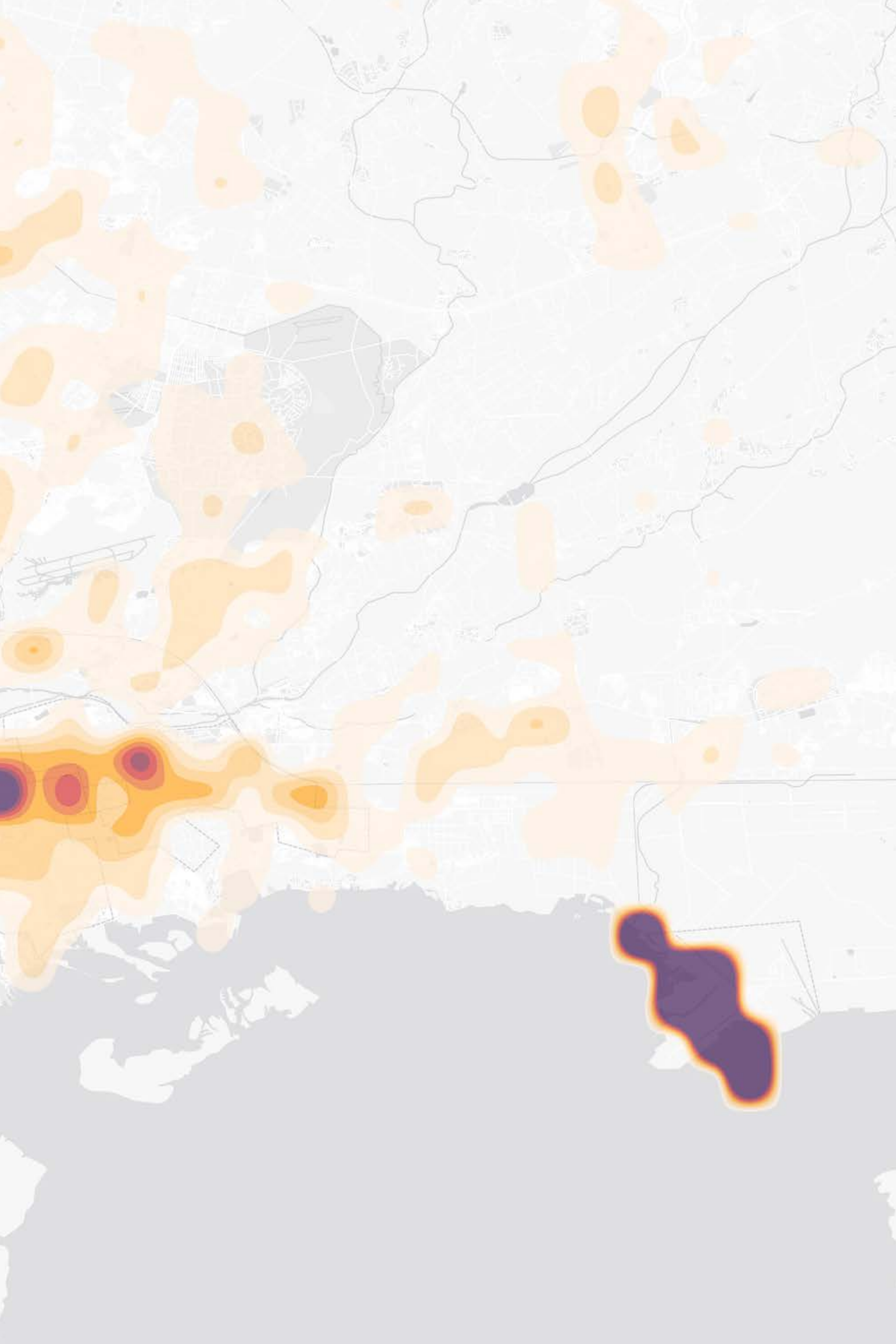

Unveiling Karachi’s Air

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Unveiling Karachi's Air: A Scientific Foundation for a Clean Air City

Dawar Hameed Butt, Mahad Naveed, and Abid Omar
Editor: Mariam Shah

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Email: hello@pakairquality.com

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Contents

Air Pollution: A Public Health Emergency

Air pollution in Karachi is a public health crisis that shortens the life of an average resident by 2.7 years. Air quality monitoring data reveals that Karachi's air is polluted year-round, consistently failing to meet both national standards and global health guidelines. In 2024, the air was unhealthy by WHO standards for 363 days, with pollution on 70 days so severe it also breached the legal limits set by the Sindh Environmental Protection Agency (SEPA).

To address this crisis, the Pakistan Air Quality Initiative (PAQI) has developed the first scientific emissions inventory for Karachi, diagnosing its primary sources of air pollution, providing the indispensable evidence needed for policymakers, industry, and civil society to implement targeted, high-impact interventions and forge a path towards cleaner air.

The Diagnosis: Identifying the Sources

Karachi's atmosphere carries a heavy load of pollutants, with annual emissions estimated at 39.11 kilotons of Particulate Matter (PM2.5), 51.52 kilotons of Sulfur Dioxide (SO_2), 100.78 kilotons of Nitrogen Oxides (NO_x) , and 203.41 kilotons of Carbon Monoxide (CO) across all major sectors within the Karachi airshed. This translates to per capita PM2.5 emissions of approximately 1.86 kg per person per year.

This inventory, with a baseline year of 2021, quantifies the major sources of anthropogenic air pollution in the Karachi airshed:

Industry: The industrial sector is the largest contributor to health-damaging fine particulate matter (PM2.5), accounting for nearly half (49%) of all emissions. This reflects Karachi's extensive manufacturing base, including steel, cement, and textile industries.

Transport: The transport sector is the second-largest source of PM2.5 (33%) and the overwhelming source of nitrogen oxides (NO_x) at 80%, largely due to a heavy reliance on an aging, diesel-powered freight vehicle fleet.

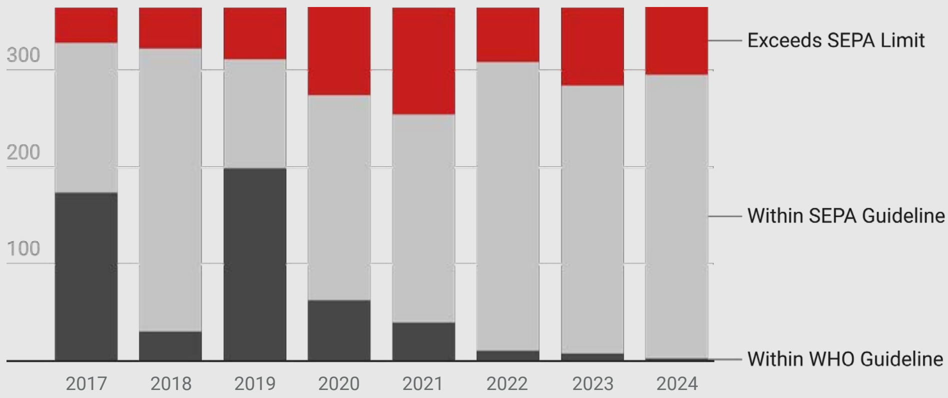


Exhibit 1: The Daily Health Burden in Karachi (2017-2024). *This chart illustrates the daily reality of breathing Karachi's air over the past eight years. The small green segments at the bottom show that days meeting WHO's clean air guideline are exceptionally rare. The vast majority of days fall into the "Unhealthy by WHO" (gray) or "Exceeds SEPA Limit" (red) categories, demonstrating a chronic, year-round public health crisis.*

In 2024, ***only three days*** *in the entire year were safe according to WHO guidelines. A staggering 99% of days were unhealthy by global standards, and on 70 of those days, pollution was so severe it also breached the legal limit set by the Sindh government.*

Power and ports: Power generation facilities are a major source of sulfur dioxide (SO2), while port and shipping operations present unique challenges with their use of high-sulfur fuels.

Evidence-Based Pathway to Cleaner Air

This inventory identifies priority interventions that could significantly improve Karachi's air quality. Full implementation of the following evidence-based recommendations could reduce urban PM2.5 emissions by up to 50%:

Industrial Emission Controls: 20-25%

Mandate and enforce the adoption of Best Available Control Technologies (e.g., Electrostatic Precipitators, Flue Gas Desulfurization) in major industries, coupled with Continuous Emissions Monitoring Systems (CEMS).

Heavy-Duty Vehicle Regulation: 15-20%

Implement targeted inspection and maintenance programs for commercial diesel vehicles, establish Low Emission Zones, improve diesel fuel quality, and optimize freight management.

Port and Shipping Interventions: 8-10%

Introduce shore power facilities for docked vessels, implement stringent fuel sulfur requirements within port boundaries, and electrify port handling equipment.

Enhanced Governance and Monitoring: 3-5%

Expand the air quality monitoring network, strengthen cross-district regulatory coordination, and harmonize industrial emission standards with national best practices.

This emissions inventory provides an indispensable scientific foundation for policymakers, industry, and civil society to collaboratively implement targeted, high-impact interventions. The findings counter misconceptions that air pollution is an intractable issue or primarily transboundary, demonstrating instead that sources are largely local and actionable. Addressing these sources offers a clear pathway toward substantial public health and economic benefits for the citizens of Karachi, transforming the city into a healthier and more sustainable urban environment.

We now know what's in our air, where it comes from, and how to stop it. What happens next is a choice.

نتیجہ: ایک قابلِ عمل راستہ

یہ جامع اخراج تخمینہ پالیسی سازوں، صنعت، اور شہری تنظیموں کے لیے ایک ٹھوس سائنسی بنیاد فراہم کرتا ہے جس پر باہمی اشتراک سے مؤثر اقدامات کیے جا سکتے ہیں۔ یہ رپورٹ اس غلط فہمی کو دور کرتی ہے کہ فضائی آلودگی ایک ناقابلِ حل معمہ ہے۔ حقیقت یہ ہے کہ آلودگی مقامی ہے، اس کی پیمائش ممکن ہے، اور اس پر قابو پایا جا سکتا ہے۔

سائنس اب واضح ہے، حل آزمودہ ہیں، اور راستہ متعین ہے۔ اب ضرورت صرف اجتماعی عزم اور عملی اقدامات کی ہے تاکہ ان نتائج کو کراچی کے شہریوں کے لیے صحت مند زندگی اور صاف ہوا کی ضمانت میں تبدیل کیا جا سکے۔ کراچی صاف ہوا کا انتخاب کر سکتا ہے—یا پھر بے عملی کے نتائج کے ساتھ زندہ رہے۔

ہمیں مسئلے کی جڑ بھی معلوم ہے اور اس کا حل بھی۔
اب عمل کرنا یا نہ کرنا ہمارا فیصلہ ہے۔

اخراج تقریباً ۱.۸۶ کلوگرام سالانہ ہے۔
یہ تخمینہ، جس کا بنیادی سال ۲۰۲۱ ہے، کراچی میں انسانی سرگرمیوں سے پیدا ہونے والی آلودگی کے بڑے ذرائع کی نشاندہی کرتا ہے۔

صنعت: صنعتی شعبہ صحت کو شدید نقصان پہنچانے والے باریک ذرّات (PM2.5) کے اخراج کا سب سے بڑا ذریعہ ہے، جو کل اخراج کا تقریباً نصف (۴۹ فیصد) ہے۔

ٹرانسپورٹ: یہ شعبہ (PM2.5) کا دوسرا بڑا ذریعہ (۳۳ فیصد) اور نائٹروجن آکسائیڈز (NOx) کا سب سے بڑا ذریعہ (۸۰ فیصد) ہے۔

پاور اور بندرگاہیں: بجلی پیدا کرنے والے پلانٹس (SO2) کے اخراج کا ایک کلیدی ذریعہ ہیں، جبکہ بندرگاہوں اور جہاز رانی کے آپریشنز ایک سنگین چیلنج ہیں۔

شواہد پر مبنی صاف ہوا کا راستہ

یہ تخمینہ ان ترجیحی اقدامات کی نشاندہی کرتا ہے جو کراچی کے فضائی معیار کو نمایاں طور پر بہتر بنا سکتے ہیں۔ اگر ان سفارشات پر مکمل عمل درآمد کیا جائے تو شہری (PM2.5) کے اخراج میں ۵۰ فیصد تک کمی لائی جا سکتی ہے:

صنعتی اخراج پر کنٹرول (۲۵٪-۲۰ کمی): بڑی صنعتوں میں جدید ترین ٹیکنالوجیز کا نفاذ لازمی قرار دیا جائے اور اخراج کی مسلسل نگرانی کے لیے خودکار نظام نصب کیے جائیں۔

ہیوی ڈیوٹی گاڑیوں کے لیے ضابطے (۲۰٪-۱۵ کمی): کمرشل ڈیزل گاڑیوں کے لیے سخت معائنے اور دیکھ بھال کے پروگرام نافذ کیے جائیں، شہر کے مخصوص علاقوں کو کم آلودگی والی گاڑیوں کے لیے مختص کیا جائے، اور ایندھن کے معیار کو بہتر بنایا جائے۔

بندرگاہ اور جہاز رانی کے اقدامات (۱۰٪-۸ کمی): بندرگاہ پر کھڑے جہازوں کو ساحل سے بجلی فراہم کی جائے اور بندرگاہی علاقوں میں استعمال ہونے والے ایندھن کے معیار پر سختی کی جائے۔

بہتر طرزِ حکمرانی اور نگرانی (۵٪-۳ کمی): فضائی معیار کی نگرانی کے نیٹ ورک کو وسعت دی جائے اور اداروں کے درمیان ہم آہنگی کو فروغ دیا جائے۔

فضائی آلودگی:
صحتِ عامہ کا سنگین بحران

کراچی میں فضائی آلودگی صحتِ عامہ کا ایک سنگین بحران ہے جو ایک اوسط شہری کی متوقع عمر میں ۲.۷ سال کی کمی کا باعث بنتا ہے۔ فضائی معیار کی نگرانی سے حاصل کردہ ٹھوس شواہد یہ ظاہر کرتے ہیں کہ کراچی کی فضا سال بھر خطرناک حد تک آلودہ رہتی ہے اور قومی و عالمی صحت کے رہنما اصولوں پر پورا اترنے میں مسلسل ناکام ہے۔

سال ۲۰۲۴ میں، ۳۶۳ دن ایسے تھے جب ہوا عالمی ادارۂ صحت (WHO) کے مطابق انسانی صحت کے لیے مضر تھی، جبکہ ۷۰ دنوں میں آلودگی اس قدر شدید تھی کہ اس نے سندھ انوائرنمنٹل پروٹیکشن ایجنسی (SEPA) کی مقرر کردہ قانونی حدود کو بھی عبور کر لیا۔

اس بحران سے نمٹنے کے لیے، پاکستان ایئر کوالٹی انیشی ایٹو (PAQI) نے کراچی کے لیے اپنی نوعیت کا پہلا سائنسی اور جامع اخراج کا تخمینہ (emissions inventory) تیار کیا ہے۔ یہ رپورٹ شہر کی آلودگی کے بنیادی ذرائع کی تشخیص کرتی ہے اور پالیسی سازوں، صنعت اور سول سوسائٹی کے لیے ایسے ناقابلِ تردید شواہد فراہم کرتی ہے جن کی بنیاد پر باہدف اور مؤثر اقدامات کیے جا سکتے ہیں، تاکہ صاف ہوا کی جانب ایک واضح راہ ہموار ہو سکے۔

تشخیص: آلودگی کے بنیادی ذرائع

کراچی کا فضائی نظام آلودگی کے شدید بوجھ تلے دبا ہوا ہے۔ یہ تخمینہ سالانہ اخراج کی مقدار کا تعین کرتا ہے، جس میں ۳۹.۱۱ کلوٹن صحت کو شدید نقصان پہنچانے والے باریک ذرّات (PM2.5)، ۵۱.۵۲ کلوٹن سلفر ڈائی آکسائیڈ (SO2) ، ۱۰۰.۷۸ کلوٹن نائٹروجن آکسائیڈز (NOx) ، اور ۲۰۳.۴۱ کلوٹن کاربن مونو آکسائیڈ (CO) شامل ہیں۔ اس کا مطلب ہے کہ فی کس (PM2.5) کا

Pakistan Air Quality Initiative

The Pakistan Air Quality Initiative (PAQI) is an independent research and advocacy organization dedicated towards a breathable and healthy Pakistan, with robust scientific insights and data-driven solutions to overcome the air pollution emergency. Our vision is a future where every Pakistani breathes clean air, supported by informed policy, effective governance, sound science, and an engaged society.

The Pakistan Air Quality Initiative (PAQI) is an independent research and advocacy organization committed to addressing the complex and pressing challenge of air pollution in Pakistan. Founded in 2016 by Abid Omar, PAQI was born out of a citizen-led concern for the deteriorating air quality in Pakistan's urban centers and the lack of accessible, reliable data and informed public discourse on this critical issue. In a nation where air pollution is recognized as a public health emergency with profound impacts on life expectancy and well-being, PAQI is dedicated to scientific understanding and promoting effective, evidence-based solutions to Pakistan's air pollution problem.

PAQI's mission is to provide data-driven scientific research and advocacy for clean air in Pakistan, promoting data accessibility and transparency, and driving informed public engagement and effective policy development.

Our approach is built on three pillars:

Scientific research: We conduct robust scientific inquiry, to provide the evidence for effective and targeted air quality management strategies. Our research includes developing comprehensive multi-sectoral emissions inventories, analyzing atmospheric chemistry, and creating foundational air quality datasets and analyses for Pakistan.

Air quality monitoring and data: We support the expansion of the national air quality monitoring infrastructure, from community-driven air quality sensor networks to robust national regulatory systems. We provide free and open access to real-time air quality data to empower citizens, researchers, and policymakers.

Policy development and advocacy: We translate scientific findings into tangible action by raising public awareness of the health and economic impacts of air pollution, providing technical advice to governmental bodies, contributing to national policy dialogues that inform strategies like the National Clean Air Policy, and working to ensure such policies are supported by robust evidence.

The challenge posed by air pollution in Pakistan is solvable through evidence-based solutions. Through science, data, and advocacy, a future with cleaner, healthier air for all Pakistanis is achievable.

> "Blue skies are a sign of good governance. Our work is to provide the science and the data to make that possible."
>
> — Abid Omar, Founder, PAQI

01. Karachi's Air Quality Crisis

Karachi's persistent air pollution is a public health crisis demanding urgent, informed action. Measurements reveal that the air quality consistently fails to meet Sindh Environmental Quality Standards (SEQS) for ambient air, and remains many times higher than global health guidelines – posing a threat to public health and economic vitality.

Key Messages

- Air pollution reduces the life expectancy of an average Karachi resident by 2.7 years.
- Karachi's official provincial air quality standard for PM2.5 is eight times weaker than the World Health Organization's (WHO) health-based guideline.
- For the last eight years, Karachi's air has never met the WHO guideline for safe PM2.5 levels. In most years, it also failed to meet the Sindh Environmental Quality Standards (SEQS) for ambient air.
- In 2024, Karachi experienced 363 days where the air was unhealthy by WHO standards; on 70 of these days, pollution was so severe it also breached the local SEQS guideline.

The consequences of breathing polluted air are not abstract; they are measured in years of life lost. According to the Air Quality Life Index (AQLI), particulate pollution (PM2.5) reduces the life expectancy of an average resident of Pakistan by 3.3 years.[1] For the citizens of Karachi, the cost is severe: an average resident could live 2.7 years longer if the city's air quality was improved to meet the WHO's health guideline.[2]

This local crisis is part of a global pollution pandemic. A 2022 report from the Lancet Commission on Pollution and Health found that pollution is responsible for approximately 9 million premature deaths globally each year — equivalent to one in every six deaths worldwide.[3] The commission crucially notes that deaths from modern pollution sources like industrial emissions and ambient air pollution are increasing, having risen by 66% since 2000.

The Governance Gap in Air Quality Standards

To manage air quality, Pakistan has established National Environmental Quality Standards (NEQS),[4] and Sindh has its own provincial standards (SEQS).[5] A significant gap exists between these regulatory limits and the guidelines recommended by the World Health Organization (WHO) based on the latest health evidence. This disparity means that even on a day when Karachi's air is considered "acceptable" by regulatory standards, it remains above safe limits for health.

WHO provides a series of Interim Targets as a roadmap for heavily polluted regions to make incremental progress. Good governance practice suggests that once a standard aligned with an interim target is consistently met, policymakers should aim for the next, more stringent target. As Exhibit 1 shows, Sindh's annual PM2.5 standard of 40 $\mu g/m^3$ is weaker than even the most lenient WHO Interim Target 1 of 35 $\mu g/m^3$, placing it far from the health-based guideline of 5 $\mu g/m^3$.

Pollutant	NEQS 2010	NEQS 2013	SEQS 2016	WHO Guideline 2005	WHO Guideline 2021
SPM	400	360	360	N/A	N/A
SO2	80	80	80	N/A	N/A
PM2.5	25	15	40	10	5
PM10	200	120	120	20	15
NO2	40	40	40	40	10
NO	40	40	40	N/A	N/A
Lead (Pb)	2	1	1	1	1

Exhibit 2: The Governance Gap in Air Quality Standards (Annual Mean, $\mu g/m^3$). *This table highlights the significant disparity between local regulations and global health recommendations. Sindh's legal limit for annual PM2.5 (40 $\mu g/m^3$) is eight times weaker than the health-based guideline set by the World Health Organization (WHO).*

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
2016										29.4	64.8	65.5	54.7
2017	86.6	59.2	29.0	26.0	19.5	24.1	22.9	19.4	17.8	32.1	62.6	67.5	40.4
2018	80.8	60.3	44.2	55.1	41.6	43.7	42.4	37.5	23.6	45.0	51.2	50.6	48.3
2019	50.8	24.1	20.7	22.5	11.6	12.3	13.5	18.0	51.2	56.6	77.8	113.4	49.6
2020	83.4	71.6	38.1	27.0	26.2	27.3	26.1	33.5	53.2	108.9	125.5	115.5	48.5
2021	87.5	87.5	45.0	41.8	31.7	32.7	29.5	24.5	33.3	54.3	99.0	90.0	46.9
2022	67.1	50.4	44.6	37.4	41.6	26.1	19.3	29.7	32.4	48.3	76.1	111.9	51.2
2023	89.5	65.0	51.6	29.7	27.6	29.7	31.0	28.0	41.6	36.9	102.3	105.6	49.3
2024	113.7	68.1	46.8	30.0	25.6	26.6	26.8	21.0	26.3	38.2	47.2	84.2	46.2

Exhibit 3: The Seasonal Cycle of Air Pollution in Karachi (2016-2024). *This chart of monthly average PM2.5 concentrations, based on eight years of continuous monitoring, reveals a stark and predictable seasonal pattern. Pollution levels consistently begin to rise in October and peak dramatically during the winter months, creating a prolonged "smog season" of hazardous air. This recurring cycle highlights that the issue is not random but is driven by a combination of increased emissions and meteorological conditions that trap pollutants.*

Karachi's Chronic Air Pollution Problem

Measurements from the PAQI air quality monitoring network reveal that the air quality in Karachi consistently fails to meet Sindh Environmental Quality Standards (SEQS) for ambient air. Exhibit 2 shows that the annual average PM2.5 concentration in Karachi has failed to meet the SEQS limit of 40 µg/m³ in six of the last eight years. Every year, the annual average has remained dangerously high — between 7 and 11 times WHO's guideline value for the safe limit.

The daily data reveals the constant health risk. In 2024, only three days in the entire year met WHO's guideline for clean air. For the remaining 363 days, the air was unhealthy by global standards. Critically, on 70 of those days, air pollution was so severe that it exceeded Sindh's own legal 24-hour limit of 75 µg/m³.

From Diagnosis to Action

Karachi faces a severe and persistent air pollution crisis that shortens lives and consistently exceeds both local and global standards. This data tells us what the problem is and how bad it is.

To craft effective solutions, we must now understand why. The emissions inventory detailed in the following chapters provides that critical diagnosis by identifying the sources of this pollution. Only by knowing the sources can Karachi forge an evidence-based path towards a healthier, breathable future.

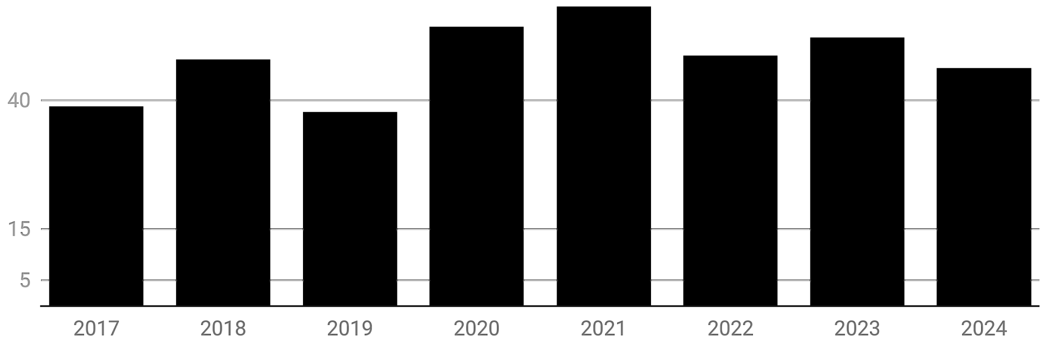


Exhibit 4: Karachi's Chronic Pollution Problem (Annual PM2.5, 2017-2024). *For the last eight years, Karachi's air has never met WHO's safe guideline. The annual average pollution consistently exceeds even the SEQS limit, with no significant trend of improvement and a notable spike during the 2020-2021 pandemic period.*

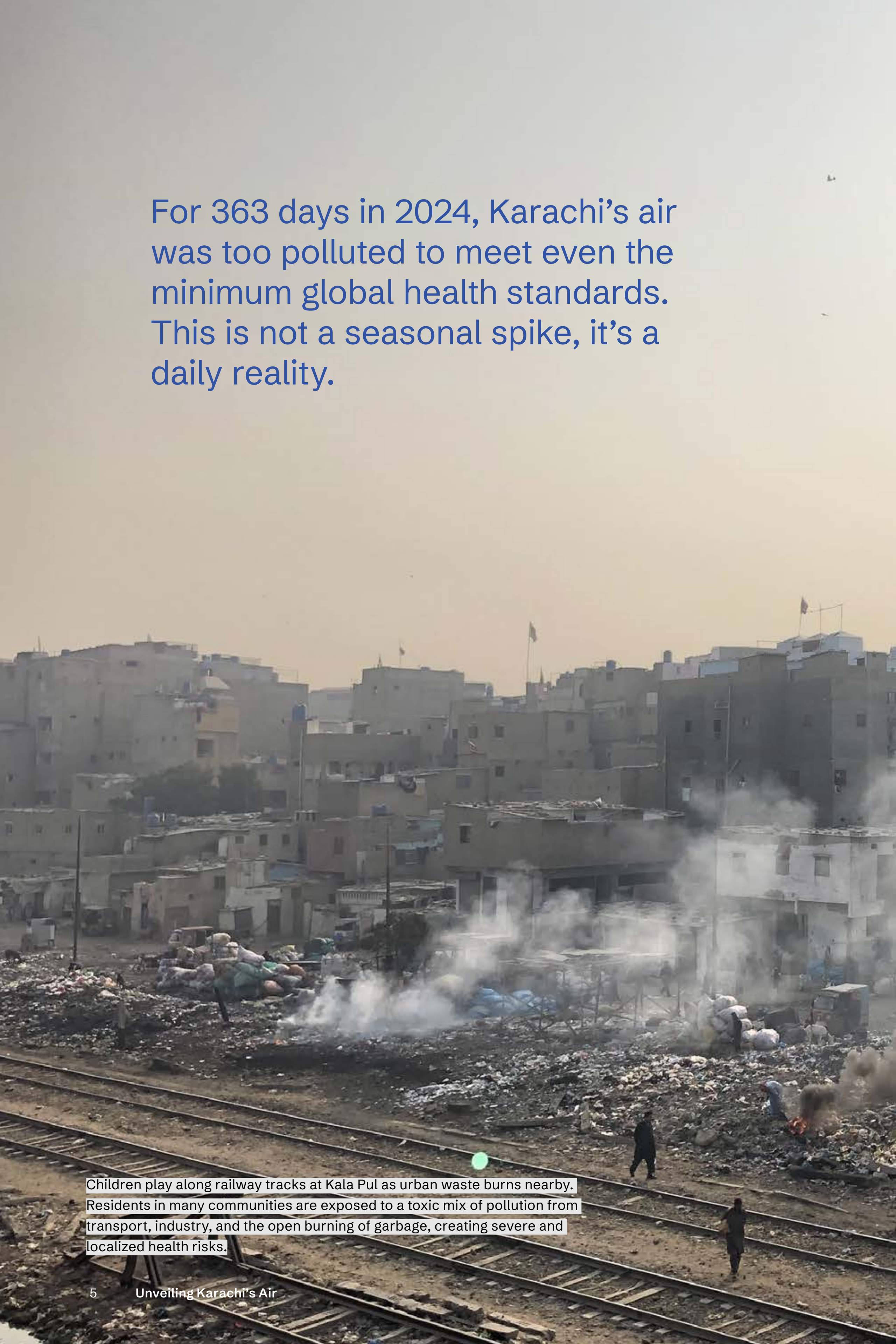
[1] Energy Policy Institute at the University of Chicago (EPIC). (2025). Air Quality Life Index (AQLI) Annual Update 2025. University of Chicago.

[2] World Health Organization. (2021). WHO global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. https://www.who.int/publications/i/item/9789240034228

[3] Fuller, R., Landrigan, P. J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M., Caravanos, J., Chiles, T., Cohen, A., Corra, L., Cropper, M., Ferraro, G., Hanna, J., Hanrahan, D., Hu, H., Kumbhoni, D., Kponou, F., McGlade, K., Papi-Garnier, B., ... Zhong, M. (2022). Pollution and health: a progress update. The Lancet Planetary Health, 6(6), e535–e547. https://doi.org/10.1016/S2542-5196(22)00090-0

[4] Government of Pakistan. (2010). National Environmental Quality Standards for Ambient Air, S.R.O. 1062(I)/2010. Ministry of Environment.

[5] Government of Sindh. (2016). Sindh Environmental Quality Standards, Notification No.EPA/TECH/739/2014. Sindh Environment Protection Agency.



For 363 days in 2024, Karachi’s air was too polluted to meet even the minimum global health standards. This is not a seasonal spike, it’s a daily reality.

Children play along railway tracks at Kala Pul as urban waste burns nearby. Residents in many communities are exposed to a toxic mix of pollution from transport, industry, and the open burning of garbage, creating severe and localized health risks.

02. Emissions Inventory for Karachi

Karachi's severe air pollution demands urgent, informed action rooted in evidence. This first scientific emissions inventory provides the critical data needed to diagnose the sources and forge effective, evidence-based solutions for cleaner air.

Key Messages

— This emissions inventory is the first comprehensive, scientific accounting of air pollution sources for the Karachi airshed.

— It addresses a critical knowledge gap that has historically hindered the development of effective, targeted clean air policies.

— The inventory's primary purpose is to identify and quantify the dominant emission sources, providing the evidence needed for high-impact interventions.

— This inventory establishes an indispensable scientific baseline for all future clean air initiatives

The megacity of Karachi, Pakistan's largest urban agglomeration and its primary economic and industrial engine, confronts complex environmental challenges, among which air pollution is not considered a concern. Home to an estimated 21 million people within its airshed, Karachi's rapid urbanization and intensive economic activities — including substantial industrial zones, two seaports, extensive power generation facilities, and dense transportation networks — collectively exert considerable pressure on its atmospheric environment. The resulting air pollution has far-reaching implications, impacting public health, ecosystem integrity, and the overall sustainable development trajectory.

Effective air quality management in such a complex urban environment necessitates a robust, evidence-based understanding of the sources, characteristics, and magnitude of atmospheric pollutant emissions.

While air quality monitoring data confirms the severity of air pollution, the lack of detailed, spatially resolved, and sectorally disaggregated emissions data has constrained the ability of policymakers, regulatory agencies, and stakeholders to formulate and implement targeted, efficient, and impactful mitigation strategies. Official, continuous air quality monitoring has also been limited, further underscoring the need for foundational data to characterize the problem accurately.

This emissions inventory is a foundational scientific report for Karachi, providing a detailed and systematic accounting of anthropogenic (human-caused) emissions of key air pollutants from all significant sectors within the airshed for the baseline year 2021. By meticulously quantifying emissions of pollutants such as Particulate Matter (PM2.5), Sulfur Dioxide (SO2), Nitrogen Oxides (NOx), and Carbon Monoxide (CO), this inventory fulfills a critical knowledge gap:

Establish a scientific baseline: Provide a robust quantitative baseline of emissions, serving as a benchmark for future air quality assessments, trend analysis, and the evaluation of intervention efficacy.

Identify key emission sources and sectors: Pinpoint the dominant sources and economic sectors contributing to Karachi's air pollution load, thereby enabling the prioritization of mitigation efforts.

Inform evidence-based policy and planning: Furnish policymakers, environmental protection agencies, urban planners, and industrial stakeholders with the critical data necessary for the formulation of scientifically informed air quality management plans, regulatory standards, and targeted abatement strategies.

Support scientific research: Offer a foundational dataset that can support a range of further atmospheric research, including air quality modeling, health impact assessments, and investigations into pollutant formation and transport dynamics.

Enhance public awareness: Contribute to a more informed public discourse on air quality issues in Karachi by providing transparent and scientifically credible information on emission sources.

Karachi has never had a clear picture of what's in its air or who is responsible. This inventory gives the city the science it needs to act.

A cargo ship emits black smoke as it enters the Phitti creek leading to Port Qasim, with residential high rises in the background. Shipping emissions, high in sulfur and particulate matter, are a significant and often overlooked source of pollution across all parts of Karachi.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03. Methodology: How we Measured Karachi’s Air

The health of millions depends on understanding Karachi's air pollution. This inventory uses internationally recognized scientific methods, adapted for local realities, to precisely quantify pollutants from all major human activities.

Key Methodological Pillars:

— Emissions are calculated based on actual activity levels (e.g., fuel use, industrial output) and specific emission factors for the baseline year 2021.

— Key pollutants (PM2.5, SO2, NOx, CO) are inventoried due to their severe health and environmental impacts.

— A hybrid Tier 1/Tier 2 approach ensures the highest accuracy with available regional and local data.

Which Pollutants Matter Most?

The analysis focused on four criteria air pollutants that are widely recognized for their significant impact on urban air quality and public health:

Particulate Matter (PM2.5): Fine inhalable particles with aerodynamic diameters generally 2.5 micrometers and smaller. These particles can penetrate deep into the respiratory system and enter the bloodstream, leading to cardiovascular and respiratory diseases and other health complications.

Sulfur Dioxide (SO2): A colorless gas with a pungent odor, primarily produced from the combustion of fossil fuels (such as coal and oil) containing sulfur, commonly found in power plants and industrial processes. It can cause respiratory problems and contributes to the formation of acid rain and secondary particulate matter.

Nitrogen Oxides (NOx): A group of highly reactive gases, primarily nitric oxide (NO) and nitrogen dioxide (NO2), formed during high-temperature combustion processes. Major sources include vehicle exhausts, power plants, and industrial boilers. NOx contributes to the formation of smog, acid rain, and secondary particulate matter.

Carbon Monoxide (CO): A colorless, odorless, and toxic gas produced by the incomplete combustion of carbon-containing fuels. Vehicle exhaust is a major urban source. CO reduces the oxygen-carrying capacity of blood.

Data Sources and Tiers

International best practices, such as those outlined by the Intergovernmental Panel on Climate Change (IPCC) for greenhouse gases and the EMEP/EEA Air Pollutant Emission Inventory Guidebook, categorize methodologies into tiers based on sophistication and data requirements.

Tier 1 methods employ readily available, often default or globally averaged EFs, combined with relatively aggregated AD.

Tier 2 methods utilize country-specific or region-specific EFs, often differentiated by major technology types, along with more detailed and disaggregated AD.

Tier 3 methods represent the most sophisticated approach, employing detailed process models, facility-specific data, and EFs that account for specific technologies and local operating conditions.

This inventory for Karachi predominantly used a Tier 1/Tier 2 hybrid approach. The selection of this approach was guided by the availability of local and regional data, aiming for the highest possible tier achievable across different sectors. The reliance on regional EFs from resources like the Urban Emissions database aligns with Tier 2 for many applications, while the use of EMEP/EEA default factors for some under-researched sectors aligns with Tier 1.

Mapping the Hotspots

To visualize the geographical distribution of emissions across Karachi, sectoral emission totals were allocated onto a 1 km x 1 km grid covering the city's airshed. This process, essential for identifying potential pollution hotspots and informing spatially targeted interventions, relied on various proxies due to limitations in precise source location data for all emitters:

Population density: Used as a proxy for distributing emissions from residential activities and open waste burning.

Road networks: Utilized for allocating transport emissions, often weighted by road type or capacity where such data were available.

Known coordinates: Employed for major point sources such as large industries, power plants, ports, and airports, where specific location data could be ascertained.

Settlement density: Used for allocating emissions related to construction activities and dust in the absence of specific project data.

While this spatial allocation provides valuable insights into emission patterns, it is acknowledged that the use of proxies introduces a degree of uncertainty. Future refinements would benefit from more sophisticated spatial surrogates, such as detailed land-use maps, traffic flow data, and comprehensive industrial site databases.

Limitations of this Study

The development of this emissions inventory encountered several limitations that contribute to uncertainty in the final estimates. These include:

Data gaps: Incomplete or outdated activity statistics, particularly for informal sector activities and small-scale industries, which constitute a substantial portion of urban economic activity in Karachi.

Emission factor uncertainties: The limited availability of Pakistan-specific, locally measured emission factors for all source types necessitated the use of regional or international default values in some instances.

Spatial allocation challenges: Imprecise location information for numerous small and diffuse sources required the use of proxy indicators for spatial mapping.

Temporal representation: While this inventory represents annual emissions for the baseline year 2021, it does not fully capture finer seasonal or diurnal variations without more detailed temporal resolution in activity data.

Despite these limitations, this emissions inventory provides the most comprehensive assessment of urban emissions currently available for Karachi. Based on the methodology described (Tier 1/2 approach, reliance on regional EFs, acknowledged data gaps, and preliminary spatial allocation), the overall confidence in this initial inventory is assessed as Moderate. Findings for sectors

How Emissions Are Calculated

The estimation of anthropogenic air pollutant emissions in Karachi for this inventory is based on the internationally recognized methodology, centered on the standard emissions calculation formula:

$$E_{p,s} = AD_s \times EF_{p,s,t}$$

Where:
Ep,s = Total emissions of a specific pollutant (p) from a source category (s), typically in tons per year.
ADs = Activity Data for the source category (s), representing the magnitude of the activity (e.g., tons of coal burned, vehicle-kilometers traveled).
EFp,s,t = Emission Factor for the pollutant (p), specific to the source (s) and the control technology (t) used (e.g., grams of $PM_{2.5}$ emitted per ton of coal burned).

Activity Data (AD): This quantitative measure reflects the level or intensity of human activity that leads to emissions. Examples pertinent to this inventory include fuel consumption by various vehicle types, volume of industrial production from different manufacturing sectors, energy generated by power plants, and quantities of waste burned. The data for this inventory were primarily compiled for the baseline year 2021, selected as the most recent year with relatively complete datasets across key sectors at the time of analysis. Challenges such as delays in official data publication and potential revisions to historical data are acknowledged as factors impacting inventory timeliness and stability.

Emission Factor (EF): This coefficient represents the average mass of a specific pollutant emitted per unit of activity. The EF is specific to the emission source, the technology employed, fuel characteristics, and prevailing operating conditions. For instance, an EF for vehicular emissions might be expressed as grams of PM2.5 emitted per vehicle-kilometer-traveled (VKT) for a specific vehicle type using a particular fuel.

The selection of appropriate EFs is critical for accuracy. This study prioritized EFs reflecting regional relevance and technology considerations, primarily sourcing from the Urban Emissions database, which is recognized for its applicability to South Asian conditions. For sectors where specific regional data were deficient, such as certain non-road mobile machinery and maritime shipping, default Tier 1 EFs from the EMEP/EEA Guidebook (2019 edition) were utilized. A key area for future improvement is the development and validation of Pakistan-specific EFs through local measurement campaigns.

with better official data (e.g., power plants, registered fuel sales for transport) likely have higher confidence than those relying more heavily on assumptions or less formal data (e.g., waste burning, informal industry, construction dust). This inventory establishes a crucial foundation for improved air quality management planning and a benchmark for future, more refined studies.

This is Karachi's first science-based emissions inventory, built with global methods, local data, and a clear aim: to uncover the invisible crisis we all breathe.

The open burning of landscape waste, seen here at a park in Clifton, is a common practice that contributes to local particulate matter and toxic smoke, turning public amenities into sources of pollution.

04. Sources: Who Pollutes Karachi's Air

Pinpointing the primary sources of pollution is the first step towards cleaning Karachi's air. Industrial operations, heavy transport, and power plants are the dominant contributors to the city's hazardous emissions.

Key Emission Sources

— Industry is Karachi's largest PM2.5 polluter, responsible for nearly half (49%) of these harmful fine particles.

— Transportation, particularly diesel vehicles, generates 80% of NOx emissions and is the second-largest PM2.5 source (33%).

— Power plants contribute a major share (30%) of Sulfur Dioxide (SO2), primarily from burning high-sulfur fuels.

This chapter details the primary anthropogenic emission sectors analyzed for Karachi's air quality assessment. Seven major sectors were identified and quantified, encompassing a wide range of activities that contribute to the city's pollutant load.

Transport: This sector includes exhaust emissions from on-road vehicles such as cars, motorcycles, rickshaws, buses, and trucks. It also accounts for non-road mobile sources, including emissions from railways, aviation (within the urban airshed, e.g., landing and take-off cycles), and shipping activities near port areas.

Industry: This broad category encompasses manufacturing facilities across multiple sectors prevalent in Karachi, such as textile, cement, steel, and fertilizer production, among others. It includes emissions from production processes themselves, as well as from on-site (captive) power generation used by industrial units.

Power: This sector covers emissions from grid-connected power plants and other large-scale electricity generators operating within Karachi's airshed.

Household: Emissions from household activities are quantified here, primarily from fuel combustion for cooking and heating, though heating is less significant in Karachi's climate.

Commercial: This sector includes emissions from commercial buildings, markets, and institutional facilities. Key sources are backup power generation (predominantly diesel generators), commercial cooking operations, and other service sector enterprises in urban centers.

Waste: This assesses contributions from the open burning of municipal solid waste and, where applicable, agricultural residues within or near the urban airshed.

Dust: While included in overall inventory calculations, dust emissions are not always shown as a separate sector in final summaries. Dust from non-exhaust particulate matter, such as road dust re-suspension from paved and unpaved surfaces are typically included within the transport sector calculations. Dust from construction and demolition activities is generally accounted for under the commercial or industrial sectors, depending on the nature of the activity. Natural dust from marine or desert environments is also a factor but treated separately from anthropogenic emissions.

	Total annual emissions in kilotons in Karachi				
Sector	**PM2.5**	**SO2**	**NOx**	**CO**	**Total**
Transport	12.77	20.29	81.11	183.87	298.04
Industry	19.10	13.37	9.55	6.59	48.61
Power	1.34	15.66	8.11	0.90	26.01
Household	0.56	0.04	0.49	7.68	10.44
Waste	2.68	0.04	0.04	7.68	10.44
Commercial	2.66	2.12	0.48	0.70	5.96
Total	**39.11**	**51.52**	**100.78**	**203.41**	**394.82**

Exhibit 5: Sectoral Breakdown of Annual Emissions in Karachi (2021). *This table details the estimated annual emission loads in kilotons (kT) for key pollutants across all major economic sectors.*

Sectoral Breakdown

Karachi generates a substantial emissions load annually. For the baseline year 2021, total estimated emissions for the four primary pollutants were:

PM2.5: 39.11 kilotons

SO2: 51.52 kilotons

NOx: 100.78 kilotons

CO: 203.41 kilotons

This translates to per capita PM2.5 emissions of approximately 1.86 kg per person per year for Karachi's population. This immense load of fine particulate matter is the direct cause of persistently hazardous air quality and health impacts.

Industrial dominance in PM2.5 Emissions: Industrial sources are the largest contributors to PM2.5 emissions, accounting for nearly half (49%) of the total. This finding directly explains the severe, year-round ambient PM2.5 concentrations that consistently exceed health guidelines, as demonstrated by the PAQI monitoring data. This underscores Karachi's status as the country's primary manufacturing center, hosting major facilities for steel production, petrochemicals, textiles, and cement manufacturing.

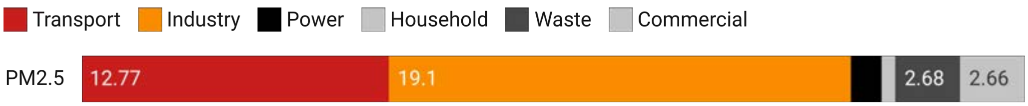

Exhibit 6: Industry as the Dominant Source of PM2.5 Emissions. *This chart shows that industrial activities are the single largest source of health-damaging fine particulate matter (PM2.5) in Karachi, contributing nearly half (49%) of the total emissions. Transportation is the second-largest contributor at 33%, highlighting that these two sectors are the primary targets for any effective PM2.5 reduction strategy.*

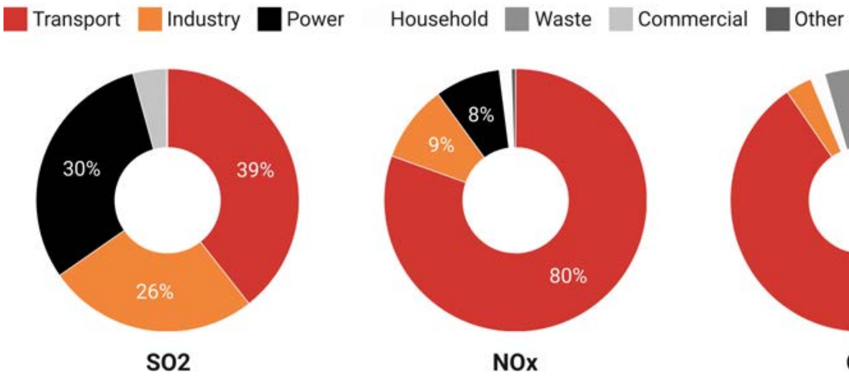

Exhibit 7: Primary Sources of Gaseous Pollutants (SO2, NOx, and CO). *This series of charts shows that while transportation overwhelmingly dominates NOx (80%) and CO (90%) emissions, the sources of SO2 are more varied, with power generation (30%) and industry (26%) being the largest contributors.*

Transportation as a major contributor: The transportation sector ranks as the second-largest source of PM2.5 , contributing approximately 33%. Crucially, it dominates NOx emissions, accounting for about 80% of Karachi's total. This is largely attributed to the city's heavy reliance on an aging fleet of diesel vehicles, particularly those supporting extensive port and industrial logistical operations.

Significant SO2 emissions from power generation: Power generation facilities, often concentrated near industrial zones and port areas, are major contributors to sulfur dioxide emissions, responsible for approximately 30% of the total SO2 for Karachi. This primarily results from the combustion of coal and high-sulfur fuel oil in plants with limited emission control technologies.

Minimal residential contribution: Reflecting Karachi's coastal, warmer climate and consequently reduced heating needs, residential sources contribute minimally (around 1%) to the city's overall PM2.5 emissions.

Karachi's Distinct Challenges

Karachi's role as Pakistan's primary maritime gateway presents unique pollution challenges.

Maritime emissions: Significant emissions, particularly of SO2 and particulate matter, originate from shipping vessels using heavy fuel oil within and near the urban airshed and port areas. These maritime emissions are characterized by high sulfur content and can disproportionately affect air quality in coastal zones.

Concentration of heavy diesel vehicles: The city's port and industrial activities necessitate a large fleet of heavy diesel vehicles, including trucks, container carriers, and industrial transport vehicles. Karachi hosts Pakistan's largest concentration of such vehicles. Despite constituting a smaller proportion of total registered vehicles, these heavy-duty diesel vehicles contribute disproportionately to transportation-related particulate emissions and NOx.

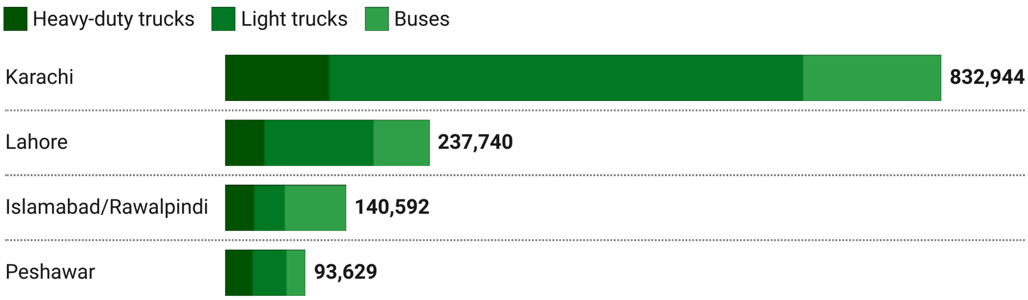

Exhibit 8: Concentration of Heavy Diesel Vehicles in Major Pakistani Cities. *This comparison highlights Karachi's unique challenge, showing its disproportionately large fleet of heavy-duty trucks and buses that support port and industrial logistics, a key factor in the city's high transportation emissions.*

Fuel quality: The prevalence of smuggled or lower-quality fuel, particularly diesel with high sulfur content, exacerbates this problem. Official fuel consumption statistics might underestimate actual usage, and substandard fuels from informal supply chains can constitute a significant portion of the fuel used by Karachi's truck and bus fleet. This presents a dual challenge: a high number of diesel vehicles and fuel quality issues that amplify per-vehicle emissions.

Urban service emissions (water tankers): Karachi faces a unique challenge from emissions related to essential urban services, notably water delivery. Due to inadequacies in the municipal piped water supply infrastructure, thousands of diesel-powered water tankers transport potable water daily throughout the city, creating a substantial and distinct mobile emission source.

Half of Karachi's deadly air pollution comes from industry. Add diesel trucks, dirty fuels, and ports — and the sources become undeniable.

A fire rages near Karachi's port area, releasing a thick plume of toxic smoke into the atmosphere. Such industrial and waste-related fires represent significant, uncontrolled emission events that can cause acute pollution episodes across the city.

05. Mapping Karachi's Emissions

Air pollution isn't uniform; some communities bear a much heavier burden. Emissions are concentrated in specific industrial zones, along major transport arteries, and around port areas, with pollution levels fluctuating daily and seasonally.

Key Spatial & Temporal Insights

— Industrial zones (e.g., Korangi, Landhi, Port Qasim) are major PM2.5 and SO2 hotspots.

— Key transport corridors exhibit high NOx and CO concentrations, impacting adjacent residential areas.

— Coastal meteorology influences pollutant dispersion, while winter conditions can worsen pollution episodes.

An understanding where and when pollution peaks is crucial for designing effective mitigation strategies and public health advisories. This inventory analysis reveals important spatial and temporal patterns in Karachi's urban emissions.

Where is the Pollution?

The spatial allocation of emissions reveals distinct patterns across Karachi, closely reflecting the city's economic geography and land use.

Industrial zones: The highest PM2.5 emission densities are consistently observed in and around designated industrial zones, also identified as the largest polluting sector. These include prominent areas such as the Korangi Industrial Area, Landhi Industrial Area, and the Port Qasim industrial zone, particularly in the eastern and southeastern portions of the city.

Transportation corridors: Significant linear patterns of emissions, especially NOx and CO, follow major freight and commuter routes. These corridors connect port facilities with industrial areas and extend to national highways, with notable concentrations along arteries like the Lyari Expressway, Northern Bypass, and National Highway.

Port hotspots: Areas immediately surrounding both Karachi Port and Port Qasim exhibit elevated emission levels. This is due to the combined impact of emissions from docked and maneuvering ships, loading/unloading operations (e.g., cranes, vehicles), and the heavy road transport associated with port activities.

Power generation: Specific locations with high emission densities are identified around major power plants, particularly those situated in the eastern parts of the city.

These spatial patterns underscore the importance of targeted interventions in high-emission zones. The concentration of emission sources in specific districts provides opportunities for focused mitigation efforts but also raises significant environmental justice concerns for communities residing near these industrial and transportation corridors.

When is the Pollution Worst?

While this inventory primarily focuses on annual emissions, insights from general patterns and data from other urban centers in the region allow for an understanding of likely temporal variations.

Seasonal variations: Urban pollution levels in Pakistan, including coastal cities like Karachi, often exhibit seasonal fluctuations, a trend confirmed by on-the-ground measurements. As shown in Exhibit 10, monitored PM2.5 data for Karachi reveals a dramatic increase in pollution during the winter months (typically November through February). This is often due to meteorological factors, such as lower wind speeds and more stable atmospheric conditions including temperature inversions (where a layer of warmer air aloft traps cooler, polluted air near the ground, hindering dispersion). While Karachi's maritime climate leads to fewer severe temperature inversions compared to inland cities, these

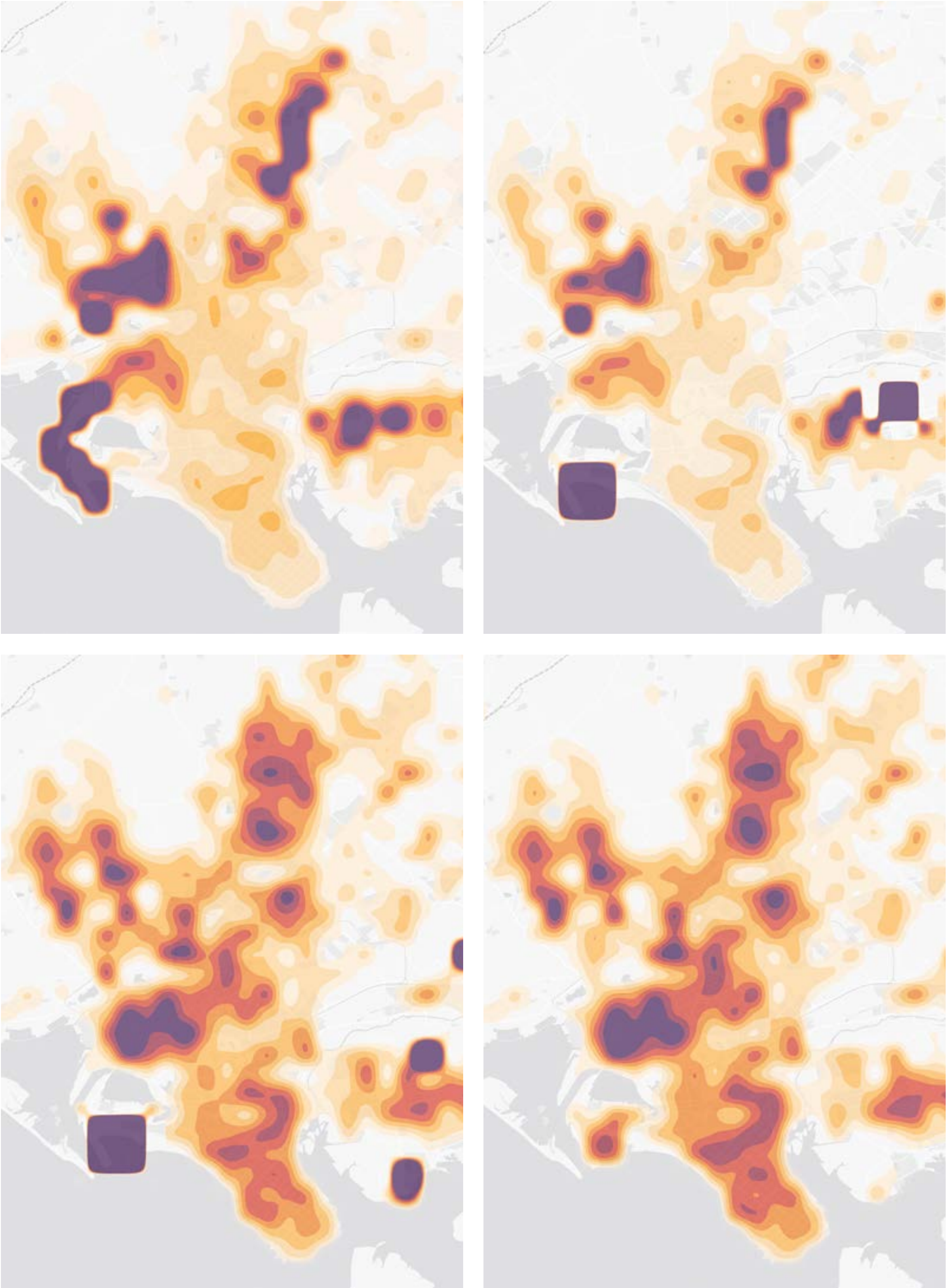

***Exhibit 9: Spatial Distribution of Pollutant Emissions in Karachi (2021)**, illustrating the calculated distribution of annual emissions for PM2.5 (top-left), SO2 (top-right), NOx(bottom-left), and CO (bottom-right) across Karachi at a 1km x 1km resolution for the year 2021. Darker shades indicate higher emission densities, highlighting hotspots in industrial zones, around port areas, and along major transportation routes.*

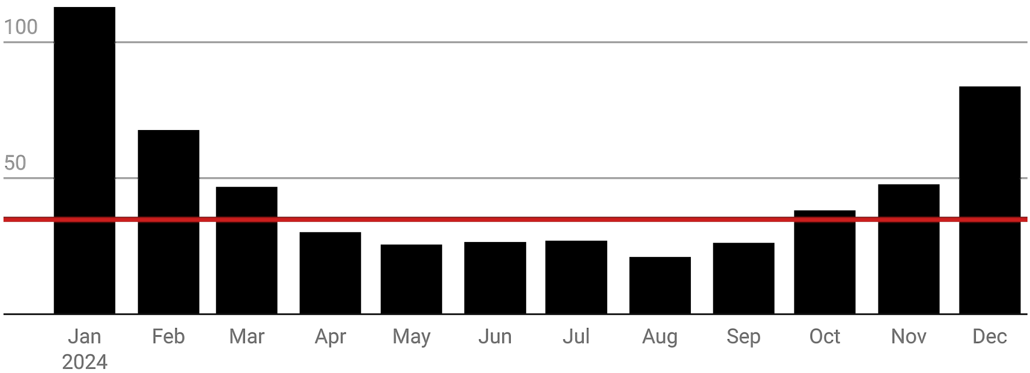

Exhibit 10: *The Seasonal Cycle of Air Pollution in Karachi. Monitored PM2.5 data from the PAQI network reveals a distinct seasonal pattern. Pollution levels begin to rise in October and peak dramatically during the winter months of November through February, when meteorological conditions often trap pollutants near the ground.*

conditions can still exacerbate pollution episodes. Reduced natural ventilation in buildings during cooler weather can also contribute.

Daily (diurnal) fluctuations: Emissions typically show distinct diurnal patterns influenced by human activity cycles:

Transportation: Peaks are commonly observed during morning and evening commute hours.

Industrial emissions: These may be more evenly distributed throughout the day but can sometimes be higher during nighttime operations, potentially influenced by factors like energy costs or specific industrial processes.

Residential contributions: While small overall for PM2.5 in Karachi, emissions from cooking are typically concentrated during morning and evening meal preparation times

Coastal breeze: Karachi's coastal location provides certain natural ventilation advantages through daily onshore (sea breeze) and offshore (land breeze) circulation, which can influence pollutant dispersion patterns throughout the day. However, these can also transport pollutants from one part of the city to another or bring in natural particles like sea salt.

A more detailed understanding of these temporal variations in Karachi would require higher-resolution activity data and continuous ambient air quality monitoring across the city.

Natural Sources and Weather

While this inventory focuses on anthropogenic emissions, it's important to acknowledge that Karachi's air quality is also influenced by natural particle sources, which can interact with human-generated pollution:

Sea salt aerosols: Originating from the Arabian Sea, these particles contribute to ambient particulate levels, particularly during periods of strong onshore winds.

Desert dust transport: Due to Pakistan's predominantly arid to semi-arid climate and strong regional winds, dust can be transported from southern and western desert regions, affecting the city, especially during specific seasons or wind events.

Road dust resuspension: While linked to human activity (vehicle movement, road conditions), the resuspension of dust from paved and unpaved road surfaces, as well as from construction sites, adds significantly to particulate levels, particularly during drier periods. This is accounted for within the anthropogenic inventory but highlights the interplay between human activities and existing surface conditions.

This complex mix of anthropogenic and natural particle sources requires a nuanced management approach, focusing on controlling human-generated emissions while understanding the background influence of natural phenomena.

Pollution doesn't blanket the city equally. Some communities breathe far more toxic air, simply because of where they live and work.

Emissions from shipping and port operations, seen here at the Karachi Port, are a major contributor to the city's air pollution, especially for sulfur dioxide (SO2) and particulate matter. Solutions like providing shore power for docked vessels, regulating vessel speed, and mandating cleaner fuels are proven, targeted interventions that could reduce overall urban PM2.5 by an estimated 8-10%.

06. Why Karachi Struggles to Breathe

Karachi's chronic air pollution is exacerbated by deep-rooted systemic issues. Outdated technology, poor fuel quality, weak enforcement, and inadequate monitoring capacity collectively undermine efforts for cleaner air.

Critical Systemic Challenges

— Widespread use of older, polluting technologies in industry and transport significantly inflates emissions.

— High-sulfur and substandard fuels, especially diesel, drastically increase SO2 and particulate pollution.

— Limited regulatory enforcement and insufficient air quality monitoring hinder effective pollution control.

The emissions landscape in Karachi, as detailed in the preceding chapters, is shaped not only by sectoral activities but also by systemic, cross-cutting challenges. Several cross-cutting factors significantly influence emission levels across multiple sectors and present systemic challenges to effective air quality management. Addressing these underlying issues is paramount for the successful implementation of targeted mitigation strategies.

The Technology Gap

A significant factor contributing to Karachi's emissions profile is the prevalent technology gap between current practices in Pakistan and established international best practices. This disparity is evident across several key areas:

Industrial production: Many industries in Karachi may rely on outdated production methods that are inherently less efficient and more polluting compared to modern, cleaner technologies available globally.

Vehicle fleet: The urban vehicle fleet, particularly in the heavy-duty diesel segment, is often characterized by older vehicles, predominantly adhering to pre-Euro III emission standards or even lower. These vehicles lack modern emission control technologies and contribute disproportionately to particulate matter and NOx emissions. This technological gap directly explains why the transportation sector is responsible for an overwhelming 80% of Karachi's NOx emissions.

Waste management: Limited and outdated waste management infrastructure leads to practices such as open burning of municipal and industrial waste, a significant source of uncontrolled emissions.

This continued reliance on outdated technologies across sectors presents substantial opportunities for emission reductions through strategic modernization programs, technology transfer initiatives, and supportive policy frameworks that incentivize the adoption of cleaner and more efficient technologies.

The Fuel Problem

The quality of fuel available and used in Karachi, particularly diesel, poses a fundamental challenge to controlling emissions. Poor fuel quality, characterized by high sulfur content and other contaminants, significantly increases emissions of SO2 and particulate matter, even from vehicles or machinery that might otherwise be equipped with emission control technologies. This largely explains why power plants and industry emerged as Karachi's top SO2 emitters.

The persistence of fuels with sulfur content reported to be 10 to 50 times higher than prevailing international standards severely limits the effectiveness of advanced emission control systems (which are often poisoned by high sulfur) and undermines efforts to improve air quality. Addressing fuel quality requires stringent regulatory standards, robust enforcement mechanisms to curb the sale of substandard and smuggled fuels, and investment in refinery upgrades to produce cleaner fuels domestically.

Standard / Region	Sulfur Content	Notes
Pakistan (Euro-II Standard)	500 ppm	This is the most common standard for diesel produced by local refineries and has been in place since 2017.
Pakistan (Imported Euro-V)	10 ppm	A higher-quality Euro-V diesel is available, primarily through imports, but it is not the universal standard across the country.
Euro-V Standard (International)	10 ppm	This is the standard in Europe and many other developed economies, enabling advanced vehicle emission control technologies.
India (Bharat Stage VI)	10 ppm	India leapfrogged to the stringent BS-VI standard (equivalent to Euro-VI) nationwide in 2020.

Exhibit 11: *Fuel Quality Gap: Sulfur Content in Diesel Fuel. This comparison highlights a critical systemic issue. The most common standard for diesel fuel in Pakistan (Euro-II, 500 ppm)* ***allows 50 times more sulfur*** *than modern international standards (Euro-V, 10 ppm) that are already in place in neighboring India and other regions. High-sulfur fuel significantly increases SO_2 and PM2.5 emissions and damages vehicle emission control systems.*

The Enforcement Gap

While Pakistan has established ambient air quality standards and some sector-specific emission limits, the capacity for effective and consistent regulatory enforcement remains severely limited. This “enforcement gap” allows many high-emitting activities to continue without adequate abatement measures.

Key limitations include:

Technical resources: Regulatory authorities often lack the requisite technical resources, including advanced monitoring equipment and skilled personnel, for continuous and comprehensive monitoring of emission sources.

Institutional capacity: The institutional capacity for consistent inspection, compliance verification, and imposition of penalties for non-compliance requires significant strengthening.

Without robust enforcement, even well-designed environmental regulations can fail to achieve their intended outcomes. Enhancing the technical capabilities, human resources, and legal authority of environmental protection agencies is crucial.

A Lack of Official Monitoring

The effective management of air quality is contingent upon the availability of reliable and comprehensive data. As demonstrated by the data gap analysis, which necessitates the use of robust third-party data from networks like PAQI, the regulatory air quality monitoring network remains inadequate, with no coverage across Sindh and significant gaps in continuous, real-time data collection for key pollutants. This deficiency complicates several aspects of air quality management:

Problem diagnosis: Accurate identification of pollution hotspots, understanding of temporal pollution dynamics, and assessment of public exposure are hampered by insufficient monitoring data.

Evaluation of interventions: The ability to scientifically evaluate the effectiveness of implemented mitigation policies and measures is compromised without a robust baseline and ongoing monitoring data.

Public information: Lack of accessible real-time data limits the ability to provide timely air quality information and health advisories to the public. Expanding the air quality monitoring network, ensuring data quality assurance and control (QA/QC), and making data publicly accessible are essential steps.

Fragmented Responsibilities

Air quality management in Karachi, as in many large metropolitan cities, involves responsibilities that are distributed among multiple federal, provincial, and municipal agencies. This fragmented governance structure, if not effectively coordinated, can lead to overlapping jurisdictions, policy inconsistencies, and gaps in accountability. Effective air quality management requires a cohesive, airshed-level approach that transcends administrative boundaries and ensures synergistic efforts among different government bodies, regulatory agencies, and other stakeholders. Establishing clear institutional mechanisms for inter-agency coordination, data sharing, and joint planning is vital for overcoming the challenges posed by fragmented governance.

Addressing these cross-cutting factors — technological gaps, fuel quality, enforcement limitations, data deficiencies, and fragmented governance — is not merely ancillary but fundamental to creating an enabling environment where sector-specific interventions can deliver sustained improvements in Karachi's air quality.

The open burning of urban waste, seen here in the Korangi Industrial Area, is a common practice across Karachi. While each fire may seem small, these ad-hoc burnings collectively represent a significant source of toxic smoke and are responsible for an estimated 7% of the city's total health-damaging PM2.5 emissions.

Karachi remains trapped in toxic air because the systems meant to protect us — regulation, enforcement, data — are broken or missing.

07. Solutions for Cleaner Air

Karachi's air pollution crisis is solvable with targeted, evidence-based action. Prioritized interventions in industry, transport, and port operations can slash harmful emissions by up to 50%, delivering major public health benefits.

Priority Actions for Karachi

— Mandate and enforce modern emission controls (e.g., ESPs, FGD) in all major industries. (PM2.5 reduction potential: 20-25%)

— Regulate heavy-duty diesel vehicles through stringent inspections, cleaner fuel standards, and Low Emission Zones. (PM2.5 reduction potential: 15-20%)

— Reduce port emissions via shore power for ships and cleaner fuels within port boundaries. (PM2.5 reduction potential: 8-10%)

The distinct emissions profile of Karachi, with major contributions from industrial activities, transportation (particularly heavy-duty vehicles), and port operations, points towards specific high-impact opportunity areas. Analysis indicates that implementation of a preliminary set of recommendations could achieve a reduction in urban PM2.5 emissions by up to 50%.

The following interventions are identified as priorities for Karachi:

Priority 1: Modernizing Industrial Controls

With industrial sources as the single largest contributor to Karachi's PM2.5 pollution (49%), mandating modern emission controls in this sector is the most impactful intervention available to address hazardous air quality.

Mandate best available control technologies: Large industrial facilities, particularly in sectors such as steel manufacturing, cement production, and power generation, must be required to install and efficiently operate state-of-the-art emission control technologies. This includes the widespread adoption of Electrostatic Precipitators (ESPs) or fabric filters (baghouses) for particulate matter abatement from all major sources.

Implement Flue Gas Desulfurization (FGD): For facilities combusting high-sulfur fuels, such as coal or fuel oil (e.g., in power plants and certain industries), the installation of FGD systems is essential for addressing Karachi's high SO_2 emissions.

Establish Continuous Emissions Monitoring Systems (CEMS): A regulatory framework emphasizing the mandatory installation and operation of CEMS for all large industrial facilities is critical. CEMS provide real-time emissions data, which improves enforcement capabilities, facilitates self-monitoring by industries, and supplies valuable data for future policy refinement and inventory updates.

Develop and enforce industry-specific standards: Emission standards tailored to specific industrial sectors, aligned with international benchmarks and best practices, should be developed and rigorously enforced.

Promote Green Financing mechanisms: Establishing financial incentives and green financing mechanisms can support industries, particularly Small and Medium Enterprises (SMEs), in adopting cleaner technologies and meeting stricter environmental standards.

Priority 2: Cleaning Up Ports and Shipping

Karachi's port-adjacent areas are major pollution hotspots, with significant contributions from shipping. To address this unique challenge for Karachi, specific interventions like shore power and cleaner fuel standards within port boundaries are essential.

Install shore power: Enabling docked vessels at both major ports (Karachi Port and Port Qasim) to connect to the electricity grid rather than running their auxiliary engines on-board can significantly reduce particulate matter, SO_2, and NO_x emissions within the port environment.

Implement fuel sulfur requirements: Enforcing stricter fuel sulfur limits for vessels operating within port boundaries and surrounding coastal waters, potentially exceeding existing international MARPOL standards, would directly address a significant source of SO2 and particulate emissions.

Electrification of port handling equipment: Transitioning port-based cargo handling equipment (e.g., cranes, yard tractors) from diesel to electric power where feasible can reduce localized emissions and noise pollution.

Regulate auxiliary maritime engines: Implement emissions controls for currently unregulated maritime auxiliary engines on various vessel types operating frequently within the urban airshed.

Establish Emission Control Zones (ECZs): Consider establishing ECZs extending into territorial waters and implementing vessel speed reduction zones in coastal approaches to ports to reduce fuel consumption and emissions.

Priority 3: Regulating Heavy-Duty Vehicles

The transport sector is the primary source of NOx (80%) and the second-largest source of PM2.5, regulation of the city's large fleet of heavy-duty diesel vehicles is critical. The systemic issues of an aging fleet and poor fuel quality must be addressed directly.

Vehicle inspection: A robust, regularly enforced vehicle inspection and maintenance program specifically targeting commercial diesel vehicles (trucks, buses, container carriers) is essential to address one of the highest-emitting vehicle categories.

Low Emission Zones (LEZs): Designating LEZs in port-adjacent areas, key industrial corridors, and potentially congested urban centers would restrict access for older, more polluting heavy-duty vehicles, thereby accelerating fleet renewal and technology adoption in these critical high-traffic regions.

Freight management system: Optimizing truck movements between ports, industrial zones, and major highways through a coordinated freight management system can reduce congestion, idling times, and associated emissions.

Diesel fuel quality: A critical prerequisite for the effectiveness of vehicle emission control technologies is the availability of low-sulfur diesel fuel. Stringent standards for diesel fuel quality must be adopted and rigorously enforced to combat adulteration and the sale of substandard fuels.

Electric truck programs: Initiating pilot programs for electric trucks, particularly for short-haul trucking between ports and nearby industrial zones can pave the way for wider adoption of zero-emission freight transport.

The Foundation: Strengthening Governance and Monitoring

Underpinning the success of sector-specific interventions is the need for strengthened institutional capacities.

Establish an air quality monitoring network: Karachi urgently requires an expanded network of regulatory-grade CAQMS providing reliable, real-time data to regulators, researchers, and the public.

Strengthen cross-district coordination: Given Karachi's complex administrative structure, establishing effective mechanisms for inter-agency and cross-district coordination is vital for consistent policy implementation and enforcement of environmental regulations.

Harmonize national best practices: Industrial emission standards applicable in Karachi must be harmonized with, and ideally strengthen, national best practices to eliminate regulatory gaps that may permit higher emissions compared to other regions or international benchmarks.

Public health warning systems: Implement systems for issuing timely public health advisories during high pollution episodes, particularly for vulnerable populations in high-emission zones. Ensure transparent public reporting of emissions data from major industrial facilities.

The implementation of these evidence-based interventions, tailored to Karachi's unique emissions profile and targeting its dominant industrial, port-related, and transportation pollution sources, offers a clear pathway to substantially reducing harmful air pollutant levels and improving public health outcomes. The concentrated nature of many emission sources in designated industrial zones and transport corridors also provides strategic opportunities for high-impact, geographically focused interventions.

We already know what works. Clean industry, better fuels, safer trucks — the solutions are proven. What's needed is political will and public awareness.

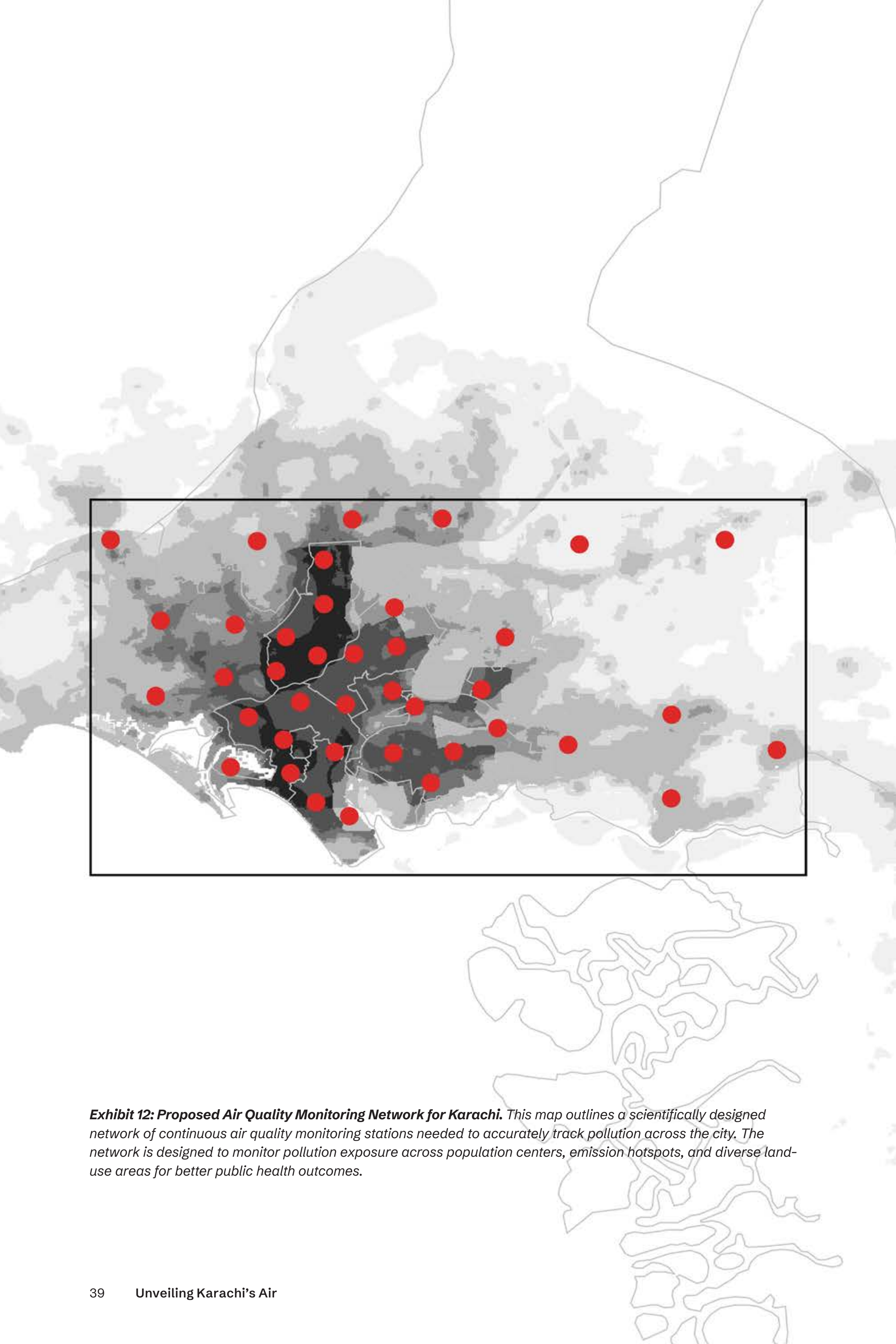

Exhibit 12: Proposed Air Quality Monitoring Network for Karachi. *This map outlines a scientifically designed network of continuous air quality monitoring stations needed to accurately track pollution across the city. The network is designed to monitor pollution exposure across population centers, emission hotspots, and diverse land-use areas for better public health outcomes.*

Hazy conditions obscure buildings as seen from Sea View. The low-lying brown haze is a typical sign of a temperature inversion, an atmospheric condition common in winter that traps pollutants close to the ground and dramatically worsens air quality for millions.

08. Karachi's Clean Air Future

A cleaner, healthier Karachi is within reach, but requires unwavering commitment and collaborative effort. This inventory provides the scientific mandate; decisive action must follow to protect the health and future of millions.

Strategic Imperatives

— Tackling industrial and maritime emissions must be central to Karachi's clean air strategy.

— Immediate investment is needed to expand air quality monitoring and strengthen regulatory enforcement.

— Sustained political will, and public engagement are vital for long-term success.

Karachi stands at a critical juncture. As Pakistan's economic powerhouse and a rapidly expanding megacity, facing an air quality crisis that reduces average life expectancy by 2.7 years, the city has the opportunity and indeed, the imperative, to transition to a sustainable model of industrial and urban development. Such a model must reconcile economic growth with the fundamental right of its citizens to breathe clean air, ensuring environmental protection is not a secondary consideration but an integral component of its development trajectory.

A Clear Diagnosis: The Key Takeaways

This emissions inventory provides unambiguous evidence that **industrial activities are the cornerstone of any effective air quality management strategy for Karachi.**

Unlike other urban centers in Pakistan where transportation emissions dominate the PM2.5 profile, Karachi's significant industrial contribution (nearly 49% of PM2.5 emissions) necessitates a fundamentally distinct approach, centered on industrial modernization, adoption of cleaner technologies, and stringent emission controls. This industrial-centric strategy mirrors global best practices in other coastal industrial cities observed in numerous coastal industrial cities globally, where decades of experience have demonstrated that technological solutions can successfully decouple economic prosperity from environmental degradation.

The **port and maritime sector represents a second distinctive and critical element** of Karachi's air quality challenge and, consequently, its solution pathway.

As Pakistan's gateway to international trade, the city's bustling port operations are indispensable drivers of economic growth but also significant contributors to the local emissions burden. Fortunately, a wealth of international precedents—from major ports like Rotterdam in Europe to Los Angeles on the US West Coast — demonstrate that interventions such as port electrification, provision of shore power for docked vessels, and promotion of cleaner shipping initiatives can dramatically reduce these environmental impacts while maintaining, and often enhancing, operational efficiency. These measures frequently offer co-benefits beyond air quality improvement, including reduced noise pollution and improved occupational health and safety in port areas.

From Diagnosis to Action: Implementing the Path Forward

Successfully implementing the comprehensive recommendations outlined in this report will require a concerted effort to address several underlying structural challenges:

Bridging the monitoring gap: Karachi cannot effectively manage its air quality without robust, continuous measurement. Expanding the air quality monitoring network and ensuring transparent data accessibility are paramount.

Strengthening regulatory capacity: Environmental protection agencies must be endowed with enhanced technical expertise, adequate resources, and unambiguous enforcement authority to ensure compliance with environmental regulations.

Leveraging economic instruments: Regulatory mandates should be complemented by well-designed economic instruments, such as emission charges, green taxes, or financial incentives, to encourage early adoption of cleaner technologies and foster innovation.

Enhancing public awareness: Raising public awareness about the health impacts of air pollution and the benefits of proposed interventions is crucial for creating the social license and political will necessary for implementing stronger pollution controls and ensuring community participation.

Karachi's natural air circulation benefit, with its potential for natural ventilation through sea breeze circulation, offers a distinct advantage. This means that targeted emission reductions are likely to translate into more rapidly perceptible improvements in ambient air quality compared to inland cities that may grapple with more persistent meteorological trapping of pollutants. Such "quick wins" can be instrumental in building public confidence and sustaining momentum for more comprehensive and long-term air quality management strategies.

The Vision: A Healthier, Breathable Karachi

By systematically addressing its primary industrial and maritime emission sources, while simultaneously leveraging its natural geographical advantages, Karachi can achieve a transformative improvement in its air quality landscape without compromising its economic dynamism. The technical solutions are largely well-established, and this emissions inventory provides the requisite scientific foundation for their targeted and effective implementation.

With appropriate investment, unwavering regulatory commitment, and collaborative action from all stakeholders, Karachi can demonstrate that robust economic growth and stringent environmental protection are not mutually exclusive but are, in fact, complementary objectives.

In doing so, Karachi can establish a compelling model for sustainable industrial development, applicable not only throughout Pakistan but also for other rapidly urbanizing coastal cities in the region and beyond.

The science is now established; what remains is the collective resolve and practical action to transform these findings into tangible breathing space and healthier, longer lives for Karachi's population.

We know the fixes. Karachi can choose clean air, or live with the consequences of inaction.

A modern coal-fired power plant at Port Qasim. While technologies to control emissions are feasible, the lack of publicly available, real-time data from smokestacks means the true environmental impact of such large facilities remains uncertain, highlighting a critical gap in regulatory oversight.

Air Quality Data

This appendix contains summary statistics and a sample of the daily 24-hour average PM2.5 data from the PAQI monitoring network used in the analysis for this report.

Table A1: Sample of Daily 24-Hour Average PM2.5 Concentrations (µg/m³) (October 2023 - March 2024)

Date	PM2.5	Date	PM2.5
01 October 2023	69.7	18 October 2023	42.8
02 October 2023	38.7	19 October 2023	40.5
03 October 2023	25.2	20 October 2023	31.4
04 October 2023	22.7	21 October 2023	35.0
05 October 2023	33.2	22 October 2023	29.2
06 October 2023	34.3	23 October 2023	37.8
07 October 2023	31.4	24 October 2023	56.9
08 October 2023	29.7	25 October 2023	38.1
09 October 2023	31.2	26 October 2023	34.2
10 October 2023	26.0	27 October 2023	44.5
11 October 2023	30.2	28 October 2023	44.6
12 October 2023	25.5	29 October 2023	46.7
13 October 2023	24.1	30 October 2023	58.6
14 October 2023	21.9	31 October 2023	65.5
15 October 2023	25.6	01 November 2023	85.1
16 October 2023	30.1	04 November 2023	45.6
17 October 2023	24.7	05 November 2023	65.0

Date	PM2.5	Date	PM2.5
06 November 2023	101.4	07 December 2023	86.4
07 November 2023	110.0	08 December 2023	21.0
08 November 2023	122.0	09 December 2023	24.2
09 November 2023	100.5	10 December 2023	25.5
10 November 2023	66.2	11 December 2023	22.5
11 November 2023	78.8	12 December 2023	92.3
12 November 2023	84.0	17 December 2023	72.7
13 November 2023	75.1	18 December 2023	73.6
14 November 2023	67.9	19 December 2023	101.7
15 November 2023	77.3	20 December 2023	94.3
16 November 2023	92.6	21 December 2023	101.3
17 November 2023	79.2	22 December 2023	106.9
18 November 2023	111.5	23 December 2023	101.2
19 November 2023	191.8	24 December 2023	80.4
20 November 2023	154.5	25 December 2023	85.5
21 November 2023	133.4	26 December 2023	178.6
22 November 2023	125.0	29 December 2023	87.2
23 November 2023	101.6	30 December 2023	98.9
24 November 2023	124.5	31 December 2023	103.9
25 November 2023	135.5	01 January 2024	101.8
26 November 2023	102.6	02 January 2024	128.9
27 November 2023	157.4	03 January 2024	123.7
28 November 2023	163.0	04 January 2024	124.8
29 November 2023	155.8	05 January 2024	130.4
30 November 2023	191.7	06 January 2024	94.1
01 December 2023	153.8	07 January 2024	99.4
02 December 2023	133.5	08 January 2024	88.6
03 December 2023	136.2	09 January 2024	99.1
04 December 2023	122.9	10 January 2024	79.6
05 December 2023	132.2	11 January 2024	100.7
06 December 2023	112.2	12 January 2024	130.9

Date	PM2.5	Date	PM2.5
13 January 2024	105.5	13 February 2024	105.6
14 January 2024	96.5	14 February 2024	118.2
15 January 2024	136.0	15 February 2024	108.9
16 January 2024	56.7	16 February 2024	89.4
17 January 2024	129.7	17 February 2024	86.2
18 January 2024	155.0	18 February 2024	21.3
19 January 2024	146.0	19 February 2024	34.9
20 January 2024	132.5	20 February 2024	29.7
21 January 2024	118.3	21 February 2024	28.5
22 January 2024	104.3	22 February 2024	41.0
23 January 2024	103.7	23 February 2024	57.1
24 January 2024	167.6	24 February 2024	55.6
25 January 2024	165.8	25 February 2024	56.9
26 January 2024	152.1	26 February 2024	41.3
27 January 2024	118.4	27 February 2024	35.6
28 January 2024	136.3	28 February 2024	48.7
29 January 2024	75.8	29 February 2024	74.4
30 January 2024	77.9	01 March 2024	87.6
31 January 2024	27.7	02 March 2024	41.1
01 February 2024	63.9	03 March 2024	25.9
02 February 2024	60.3	04 March 2024	51.9
03 February 2024	79.4	05 March 2024	59.5
04 February 2024	90.7	06 March 2024	67.2
05 February 2024	84.5	07 March 2024	52.7
06 February 2024	90.3	08 March 2024	73.3
07 February 2024	81.3	09 March 2024	73.7
08 February 2024	51.8	10 March 2024	62.6
09 February 2024	83.8	11 March 2024	32.1
10 February 2024	75.3	12 March 2024	34.5
11 February 2024	81.4	13 March 2024	42.3
12 February 2024	87.1	14 March 2024	73.2

Table A2: Monthly and Annual Average PM2.5 Concentrations (µg/m³) in Karachi (2016-2024).

Karachi's winter months (Nov–Jan) consistently show the highest PM2.5 levels, with several years exceeding 100 µg/m³ in monthly averages, over 20x WHO guidelines.

Months	2016	2017	2018	2019	2020	2021	2022	2023	2024
Jan		86.6	80.8	50.8	83.4	115.5	67.1	89.5	113.7
Feb		59.2	60.3	24.1	71.6	87.5	50.4	65.0	68.1
Mar		29.0	44.2	20.7	38.1	45.0	44.5	51.6	46.8
Apr		26.0	55.1	22.5	27.0	41.8	37.4	29.7	30.0
May		19.5	41.6	11.6	26.2	31.7	41.6	27.6	25.6
Jun		24.1	43.7	12.3	27.3	32.7	26.1	29.7	26.6
Jul		22.9	42.4	13.5	26.1	29.5	19.3	31.0	26.8
Aug		19.4	37.5	18.0	27.3	24.5	29.7	28.0	21.0
Sep		17.8	23.6	51.2	33.5	33.3	32.4	41.6	26.3
Oct	29.4	32.1	45.0	56.6	53.2	54.3	48.3	36.9	38.2
Nov	64.8	62.6	51.2	77.8	108.9	99.0	76.1	102.3	47.2
Dec	65.5	67.5	50.6	113.4	125.5	90.0	111.9	105.6	84.2
Average	**54.7**	**40.4**	**48.3**	**49.6**	**48.5**	**46.9**	**51.2**	**49.3**	**46.2**

Note on Complete Dataset: *The tables above presents a sample of daily data. The complete, unabridged dataset, spanning from October 2016 to the present, is openly available for research, public use, and verification. The full dataset has been permanently archived and can be accessed and cited via the following Digital Object Identifier (DOI): https://doi.org/10.5281/zenodo.15845428*

Glossary

Activity Data (AD): Quantitative information on the extent of human activities that lead to emissions. Examples include fuel consumption by various vehicle types, volume of industrial production from different manufacturing sectors, or energy generated by power plants.

AQLI (Air Quality Life Index): A metric developed by the Energy Policy Institute at the University of Chicago (EPIC) that quantifies the impact of particulate air pollution on life expectancy.

Airshed: A geographical area within which air pollutants tend to be confined and mixed due to topography, meteorology, and emission patterns, meaning that sources within the airshed primarily affect the air quality in that region.

Anthropogenic Emissions: Emissions resulting from human activities, such as industrial processes, transportation, and energy generation, as opposed to natural sources.

Best Available Control Technologies (BACT): The most effective and advanced emission reduction techniques, processes, methods, or systems that have been demonstrated and are economically feasible for a particular industry or source category.

Carbon Monoxide (CO): A colorless, odorless, and toxic gas formed by the incomplete combustion of carbon-based fuels. Major urban sources include vehicle exhausts and some industrial processes.

Continuous Emissions Monitoring Systems (CEMS): Equipment that continuously measures pollutant emissions from sources like industrial smokestacks or power plants, providing real-time data on emission rates.

Cold Ironing (Shore Power): The process of providing electrical power to ships at berth from the shore, allowing them to turn off their auxiliary engines, thereby reducing emissions of pollutants and noise in port areas.

Emission Factor (EF): A representative value that relates the quantity of a pollutant released into the atmosphere with an activity associated with the release of that pollutant. It's typically expressed as the weight of a pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., grams of PM2.5 emitted per kilometer driven).

Emissions Inventory: A comprehensive and detailed listing, by source category, of the amounts of air pollutants discharged into the atmosphere of a specific geographical area during a specific time period.

EMEP/EEA Guidebook: The EMEP/EEA air pollutant emission inventory guidebook, providing technical guidance for the preparation of national emission inventories by the European Monitoring and Evaluation Programme (EMEP) and the European Environment Agency (EEA).

Electrostatic Precipitator (ESP): An air pollution control device that removes suspended dust particles from a gas or exhaust stream by applying a high-voltage electrostatic charge and collecting the particles on charged plates.

Fabric Filters (Baghouses): Air pollution control devices that remove particulate matter from air or gas released from commercial processes or combustion, by passing the dirty air stream through a series of fabric bags that capture the particles.

Flue Gas Desulfurization (FGD): A set of technologies used to remove sulfur dioxide (SO2) from exhaust flue gases of fossil-fuel combustion sources, such as power plants and industrial boilers.

Kiloton (kT): A unit of mass equal to 1,000 metric tons, or 1,000,000 kilograms.

Low Emission Zone (LEZ): A geographically defined area where access by certain polluting vehicles is restricted or charged, with the aim of improving air quality within that zone.

MARPOL (International Convention for the Prevention of Pollution from Ships): The main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes.

NEQS (National Environmental Quality Standards): The set of legally enforceable standards for various pollutants, including ambient air quality, established by the Government of Pakistan.

Nitrogen Oxides (NOx): A group of highly reactive gases, primarily nitric oxide (NO) and nitrogen dioxide (NO2), formed during high-temperature combustion from vehicles, power plants, and industries. They contribute to the formation of smog, acid rain, and secondary particulate matter.

Particulate Matter (PM2.5): Fine inhalable particles with aerodynamic diameters that are generally 2.5 micrometers and smaller. These particles can penetrate deep into the lungs and enter the bloodstream, posing significant health risks.

SEQS (Sindh Environmental Quality Standards): The set of legally enforceable standards for various pollutants established by the Sindh Environmental Protection Agency, applicable within Sindh province.

Sulfur Dioxide (SO2): A colorless, reactive gas with a pungent odor, primarily produced by burning sulfur-containing fossil fuels (coal and oil) in power plants and other industrial facilities. It contributes to respiratory problems, acid rain, and the formation of secondary particulate matter.

Temperature Inversion: An atmospheric condition in which a layer of warm air sits over a layer of cooler air near the ground. This “inversion” traps air pollutants close to the surface, preventing them from dispersing and often leading to higher pollution concentrations.

WHO Interim Targets: A series of incremental air quality targets provided by the World Health Organization to guide pollution reduction efforts in highly polluted regions on the path toward meeting the final, health-based Air Quality Guideline.

Unveiling Karachi’s Air: A Scientific Foundation for a Clean Air City

We know the fixes. Karachi can choose clean air, or live with the consequences of inaction.

Karachi's polluted air costs the average resident 2.7 years of life.

For 363 days a year, the air fails to meet global health guidelines — creating a city-wide public health crisis that affects millions.

For years, the scale of this crisis was visible, but its sources remained unclear. *Unveiling Karachi's Air* offers the city's first science-based emissions inventory — a landmark diagnosis that moves beyond speculation. It quantifies the dominant role of industrial emissions, diesel-powered freight, and port activity in poisoning the air we breathe.

But this report is more than a diagnosis — it's a blueprint for action. It lays out a targeted, evidence-based path to reduce pollution, improve public health, and reclaim the promise of a healthier, more sustainable Karachi. The problem is not mysterious or unmanageable — it is local, measurable, and solvable.

This report provides the science needed to clear the air.

Pakistan Air Quality Initiative

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