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Air Quality Evolution Characteristics and Driving Factors in Asian Megacities: A Systematic Review

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Abstract. Urban air pollution has evolved into one of the most severe environmental problems in Asia, driven by rapid industrialization, urbanization and complex climate interactions. This study is a synthesis of the spatiotemporal patterns, driving forces and governing responses of air quality in major Asian cities. Distinct interannual and seasonal trends were identified: air quality is improving in East Asia, stagnating in South Asia and fluctuating in Southeast Asia; pollution peaks in dry or winter months and eases in wet or summer seasons. These variations arise from the combined effects of emissions intensity, meteorological dynamics, and regional climate regimes of different regions. Socioeconomic factors such as energy structure, land-use change and urban morphology influence local patterns of pollutant production and exposure inequalities. Despite the continued implementation of policies aimed at improving air quality, persistent ozone pollution and transboundary haze exposure highlight deficiencies in co-governance. Improving air quality will ultimately depend on greater cooperation between the Asian cities and regions in the 2030 agenda, synergistic $PM_{2.5}$-O_3 control interactions, optimized monitoring networks, and more inclusive public participation. This review, drawing on 577 studies provides a detailed overview of how Asian megacities have changed, the mechanistic and management processes at play. It provides insights into designing multi-pollutant management approaches.

Keywords: air quality, Asian megacities, driving factors, air quality management

1. Introduction

Air pollution is the presence in the atmosphere of substances harmful to health or the environment, such as PM, NO_x, and O_3. Pollutants in the air threaten human beings, ecosystems, and the climate system [1]. Cities are both sources of air pollutants and a significant source of greenhouse gas (over 70% of global CO_2 emissions are emitted in urban areas) and a significant source of particulate pollution [2]. Urban air pollution has started emerging emphatically as one of the most formidable and pressing environmental problems in Asia, where rapid industrialisation, urbanisation and population growth meet complex climate and socioeconomic realities [3,4].

While several studies discuss trends in air quality globally or regionally, Asian megacities present unique features that merit a systematic synthesis. The energy structure rooted in coal, a compact urban morphology, and unfavourable meteorological conditions (like winter inversions and

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monsoonal circulation) exacerbate complex pollution including both $PM_{2.5}$ and O_3 [5] on the one hand, while delayed policy responses and weaker regional coordination relative to Europe and North America result in slower reductions in pollution concentrations [6]. Through a multicity study, the Public Health and Air Pollution in Asia (PAPA) project demonstrates that short-term air pollution exposure is associated with daily mortality, providing evidence to conclude that air pollution exerts adverse health effects in the Asian urban context [7]. Most previous studies focus on one pollutant or locality, a single city, or a short episode; they do not address cross-city, multi-pollutant comparisons that can reflect longer-term trends over the continent of Asia.

In light of these and other gaps, the progression of methodologies has been key. Existing ground-based monitoring networks supply high-temporal-resolution data but are imbalanced spatially, particularly between city cores and peripheries [8]. Remote sensing techniques alongside chemical transport models (e.g., GEOS-Chem) have allowed for large-scale evaluations of PM2.5 and O_3 distributions, double-high pollution episodes (O3-PM2.5 PDs), and evaluation of meteorological drivers [9]. At finer scales, geographically weighted regression (GWR) is ususally used to untangle heterogeneous socioeconomic and natural driving forces of air quality [10,11]. Such a range and combination of methodological avenues provide more fragments into the understanding of urban air quality evolution across studies.

Against this context, we conduct a systematic mega review of the air quality evolution of Asian megacities, to capture the diversity of regional trajectories but also the commonality of drivers. Specifically, our study will (1) collate the temporal and spatial evolution of major pollutants in Asian cities; (2) identify key natural and anthropogenic drivers; and (3) consider how the answers to these questions can advise policy outlines and future research directions. By bringing together evidence from different parts of Asia, this study considers factors affecting air quality in Asian megacities through an integrated cross-city lens of factors, establishing a scientific basis for designing differentiated, regionally coordinated air pollution control pathways. In this review, we use the term megacity to refer to an urban agglomeration of >10 million people; our regional scope covers East, South, Southeast, and North Asia. West Asia was excluded due to the small population and lack of data and literature.

2. Materials and methods

2.1. Data collection and processing

To review the development, drivers and management of air quality in major Asian cities, we systematically searched for literature across the following primary data sources. Main data sources: Web of Science Core Collection, Scopus, PubMed and CNKI for policy documents and statistical yearbooks. Others from official websites such as WHO, UNEP, ADB and National Environmental Monitoring Websites. Search strategy: a keyword search with search terms such as 'urban air quality’, 'PM2.5’, 'Asia’, etc over the time span of 2005-2025, in English and Chinese queries, using keywords search operators. The initial literature search yielded 825 documents. Based on abstracts and keywords, studies focusing on the evolution of air quality in Asian cities and its driving factors were selected. Limiting the research to articles and review articles, ultimately, 577 high-quality documents were included in the software analysis.

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2.2. Data analysis

After collecting the original literature data, bibliometric analysis methods were used to perform a visual analysis of the literature. Cite Space was used for this study due to its timeline and burst-detection capabilities. A keyword co-occurrence timeline view (Figure 1) was obtained.

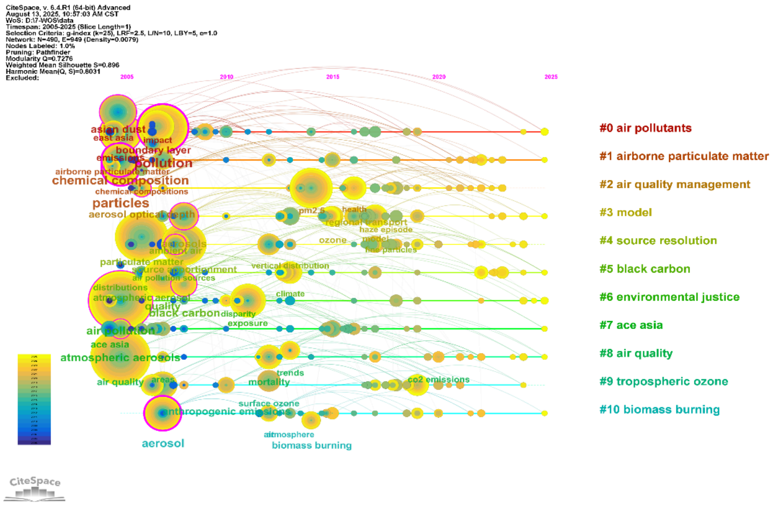

Figure 1. Keyword co-occurrence timeline view of Asian urban air quality research (2005–2025)

The visualisation of literature illustrates the evolution of research themes in Asian urban air quality studies over the past two decades. Between 2005 and 2010, research primarily focused on foundational issues such as particulate matter pollution and emission inventories, reflecting the emphasis at the time on pollutant characterisation and source identification. Between 2010 and 2015, new research clusters related to health risk assessment and the application of remote sensing technology began to emerge, indicating that air quality was beginning to incorporate health perspectives and spatial monitoring technologies. In the most recent decade, themes such as climate change, extreme weather events, and machine learning have gradually emerged, with research priorities shifting toward predictive modelling and the interaction between climate and air quality. Research on the quality of air in Asian cities has progressed from an assessment of the various pollutants found in the air to an integrated and cross-sectoral study of air quality.

3. Evolution characteristics of air quality in Asian megacities

3.1. Temporal characteristics

East Asian cities have made significant gains in air quality over the past decade. There have been major reductions in PM2.5 concentrations in China. Since the Air Pollution Prevention and Control Action Plan was implemented in 2013, PM2.5 concentration has dropped significantly [12]. The annual average PM2.5 concentration in the Beijing-Tianjin-Hebei region fell from about 106 μg/m3 in 2013 to under 60 μg/m3 in 2017, a reduction of over 40% [13]. Taking advantage of optimization of energy structure and industrial upgrading, declines in concentrations of SO_2 and PM2.5 in the Pearl River Delta urban cluster have been particularly rapid since 2013 [14].

By contrast, South Asian megacities rank at the bottom in terms of air quality. Delhi's annual average PM2.5 concentration has exceeded 98 μg/m3since 2019, while Dhaka and Lahore exceeded 90, well above WHO's annual standard of 5 μg/m3 [4]. While some mitigation measures have been

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implemented particularly by India and Pakistan, overall improvements are hampered by coal-dependent energy systems, traffic congestion, and lax enforcement of regulations [15]. This prolonged state of stagnation seems to contrast with the trajectory of East Asian cities, and reflects the different governance systems and policy implementation strengths.

There are also seasonal air quality contrasts in Asian cities. In East Asia, wintertime $PM_{2.5}$ peaks are primarily attributed to heating and extremely stable atmospheric conditions, while summer convection and rainfall dilute pollutants, but also support ozone formation under very high temperature and strong radiation [16,17]. Similar contrasts can be found in South Asian cities: pollution episodes in winter are prominent due to biomass burning and temperature inversion that often develops, whereas the monsoon season strongly dilutes the pollutants [18]. In Southeast Asia, air quality variations are primarily dictated by the seasonal cycle. Fires associated with agriculture, especially forest and peatland fires during the dry period, lead to severe transboundary haze and sharp spikes of PM2.5 peaks in cities such as Singapore and Manila. The wet season provides temporary relief yearly via rain and wind dispersion [19,20].

In general, the temporal variability in urban air quality is manifest as both interannual and seasonal variability across Asia. Interannually Asia is of improvement in East Asia cities, stagnation in South Asia cities, and fluctuation in Southeast Asia cities, primarily determined by the respective emissions intensity, pollution resources, and governance capacity of each city-cluster. Seasonally, pollution generally waxes to a peak in the dry, winter months and wanes towards the summer wet-season, resulting from coal burning, biomass burning and monsoonal dispersion of pollution. Such spatiotemporal changes attest to the importance of emissions, meteorology and regional climate coupling of urban air quality in Asia.

3.2. Spatial characteristics

Regional. Major cities in East, South, Southeast, and North Asia have very distinct air quality trajectories. Between 2013 and 2020, Beijing's PM2.5 concentration declined by more than 60%, and SO_2 also fell sharply, indicating important critical coal combustion control and industrial transformation [21]. Tokyo and Seoul, through stringent vehicle emission regulations, maintained low PM2.5 and NO_2 levels at an earlier stage, with regional collaborative governance being a key to the low air pollution of the region [22]. South Asian cities are among the most polluted cities in the world, several major cities still exceed annual PM2.5 concentrations of 80 μg/m3 decade after decade with no obvious decline [23]. In Faisalabad, Pakistan, the analysis on SMS has selected for traffic and industry-related air pollution exposure suggests high particulate matter, a gaseous pollutants and organic-inorganic content endemic to an unsafe degree, highlighting gaps and suggesting improvements for the current condition [24]. Southeast Asian cities are strongly affected by the monsoons, forest fires and transboundary haze, leading to highly variable air quality patterns: during dry years in Indonesia, regional haze can drive rapid swoops in PM2.5 concentration throughout the entire Malacca Strait urban cluster [25]. In the north Asian cities of Russia, air pollution, natural and anthropogenic influences of which make the greatest significant to contribution to industrial pollution, directly links public health to the protection of abuses by government agencies and corporations with agitations of air [26].

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3.3. Impact of special events

3.3.1. Dust storm event

In northern East Asia, sandstorms are ubiquitous natural events making urban air quality rapidly susceptible to deterioration. In spring or dry seasons, dust storms in Mongolia are the primary source of sand pollution in East Asia. The dust of these contaminants not only affect Northern China but also transports to the Korean Peninsula through the atmosphere. Under dust storm episodes, PM2.5 may rise by several-fold within hours in Ulaanbaatar and due to long-range transport and substantial chemical reaction as well, which worsens the health risk [27]. For instance, it has been found that during an average dust event, in August, the PM10 concentration in Beijing may rise to above 1000 μg/m3 in just a few hours, far exceeding the standard of the national air quality standard [28]. This not only reduces visibility tremendously but also causes secondary transformation of the dust particles in long-distance transports when they meet other pollution sources from anthropogenic activities thus becoming more toxic in the process [29].

3.3.2. Forest fires and transboundary haze

In Southeast Asia, transboundary haze from forest fires and peatland burning is a significant challenge to urban air quality [30]. The persistent occurrence of fires in Kalimantan and Sumatra, Indonesia during the dry season, coupled with the voluminous smoke they generate, can generate smoke that traverses the regional atmosphere to impact multiple cities in Singapore, Malaysia and the Philippines [31]. Research suggests that during Indonesia's severe fires in 2015, the Singapore daily average PM2.5 concentration in some locations exceeded 150 μg/m3; far above health thresholds [31]. These transboundary haze events tend to persist for weeks to months, not a mere challenge to environmental management in a single city, but effectively a regional crisis impacting multiple nations [32]. There is a failure of regional cooperation mechanisms, with ASEAN lacking the adequacy or governance capabilities for enforcement [33].

3.3.3. COVID-19

The COVID-19 outbreak led to lockdowns in 2020 became a "natural experiment" of how human emissions impact air quality. Urban areas across East and South Asia had improved air quality during pandemic lockdowns [34]. Research in China indicated a nationwide decrease of over 30% in NO_2 concentrations and 20% in $PM_{2.5}$ levels over the spring of 2020, and Beijing and Shanghai had improved air quality short term [35]. In Delhi, India, $PM_{2.5}$ concentrations were down by more than 50% during the strict lockdown, reaching the lowest level in a decade [36]. In contrast, this improvement was not observed fully in ozone pollution. As a result of the sudden decline in nitrogen oxide (NOx) emissions weakened the titration effect on ozone, most cities experienced rising O3 concentrations during lock downs [37]. The chemical nonlinear relationships between this and other pollutants are highly complex, where in many single reduction initiatives, the kind of pollution was relocated elsewhere [38]. The temporary nature of air quality improvements during the pandemic also suggests that activity controls alone cannot achieve sustainable pollution control, therefore long-term institutional emission reductions are key.

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4. Drivers of air quality change

Both natural and human factors shape the spatial and temporal variations of urban air quality. Natural factors such as meteorological conditions, precipitation, temperature, and terrain influence pollutant dispersion, accumulation, and chemical transformation processes. Meanwhile, human activities serve as dominant sources of air pollutants and greenhouse gases, and policy interventions and urban planning strategies further determine the effectiveness of emission reduction efforts. Table 1 summaries the key factors and their typical impact patterns on urban air quality.

Table 1. Major driving factors and mechanisms of urban air quality variation

Factors			Impact Pattern
Natural factors	meteorological factors	wind speed / direction	High wind speed/convective → favourable diffusion and dilution
			low wind speed/stable weather → pollutant accumulation
		precipitation /humidity	Wet deposition → removal effect
			high humidity → exacerbate secondary inorganic aerosol production and $PM_{2.5}$ pollution
		temperature	high temperature → enhance photochemical reaction → increased O_3 concentration
	geographical factors	terrain	basin → pollutant retention, high $PM_{2.5}$ and NO_2
			ring mountainous terrain→ high pollution accumulation
		location	coastal cities→ good dispersion by sea and land winds, less polluted
Human factors	industrial factors	industrial emissions	SO_2, NO_x and particulate matter →main source of $PM_{2.5}$ and the acid rain
		traffic emissions	major sources of NO_2 and primary particulate
			motor vehicle exhaust→ photochemical reaction to produce O_3
		energy structure	coal dominated → high SO_2, NO_x and particulate
			China's "coal to gas, coal to electricity" → $PM_{2.5}$ improvement
			south Asian coal dependence + poor fuel quality → difficult to reduce emissions
		industrial layout	concentration of energy-intensive industries → regional high-pollution zones
	urban development	urbanisation	rising demand for energy and transport → increased pollution;
			urban fragmentation → vehicle traffic increased → increased emission dispersion pathways
			urban renewal/centralised energy supply → reduction of sources
		policy intervention	China: "Ten Atmospheric Rules", "Blue Sky Defence Campaign" → Significant reduction of $PM_{2.5}$
			Japan, Korea: emission regulations and oil standards → effective improvement
			South Asia: lack of systematic management → fragmentation of governance
			Southeast Asia: lack of regional synergies → limited trans-regional pollution control

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As summarised in Table 1, meteorology governs short-term dispersion/accumulation, while anthropogenic sources and policies determine long-term trajectories; we elaborate below on how wind, humidity, and temperature interact with emissions to shape $PM_{2.5}$ and O_3.

5. Current policies and future recommendations

5.1. Air quality governance case studies in representative countries

China, Russia, and India offer distinct yet instructive case studies in megacity air quality governance. China's experience exemplifies robust top-down policy interventions. The Air Pollution Prevention and Control Action Plan (2013) designated PM2.5 as a key indicator, setting reduction targets for key area in China. By 2017, PM2.5 concentrations in Beijing-Tianjin-Hebei had fallen by over 35% [39]. The following Three-Year Action Plan for Blue Sky Protection (2018) reinforced ultra-low emissions reforms in industry, clean energy transitions and regional collaboration [40]. These projects are rewards from binding national targets and multi-pollutant or inter-regional strategies [41].

Russia's story reveals the long shadow of the difficulties in managing industry and ecosystem. The 2018 Clean Air Federal Project focused on 12 of the most polluted urban areas, including Moscow, requiring the modernization of industry, refining of fuel and tightening the standards for vehicles [42]. By 2023, target cities had managed a decrease of hazardous emissions of just over 11% from the baseline established in 2017, surpassing the target of an absolute reduction of 9% [43] Moreover, wildfires and extreme heat in Siberia and the Far East worsened PM2.5 pollution [44].

Indian case shows the importance of implementation capacity. The National Clean Air Programme (NCAP) was launched in India in 2019 as an approach to cutting pollution levels of PM2.5 and PM10 by 20-30% in 102 non-attainment cities by 2024 [45] but poor funding and lack of accountability have hindered these efforts with cities such as Delhi and Lahore still rated among the world's most polluted [46]. It has been proposed that policy frameworks are not enough without the capacity to enforce them [47].

5.2. Recommendations for future work

To further enhance air quality governance across Asia, efforts should focus on regional understanding, technological advancements, and multi-actor engagement. The recognized instances of transboundary transport and agricultural burning in South and Southeast Asia highlight the potential of improving cross-regional coordination mechanisms. Future efforts should ensure coordinated multi-pollutant approaches that also allow the joint mitigation of $PM_{2.5}$ and O_3. Finally, optimizing air quality monitoring through expanded ground-based networks and integrating remote sensing with low-cost sensor technologies for real-time, multi-scale assessments, can tackle existing urban-rural gaps in monitoring. The recognized institutional fragmentation and limited public engagement across a number of cities in Asia indicate a gap in environmental literacy and in moving towards more participatory, multi-actor arrangements to maintain air quality efforts in the long run.

6. Conclusions

Overall, this review indicates significant heterogeneity in air quality across Asian megacities, driven by governance capacity, energy structure, and transboundary influences. By coupling long-term pollution trends, spatial heterogeneity, and the drivers of actions (or inactions) into a common cross-city comparable framework, we build on previous regional and global reviews and add a concise

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model linking natural causes, pollution sources and measures, and regulatory responses to observed PM2.5 and O3 trends. Given the strong effects of air pollution on health and ambient air quality in Asia, the evidence of this review could help foster continued and strengthened regionally coordinated air quality governance in the region. Future research should focus on developing harmonized multi-pollutant datasets and comparable indicators for evaluating policy effectiveness across diverse urban contexts.

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