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Perspective

# Assessment and Critical Review of $PM_{0.1}$ Pollution in Pakistan

Faiza Irfan[1], Rida Munir[2], Sadique Akbar[1] and Ramna Zafar[1]*

[1]Department of Physics, University of Education, Township, Lahore 54570, Pakistan
[2]Canterbury Christ Church University, Canterbury, England
* Corresponding Email: ramnazafar96@gmail.com (R. Zafar)

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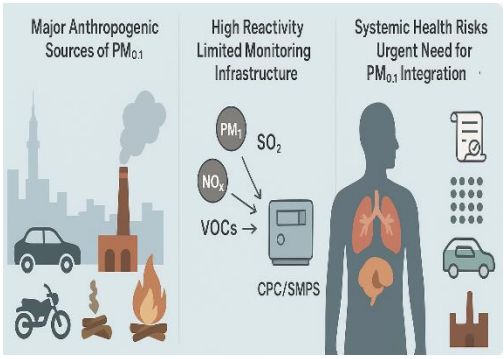
## ABSTRACT




Particulate matter (PM) is among the most significant air pollutants globally, with severe implications for environmental integrity, human health, and climate stability. Among its various fractions, ultrafine particles ($PM_{0.1}$, particles with an aerodynamic diameter ≤ 0.1 μm) are gaining increasing attention due to their high surface area-to-mass ratio, deep pulmonary penetration, and potential to translocate into systemic circulation and vital organs. This paper presents a comprehensive critical review of $PM_{0.1}$ assessment in Pakistan, emphasising its sources, spatiotemporal distribution, measurement limitations, and health consequences. Despite the mounting evidence of air quality degradation in Pakistan, data on $PM_{0.1}$ remain scarce and fragmented. The few available studies indicate that urban centres such as Lahore, Karachi, Islamabad, and Faisalabad exhibit ultrafine particle concentrations substantially higher than international safety benchmarks. Anthropogenic activities, including vehicular emissions, industrial combustion, biomass burning, and construction dust, are dominant contributors. This review identifies key gaps in current research, highlighting the lack of long-term monitoring, standardised methodologies, and toxicological assessments specific to $PM_{0.1}$ exposure in local populations. It further stresses the urgent need for policy integration, investment in high-resolution monitoring technologies, and public health interventions. Overall, the assessment underscores that $PM_{0.1}$ pollution in Pakistan poses an emerging environmental health crisis that remains scientifically underexplored and administratively underprioritized.

**Keywords***:* Air pollution; Air quality monitoring; Combustion emissions; Environmental policy; Health effects; Ultrafine particles

## 1. Introduction

Air pollution has emerged as a global environmental concern, and particulate matter (PM) is recognised as a leading cause of premature mortality, chronic respiratory disease, and reduced life expectancy [1],[2],[3],[4]. In Pakistan, where industrialisation, rapid urbanisation, and energy consumption patterns have intensified over the past two decades, particulate pollution has reached critical levels [5],[6],[7]. The country consistently ranks among the most polluted nations globally, with urban air quality indices (AQI) frequently exceeding the World Health Organization (WHO) guidelines several times. While coarse ($PM_{10}$) and fine ($PM_{2.5}$) particles have been the primary focus of air quality monitoring, the ultrafine fraction ($PM_{0.1}$) remains largely overlooked in Pakistan's environmental assessment frameworks [8].

$PM_{0.1}$ particles, owing to their nanoscale dimensions and physicochemical reactivity, differ fundamentally from larger PM fractions. They can penetrate deep into the alveolar region of the lungs, cross biological membranes, and even reach the bloodstream and brain through systemic circulation [9],[10],[11]. Consequently, their potential for causing oxidative stress, inflammation, and multi-organ toxicity is far greater than that of coarser particulates. Yet, Pakistan's monitoring networks and academic research have not adequately addressed this pollutant category, leaving significant knowledge gaps regarding its prevalence, sources, and health effects .

This study aims to critically evaluate existing assessments of $PM_{0.1}$ in Pakistan, synthesise findings from national and international research, and highlight the methodological, policy, and public health challenges associated with this pollutant. By analysing the limited but growing body of evidence, this review intends to (i) identify dominant emission sources and exposure hotspots, (ii) assess health implications and potential societal burdens, (iii) examine deficiencies in monitoring infrastructure, and (iv) propose strategies for future research and policy action. The broader purpose is to underscore the urgency of integrating ultrafine particulate pollution into Pakistan's air quality management and public health planning.

## 2. Critical Analysis

$PM_{0.1}$ particles, often referred to as ultrafine particles (UFPs), constitute a distinct class of aerosols characterised by their small size, large surface area, and high number concentration. These particles are primarily generated through combustion-related processes, both anthropogenic and natural, rather than mechanical disintegration [10],[12]. Their aerodynamic diameter (<0.1 μm) allows them to remain suspended for long periods and facilitates deep penetration into human respiratory systems. Because $PM_{0.1}$ particles can adsorb heavy metals, volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs), their toxic potential is amplified compared to coarser PM fractions.

In the South Asian context, where population density and energy consumption are high, $PM_{0.1}$ represents a largely invisible yet potent public health threat [13]. The absence of $PM_{0.1}$ in most air quality standards, including Pakistan's National Environmental Quality Standards (NEQS), further complicates the issue, as policymakers and researchers rely primarily on $PM_{2.5}$ as a proxy indicator. However, recent studies demonstrate that $PM_{2.5}$ mass concentrations do not reliably reflect $PM_{0.1}$ number concentrations, making it essential to address UFPs independently.

### 2.1. Sources of $PM_{0.1}$ in Pakistan

$PM_{0.1}$ emissions in Pakistan predominantly arise from anthropogenic activities [6],[7]. Vehicular exhaust, particularly from diesel engines and two-stroke motorcycles, is the single largest contributor in urban areas. The lack of emission control technologies, poor fuel quality, and ageing vehicle fleets exacerbate ultrafine particle emissions. Karachi and Lahore, both megacities with dense traffic networks, exhibit consistently high ultrafine particle number concentrations near major roadways and intersections.

Industrial processes, including steel manufacturing, brick kilns, cement production, and power generation, represent another significant source. Many industries in Pakistan operate on outdated combustion systems, using low-grade fuels such as furnace oil and coal, which emit substantial quantities of nucleation-mode particles. Brick kilns, especially those employing traditional clamp or Bull's trench technologies, release ultrafine carbonaceous soot mixed with trace metals.

Biomass burning, both intentional (crop residue burning) and domestic (firewood, charcoal, and dung combustion), adds another layer of complexity. Rural communities depend heavily on biomass for cooking and heating, leading to elevated $PM_{0.1}$ exposures indoors. During post-harvest seasons, open burning of agricultural residues in Punjab and Sindh contributes significantly to regional haze events and cross-border pollution episodes.

Additionally, secondary formation of $PM_{0.1}$ through atmospheric reactions involving sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), ammonia ($NH_3$), and volatile organics plays a considerable role. The combination of high solar radiation, stagnant air conditions, and urban heat islands enhances these photochemical processes, particularly in Lahore and Islamabad.

### 2.2. Assessment and Measurement Limitations

The scientific assessment of $PM_{0.1}$ in Pakistan remains highly limited due to the absence of dedicated monitoring networks and standardised measurement protocols [14]. While $PM_{2.5}$ is monitored intermittently by the Pakistan Environmental Protection Agency (Pak-EPA) and some universities, ultrafine particle number concentrations are rarely reported [15],[7]. Only a few research studies, mostly pilot investigations, have used condensation particle counters (CPCs) or scanning mobility particle sizers (SMPS) in Karachi, Lahore, and Islamabad to characterise $PM_{0.1}$ levels.

Results from these isolated studies indicate that $PM_{0.1}$ concentrations in Pakistan's urban areas often exceed those observed in developed countries by an order of magnitude. For example, mean UFP concentrations of $1–3\times10^5$ particles/cm$^3$ have been reported in traffic-dominated zones of Lahore, while background levels remain above $5\times10^4$ particles/cm$^3$ even during low-traffic hours [16]. However, data remain fragmented, short-term, and largely non-comparable due to inconsistencies in sampling duration, instrumentation, and meteorological adjustments.

Another critical limitation lies in the lack of chemical characterisation. Most studies measure total particle number or mass without identifying elemental composition or toxicity profiles. Consequently, the relative contributions of metals, organic carbon, and secondary aerosols remain uncertain. Without such data, it is challenging to develop source apportionment models or to evaluate specific mitigation strategies.

### 2.3. Health Effects of $PM_{0.1}$ Exposure

The health effects of $PM_{0.1}$ are increasingly recognised as severe, with both epidemiological and toxicological studies linking exposure to cardiovascular, respiratory, and neurological disorders. Due to their nanoscale size, $PM_{0.1}$ particles can bypass the mucociliary clearance system, penetrate alveolar membranes, and enter systemic circulation. Once in the bloodstream, they induce oxidative stress, inflammation, and endothelial dysfunction, leading to hypertension, atherosclerosis, and other cardiovascular complications [2],[6].

Inhalation of ultrafine particles has also been associated with reduced lung function, asthma exacerbation, and chronic obstructive pulmonary disease (COPD). Neurological studies suggest potential associations between $PM_{0.1}$ exposure and cognitive decline, neurodegenerative disorders, and altered neurotransmitter regulation. Maternal exposure may affect fetal development, contributing to low birth weight and developmental impairments.

In Pakistan, where baseline exposure to ambient air pollution is already high, these health effects are likely exacerbated. However, no large-scale epidemiological studies have specifically evaluated $PM_{0.1}$-related health outcomes. Public health assessments continue to rely on $PM_{2.5}$-based dose-response relationships, which may underestimate the actual risk. The absence of hospital-based exposure tracking, combined with inadequate medical data integration, hinders the quantification of health burdens attributable to ultrafine particles.

### 2.4. Policy, Research and Institutional Gaps

Pakistan's air quality management system faces multiple structural deficiencies. The National Environmental Quality Standards (NEQS) currently define permissible limits for $PM_{10}$ and $PM_{2.5}$ only, with no reference to ultrafine fractions [17]. This omission stems from limited scientific awareness and technical capacity. Moreover, real-time monitoring infrastructure remains inadequate

few continuous air monitoring stations existing, and most lack the sensitivity to detect $PM_{0.1}$.

At the institutional level, coordination among federal, provincial and municipal agencies is weak. While the Clean Air Program and National Climate Change Policy acknowledge particulate pollution, they do not specifically address $PM_{0.1}$. Academic research on ultrafine particles is restricted to small-scale university projects, often unsupported by long-term funding or national datasets. International collaborations remain sporadic, and there is no centralised database for air quality data integration.

### 2.4. Toward an Integrated Approach

To address $PM_{0.1}$ pollution effectively, Pakistan must adopt a multi-pronged approach integrating technology, policy, and public engagement. Establishing a national ultrafine particle monitoring network using advanced instruments such as CPCs, SMPS, and aerosol mass spectrometers is essential. Data from such networks should inform the revision of NEQS to include $PM_{0.1}$ concentration limits and exposure guidelines.

On the mitigation front, strict vehicular emission standards, phasing out of old vehicles, and promotion of electric mobility could substantially reduce UFP emissions. Industrial modernisation, particularly the replacement of traditional brick kilns with zigzag technology and the adoption of cleaner fuels, should be prioritised. Rural energy transitions such as biogas and solar-based cooking systems would alleviate domestic ultrafine particle exposure.

Furthermore, public awareness campaigns and health advisories should communicate the risks associated with ultrafine particles. Academic institutions should be encouraged to develop interdisciplinary research programs that link environmental science, toxicology, and epidemiology. International partnerships with institutions experienced in UFP assessment (e.g., in Japan, Europe, and the U.S.) could accelerate knowledge transfer and technical training.

## 3. Conclusion

$PM_{0.1}$ pollution in Pakistan represents a critical yet largely overlooked environmental and public health issue. The limited evidence available indicates that ultrafine particle concentrations in major urban centres such as Lahore, Karachi, and Islamabad far exceed global safety limits, driven by vehicular emissions, industrial combustion, and biomass burning. Owing to their nanoscale size and high surface reactivity, these particles can penetrate deep into the lungs and enter systemic circulation, causing oxidative stress, inflammation, and multi-organ toxicity. However, the absence of standardised monitoring systems, comprehensive chemical characterisation, and health-focused studies severely restricts understanding of their true impact. To mitigate this emerging threat, Pakistan must urgently integrate $PM_{0.1}$ into its national air quality standards, establish advanced monitoring infrastructure, and promote cleaner technologies across transportation, industry, and domestic sectors. A coordinated approach combining scientific research, policy reform, and public awareness is essential to protect population health and ensure sustainable environmental management.

## Declaration

**Competing Interests:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Ethical Issues:** There are no ethical issues. All data in this paper is publicly available.

**Author Contribution Statement:** F.I., R.A., S.A. and R.Z conceived the idea and designed the research; Analysed and interpreted the data and wrote the paper.

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