



Distribution of Bioaerosols in Association With Particulate Matter: A Review on Emerging Public Health Threat in Asian Megacities

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OPEN ACCESS

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Specialty section:

This article was submitted to
Toxicology, Pollution and the
Environment,
a section of the journal
Frontiers in Environmental Science

Received: 21 April 2021

Accepted: 26 July 2021

Published: 20 August 2021

Citation:

Shammi M, Rahman MM and
Tareq SM (2021) Distribution of
Bioaerosols in Association With
Particulate Matter: A Review on
Emerging Public Health Threat in
Asian Megacities.
Front. Environ. Sci. 9:698215.
doi: 10.3389/fenvs.2021.698215

Occurrences and exposure to high levels of microbial bioaerosols such as pathogenic bacteria, fungi, fungal spores, and viruses can be linked to the deterioration of the environment and public health. This study aimed to review the results available for the unusual bioaerosol distribution scenario in the Asian regions. The amount of bioaerosol load and their environmental behavior in the atmosphere is heavily influenced by air pollution such as haze, fog, dust, and particulate matter (PM) and thus strongly affect the air quality index (AQI). Human factors such as heavy traffic, overcrowds, and biomass burning also affected the prevalence or occurrences of bioaerosols in the atmosphere. Seasonal/temporal and diurnal variation was significantly observed from these studies and in the case of South Asia, post-monsoon and winter months were incredibly concentrated with pathogenic bioaerosols. Many human infections, for example, pneumonia, tuberculosis, brucellosis, anthrax, and query fever (Q-fever), are linked to pathogenic bacterial bioaerosols. Respiratory diseases such as asthma and chronic pulmonary obstructiveness are related to fungal bioaerosols, spores, and viral infections. To facilitate the testing and monitoring appraisal of airborne bioaerosols, artificial intelligence, deep neural networks, and machine learning can be used to develop real-time PCR-based bioaerosol sensors. Moreover, mobile apps and compatible electronic gadgets can be developed for the city dwellers to real-time monitor the concentration of bioaerosols in the air they are breathing.

Keywords: particulate matter, airborne bioaerosols, human health, PM_{2.5}, seasonal variation, inactivation

INTRODUCTION

In urban areas, global anthropogenic air pollution is pervasive (Groulx et al., 2018). The rapid urbanization, industrial activities, substantial energy consumption, and economic growth are indicated by a significant increase in traffic and the worsening air quality in the developing countries (Lu et al., 2018; Yan et al., 2019). High ambient particulate matter (PM) exposure can be responsible for unintended human health effects (Lu et al., 2018). Repeated hazy days can be caused by fine particulate matter (PM_{2.5}) in China, and many other Asian megacities have caused substantial environmental and public health crises (Xie et al., 2018). Subsequently, World Air Quality Report 2019 stated the accretion of airborne PM and its atmospheric and environmental

disturbances around the Asian and South Asian countries (IQAir 2020). Yet in 2020, lockdown actions to reduce COVID-19 pandemic across many Asian megacities have resulted in a substantial shift in air pollution.

When a consortium of airborne microorganisms of numerous sizes and types are present in the air in association with PMs, it is called airborne particles or bioaerosols (Caruana, 2011). It combines solids and semi-solids material in association with biotic and abiotic pieces with sizes ranging from 0.001 nm to 100 μm (Humbal et al., 2018). Bioaerosols may comprise 15–25% of PM by mass combined with living or dead bacteria, fungi, viruses, secondary metabolites, pollens, and dust (Ghosh et al., 2015; Samake et al., 2017). The study of airborne bioaerosols has gained significant interest in recent years (Fatahinia et al., 2018). Bioaerosols can result in infectious diseases, respiratory and chronic health issues (Valdez-Castillo and Arriaga 2021). Considering the recent COVID-19 pandemic, bioaerosols might have a significant role to play in the transmission of coronavirus (Noorimotlagh et al., 2020). A growing quantity of data implying that the airborne microbial portion of the particulate matter is responsible for critically escalating adverse effects on public health (Gandolfi et al., 2013).

Bacteria contribute significantly to the occurrence and composition of airborne aerosols formed by seasonal changes induced by the atmospheric and local terrestrial environment (Bowers et al., 2012). Furthermore, concentrations of cultured bacteria and fungi showed a strong connection to the AQI. When AQI <200, the concentration of airborne fungi gradually increased while AQI >200 increased airborne bacteria (Yan et al., 2019). Chemical composition, along with microbiological compositions, is significant in identifying the relationships between PM and AQI and, thus, the microorganism residing in them (Gandolfi et al., 2013). However, the question is why bioaerosols increase with air pollution remaining unclear. One hypothesis may be that high or extreme pollution levels primarily affect the diversity and composition of bioaerosols (Fan et al., 2019). The viability of the microbes in the bioaerosols depends on the surrounding environment, climate, and atmospheric chemistry, in conjunction with microbial concentrations (Gong et al., 2020). Therefore, knowing the microbiological structure and composition of PM is necessary to identify the mode of disease transmission and the possible human health impact (Wang et al., 2019). South Asia and many other Asian megacities are currently undergoing rapid development in urban and industrial sectors and eventually deteriorating the air quality. Thus, this review aims to identify bioaerosols in relationship with PM reported from Asian megacities and their impact on human health.

REVIEW METHODOLOGY

Electronic databases (PubMed central) and grey literature (Google Scholar) and bibliographies were searched for studies reporting bioaerosols and PM in Asian cities from 2010 to 2021. From the Pubmed and Google Scholar search, articles were

exported to Endnote and indexed. Duplicates were removed. The exclusion has been rendered in two phases: title and summary, then complete text using Ryaan (<https://rayyan.qcri.org/>). Two reviewers checked both abstracts and titles. An independent review by two authors had reported more inconsistencies. Full-text copies were then retrieved for inclusion in the study and likewise reviewed.

BIOAEROSOL RESEARCH IN THE ENVIRONMENT OF ASIAN MEGACITIES

Bioaerosols play a significant role in the earth's environment by interacting with the atmosphere, biosphere, micro-climate, and human health (Fröhlich-Nowoisky et al., 2016). While airborne microorganisms are omnipresent in the ambient near-surface, the spatiotemporal shifting aspects of their communities vary due to anthropogenic activities (Bowers et al., 2012). The exchanges may shape the variation of airborne microbes with the surrounding matrix of particles such as topsoils, soots, and dust that might inhibit or strengthen environmental growth and potency (e.g., resistance to alteration in seasonal and ecological parameters, temperature, humidity, and others.) (Groulx et al., 2018). The level of atmospheric pollutants impacts the entire structure of the bacterial community, including bacterial pathogens and ammonia-oxidizing microorganisms, than fungi (Fan et al., 2019). The prevailing harsh environment of minimal nutrition, dryness, and severe radiative heat in the ambiance and seasonal variations in the concentration of air pollutants shapes the community composition of microbes (Fan et al., 2019; Wei et al., 2019). PM and bioaerosols can both modify the oxidative capability of the harmful compounds and their toxicity present therein (Samake et al., 2017). The contribution of PM and airborne bioaerosols are, therefore, intrinsically interlinked. **Table 1** indicates the list of research done in Asian cities' outdoor environments identified from 2010 to 2020. Approximately 54% of studies found were conducted in China, followed by India and Japan.

Detection of Airborne Bioaerosols

Detection and recognition of natural bioaerosols is an analytic task that requires many approaches (Caruana, 2011). The extreme-low biomass nature of the atmosphere represents an inherent analytical challenge confounded by temporal fluctuations in community structure (Luhung et al., 2021). Consequently, environmental sampling and quantitative analysis of bioaerosols are conducted using several fundamental and applied technical disciplines that vary from microbial plating, physical-chemical assays, molecular techniques, etc., each having individual targets, expectations, and terminology (Šantl et al., 2019; King et al., 2020). Bioaerosols can vary spatially and temporally depending on the air pollution level, PM, AQI, dust storms, haze or fogs, aerodynamics, social gatherings, and crowding and pollution source such as biomass burning. The development of standardized methods for detecting and quantitating bioaerosols has become an important issue (King et al., 2020).

TABLE 1 | Types of airborne bioaerosols studied from outdoor environments from Asian cities.

Author	Year	City	Country	Airborne bioaerosols
1. Li et al.	2011	Qingdao	China	Total bioaerosol concentration
2. Dong et al.	2016	Qingdao	China	Total bioaerosol concentration
3. Gao et al.	2016	Beijing	China	Total bioaerosol concentration
4. Gao et al.	2015	Beijing	China	Bacteria and fungi
5. Li et al.	2018	Beijing	China	Airborne Bacterial Concentration (C_{ab})
6. Liu et al.	2018	Hangzhou	China	Pathogenic bacteria
7. Lu et al.	2018	Xi'an	China	Pathogenic bacteria
8. Ye et al.	2016	Hangzhou	China	Respiratory syncytial virus (RSV)
9. Yan et al.	2019	Xinxiang	China	Bacteria, fungi
10. Zeng et al.	2019	Hubei	China	Fungi
11. Wei et al.	2019	Mount Tai, North China Plain	China	Bacteria, fungi
12. Wang et al.	2019	Beijing	China	Bacteria
13. Fan et al.	2019	Beijing	China	Bacteria and fungi and ammonia-oxidizing microorganisms
14. Gong et al.	2020	Qingdao	China	Atmospheric bacterial bioaerosols under AQI
15. Yoo et al.	2019	Seoul	Korea	Bacteria
16. Madhwal et al.	2020	Dehradun city	India	Bacteria and Fungi conc.
17. Priyamvada et al.	2017	Chennai	India	Fungi
18. Rajput et al.	2017	Indo-Gangetic Plain (IGP; at Kanpur)	India	Bacteria, Fungi
19. Yadav et al.	2013	Gwalior	India	Bacteria
20. Amarloeia et al.	2020	Ilam City	Iran	Bacteria
21. Fatahinia et al.	2018	Ahvaz, Khuzestan province	Iran	Fungi
22. Kobayashi et al.	2015	Noto Peninsula	Japan	Bacteria
23. Khan et al.	2018	Kyoto	Japan	airborne particle, protein, and endotoxin
24. Park et al.	2018	Beijing and Osaka	China and Japan	Bacteria
25. Kallawicha et al.	2015	Greater Taipei area	Taiwan	Fungal spores
26. Luhung et al.	2021	Singapore	Singapore	Bacteria and Fungi

Broadly defined, the sampling of bioaerosols and particulate matters is simultaneously done using particle counters, dust collectors, high-volume air sampler with filters or impactors, aerosol samplers, and total suspended particulate (TSP) sampler with filters. **Table 2** displays various environmental surveillance of bioaerosols associated with particulate matters and other airborne pathogens. The benefit of passive sampling using electrostatic dust fall collectors (EDCs) increases the sampling period for a long time (Liebers et al., 2012). The cyclonic aerosol sampler was efficient for collecting bacterial samples, while the filter-type showed similar efficacy in collecting airborne fungal samples. Each has a different level of efficiency for sampling a sizable sum of microbes. Filter samplers operate under low temperatures, whereas cyclonic aerosol samplers have a temperature limit during the sampling period. Wang et al. (2019) showed that the cyclonic aerosol sampler was more efficient in collecting more genera than the high-volume air sampler with filters.

The cultured and non-cultured-based methods can estimate airborne bioaerosols by different samplers. Culturable airborne microbes can be identified by colony-forming units (CFU/m³) by plate counts or microscopes. However, over 99% of airborne microbes in bioaerosols collected by different methods are not culturable. For example, Wang et al. (2019) identified five airborne bioaerosol methods and particulate matter detection that identifies concentration and size. Among the five techniques, Andersen's six-stage impactor device or sampler can collect culturable bacteria and fungi in the air where the aerodynamic diameter varies between >0.7 and 10 μm (Yadav et al., 2015; Yan et al., 2019). Andersen's six-stage impactor device is a culture-

based approach that enhances the survival rate of culturable microorganisms (Wang et al., 2019).

Biological composition analysis of bioaerosol samples can be performed by molecular methods of bacterial 16S ribosomal DNA and fungal internal transcribed spacer region sequence, respectively, instead of microorganism culture (Wang et al., 2019; Luhung et al., 2021). Furthermore, PCR, quantitative/real-time PCR, reveals microbial cell numbers instead of total bacterial count assessment (Wei et al., 2019). In addition, it is essential to identify a device or method for on-site real-time-air sampling of bioaerosols. Many potential respiratory diseases can be prevented and deactivated by such devices. An automated bioaerosol-monitoring system developed by Cho et al. (2020) can provide a continuous real-time monitoring system with significant sensitivity. It uses a combination of units such as a wet-cyclone bioaerosol sampler, a thermal-lysis unit for extracting adenosine triphosphate (ATP), and an ATP-detection unit based on the immobilization of luciferase/luciferin for bioluminescence reactions, and a photomultiplier tube-based detector. The bioaerosol concentration reported from different studies with the declared variables is given in **Table 3**. The types of bioaerosols such as bacterial, fungal, and virus bioaerosols are discussed in the following subsections.

Bacterial Bioaerosols

Bacterial bioaerosols significantly change atmospheric chemistry and impact human health (Gong et al., 2020). The highest bacterial abundances, rates, and relative bacterial contributions to total aerosol loads are typically observed during the autumn and spring. This variability in bacterial cells represents a

TABLE 2 | Methods of bioaerosol collection from air particulate matter identified from this review.

Methods	Type and size of PM and bioaerosol along with other parameters	References
Bioaerosol sampling monitoring		
1. Laser particle counter	0.3–0.5 μm , 0.5–0.7 μm , 0.7–2.5 μm , 2.5–5 μm , 5–10 μm and >10 μm .	Wang et al. (2019)
2. Optical total and viable Particles Counter	Also measured temperature and relative humidity 0.5–25 μm ; Inorganic and organic particles. Viable particles are then determined by autofluorescent detection	(Soret et al., 2018)
3. Environmental dust collector	2.5–10 μm	Amarloei et al. (2020)
4. High-volume air sampler with filters	0.5–10 μm	Dong et al. (2016), Rajput et al. (2017), Fatahinia et al. (2018), Li et al. (2018), Liu et al. (2018), Lu et al. (2018), Fan et al. (2019), Wang et al. (2019), Xu et al. (2019), Zeng et al. (2019), Luhung et al. (2021)
5. Cyclonic aerosol sampler	0.3–0.5 μm , 0.5–0.7 μm , 0.7–2.5 μm , 2.5–5 μm , 5–10 μm and >10 μm .	Wang et al. (2019)
6. High-volume air sampler equipped with an impactor	$\leq 2.5 \mu\text{m}$ - $\geq 2.5 \mu\text{m}$; Temperature, Relative humidity, Wind speed, Air pressure. >0.6 μm	Rajput et al. (2017), Khan et al. (2018)
7. Total suspended particulate (TSP) sampler with filters	Six size groups: >7.0, 4.7–7.0, 3.3–4.7, 2.1–3.3, 1.1–2.1, and 0.65–1.1 μm ; 10 μm	Dong et al. (2016), Yoo et al. (2019)
Cultured Methods		
1. Bioaerosol sampling by Andersen six-stage impactor type sampler/Impactor type sampler/six-stage culturable microorganism FA-1 cascade impactors/SKC Quick Take	>10 to <1.0 μm .	Li et al. (2011), Gao et al. (2015), Yadav et al. (2015), Dong et al. (2016), Gao et al. (2016), Wang et al. (2019), Yan et al. (2019), Amarloei et al. (2020), Madhwal et al. (2020)
2. Culturable microbes Colony-forming units (CFU/m ³) for bioaerosols	2.5–10 μm , humidity, temperature, O ₃ , SO _x , NO _x ; dust particles, fungi, bacteria	Li et al. (2011), Gao et al. (2015), Yadav et al. (2015), Gao et al. (2016), Uk Lee et al. (2016), Rajput et al. (2017), Fatahinia et al. (2018), Yan et al. (2019), Madhwal et al. (2020)
Non-cultured methods for bioaerosol compositional analysis		
1. Bacterial 16SrDNA and fungal ITS region sequencing for bioaerosol composition; DNA extraction and high-throughput sequencing to identify bioaerosol types/RT-PCR/the quantitative PCR (qPCR)	1.0–2.5 μm	Kobayashi et al. (2015), Priyamvada et al. (2017), Fatahinia et al. (2018), Li et al. (2018), Liu et al. (2018), Lu et al. (2018), Park et al. (2018), Fan et al. (2019), Wang et al. (2019), Wei et al. (2019), Yoo et al. (2019), Zeng et al. (2019), Luhung et al. (2021).
2. Fungal spore count under a microscope	$\leq 10 \mu\text{m}$	Kallawicha et al. (2015)
3. D3 Ultra DFA Respiratory Virus Screening and ID kit	2.5–10 μm	Ye et al. (2016)
Other methods		
1. Automated, continuous, and real-time monitoring of bioaerosols in real environments	ATP-based-detection unit, size not mentioned	Cho et al. (2020)
2. Atmospheric bioaerosol sampling apparatus used with the airplane	2900 m altitude; Aerosol size not mentioned	Kobayashi et al. (2015)

significant fraction (22% on average) of overall variations in PM concentrations of the near-surface aerosol particles of >0.5 μm . The massive- or severe-pollution levels vastly altered bacterial structure (Fan et al., 2019). For example, Li et al. (2018) reported enrichment of pathogenic bacteria *Halomonas* and *Shewanella* on hazy days in Beijing, particularly in the autumn and early winters.

Airborne bacteria principally occurred in the particles larger than 2.1 μm along with the total bioaerosols concentration, identified in Qingdao coastal region, China (Li et al., 2011) (Table 4). From massive traffic junctions of Dehradun city, India, airborne *Micrococcus*, *Staphylococcus*, and *Bacillus* bacterial species were identified in the percentage of 25.73,

17.98, and 13.8%, respectively (Madhwal et al., 2020). Furthermore, methicillin-resistant staphylococci (MRS) *S. aureus* (MRSA), coagulase-negative staphylococci (CNS) were identified in the airborne bioaerosols from India associated with global environmental health (Kumar and Goel, 2016).

Fungal Bioaerosols and Spores

Quantitative assessments of fungi and their spores in bioaerosols are crucial to comprehend human respiratory diseases in densely populated developing countries. The climatological parameters significantly control fungal bioaerosols load in the atmosphere, including ambient temperature, humidity content, precipitation,

TABLE 3 | Bioaerosol concentration reported from different studies with the reported variables.

Total bioaerosol concentration	Bioaerosol concentration (CFU/m ³)	Variables	References
-	125.98 ± 107.78	Non-dusty days	Amarloei et al. (2020)
-	495.95 ± 427.51	Dusty days	
85,015–166,094 (Cells/m ³)	Terrestrial bacteria 33–664 Marine bacteria 63–815 Terrestrial fungi 2–777 Marine fungi 66–1,128	Monthly variations for 1 year	Li et al. (2011)
-	Bacteria 5,035	Hazy days	Gao et al. (2015)
-	Fungi 7,208		
-	Bacteria 129	Non-hazy days	
-	Fungi 117		
6,55,000 (Cells/m ³)	-	Non-hazy days	Dong et al. (2016)
7,09,000 (Cells/m ³)	-	Hazy days	
9,00,000 (Cells/m ³)	-	Foggy days	
-	Bacteria 1962.95 ± 651.85	High traffic density	Madhwal et al. (2020)
-	Fungi 1,118.95 ± 428.34		
-	Bacteria 80–5,800	Airborne bacteria and fungi	Gao et al. (2016)
-	Fungi 41–7,210		
-	Bacteria 277 ± 267	Particulate bacteria and fungi on PM _{2.5}	
-	Fungi 404 ± 511		
-	Bacteria 4595 ± 3,410	Winter	Yan et al. (2019)
-	Fungi 6,358 ± 5,032		
-	Fungi 929	Autumn	Fatahinia et al. (2018)
-	Fungi 311	Spring	
4,729.63 ± 3,387.46 (Spores/m ³)	Fungal spore	Spring	Kallawicha et al. (2015)
4,422.20 ± 4,235.73 (Spores/m ³)	Fungal spore	Summer	
386.31 ± 399.44 (Spores/m ³)	Fungal spore	Winter	
347.31 ± 505.57 (Spores/m ³)	Fungal spore	Fall	
5,41,000 (Cells/m ³)	Bacterial concentration	Clean days	Li et al. (2018)
11,70,000 (Cells/m ³)	Bacterial concentration	Slightly polluted	
20,60,000 (Cells/m ³)	Bacterial concentration	Haze days yellow	
18,50,000 (Cells/m ³)	Bacterial concentration	Haze days orange	
20,50,000 (Cells/m ³)	Bacterial concentration	Haze days red	
77,000–16,000,000 (Cells/m ³)	Bacterial concentration	Air pollution	Liu et al. (2018)
1,57,000 ± 0.68 (Cells/m ³)	Bioaerosol concentration in PM _{2.5}	Non-hazy days	Lu et al. (2018)
4,69,000 ± 2.08 (Cells/m ³)		Hazy days	
20,3000 ± 0.79 (Cells/m ³)	Bioaerosol concentration in PM ₁₀	Non-hazy days	
6,65,000 ± 2.74 (Cells/m ³)		Hazy days	
26,0000 ± 0.69 (Cells/m ³)	Bioaerosol concentration in TSP	Non-hazy days	
10,57,000 ± 4.23 (Cells/m ³)		Hazy days	
40,000 ± 3 (Cells/m ³)	The spatial distance of bioaerosol concentration	Asian dust events in Beijing	Park et al. (2018)
1,000 ± 0.5 (Cells/m ³)		Non-Asian dust days in Beijing	
10,000 ± 0.5 (Cells/m ³)		Asian dust events in Osaka	
1,000 ± 0.5 (Cells/m ³)		Non-Asian dust days in Osaka	
-	189 in December-January	Gram-positive bacteria (GPB) in biomass burning	Rajput et al. (2017)
-	244 in November	Gram-negative bacteria (GNB) in biomass burning	
-	188 in September	Fungi in biomass burning	
1.26×10 ⁴ Cells/m ³	Bacteria on PM _{1.0}	Biomass burning during crop harvest	Wei et al. (2019)
2.77×10 ⁴ Cells/m ³	Bacteria on PM _{2.5}		
3.38×10 ³ Cells/m ³	Fungi on PM _{1.0}		
5.75×10 ³ Cells/m ³	Fungi on PM _{2.5}		

wind directions, and speed (Li et al., 2011; Priyamvada et al., 2017). Diurnal variation, presence of haze days in winter significantly affects the mycological population in PM_{2.5} samples. DNA proportion of fungi in the PM_{2.5} (R_{D/P}) altered air quality and demonstrated a substantial adverse correlation with PM_{2.5} and temperature. Moreover, the fungal species richness of night samples was more significant than the day samples [119–537 > 71–198 OTUs (operational taxonomic units)]. Subsequently, the night-sample accounted for enriched fungal taxa compared to the day samples (29 taxa >9 taxa).

Likewise, haze periods also affected species richness significantly, with 198 OTUs before haze incidence compared to the 76 OTUs after haze incidence. Moreover, 8.6% of the entire fungal population was pathogenic (Zeng et al., 2019).

Fatahinia et al. (2018) identified 1,240 fungal colonies of 24 genera from the atmospheric bioaerosols of Ahvaz, Iran. The humid environment registered for many airborne fungi (32.3%) than the industrial atmosphere (17%). Priyamvada et al. (2017) identified three fungal species from the ambient PM₁₀ from tropical city Chennai, India, which were the most dominant

TABLE 4 | Pathogenic bacterial and fungal genus and species detected in PM and dust samples.

Bioaerosols sampled	Genus	Pathogenic species	References
Bacteria from PM	<i>Bacillus</i> <i>Burkholderia</i> <i>Clostridium</i> <i>Corynebacterium</i> <i>Enterobacter</i> <i>Enterococcus</i> <i>Haemophilus</i> <i>Klebsiella</i> <i>Legionella</i> <i>Mycobacterium</i> <i>Nocardia</i> <i>Pseudomonas</i> <i>Staphylococcus</i> <i>Stenotrophomonas</i> <i>Streptococcus</i> <i>Vibrio</i>	<i>anthracis</i> <i>cepacia</i> <i>botulinum, baratii, perfringens, tetani</i> <i>diphtheriae</i> <i>aerogenes</i> <i>faecium, faecalis</i> <i>influenzae</i> <i>pneumoniae, oxytoca</i> <i>longbeachae</i> <i>scrofulaceum</i> <i>brasiliensis</i> <i>aeruginosa</i> <i>haemolyticus, saprophyticus</i> <i>maltophilia</i> <i>pneumoniae, pyogenes</i> <i>cholerae</i>	Liu et al. (2018)
Bacteria from AD events	<i>Staphylococcus</i> <i>Cryptococcus</i> <i>Corynebacterium</i> <i>Bacillus</i> <i>Actinosynnema</i> <i>Nocardioides</i> <i>Arthrobacter</i> <i>Flavimonas</i> <i>Paenibacillus</i> <i>Pseudomonas</i> <i>Microbacterium</i> <i>Planococcus</i> <i>Streptomyces</i> <i>Kurthia</i> <i>Neisseria</i> <i>Agrococcus</i> <i>Curtobacterium</i> <i>Duganella</i> <i>Ancylobacter</i> <i>Paracoccus</i> <i>Propionibacterium, Pseudomonas</i> <i>Rhizobium</i> <i>Enterococci</i>	Not mentioned	Amarloei et al. (2020)
Fungi from dust storms	<i>Cladosporium</i> spp. (37.1%) <i>Alternaria</i> spp. (25.7%) <i>Aspergillus</i> spp. (13.5%) <i>Penicillium</i> spp. (5.9%) <i>Drechslera</i> spp. (3.46%) <i>Stemphylium</i> spp. (3.46%)	Not mentioned	Fatahinia et al. (2018)
Fungi from PM	<i>Aspergillus</i> <i>Cladosporium</i> <i>Alternaria</i>	<i>fumigatus</i> <i>cladosporioides</i> <i>alternata</i>	Priyamvada et al. (2017)
Fungi from road junctions PM	<i>Aspergillus</i> (27.58%) <i>Penicillium</i> (23%) <i>Cladosporium</i> (14.05%)	Not mentioned	Madhwal et al. (2020)
Fungal spores from PM	<i>Aspergillus</i> <i>Penicillium basidiospores</i> <i>Cladosporium</i>	Not mentioned	Kallawicha et al. (2015)

allergenic fungi. Likewise, from the massive traffic junctions, Madhwal et al. (2020) also identified those genera from India (Table 4).

Airborne fungal spores are another bioaerosol in which peak concentrations were found in spring, followed by summer, winter, and autumn, respectively (Table 4). Ascospores were

the highly dominant class identified from Taipei, Taiwan. The concentrations of *Aspergillus/Penicillium* spores were prevalent in the residential or commercial areas, whereas *basidiospores* were dominant in regions with shorter road lengths (Table 4) (Kallawicha et al., 2015). It is crucial to carry out the ecological diagnosis of respiratory symptoms caused by

the breathing of fungi and fungal spores in any metropolitan area (Fatahinia et al., 2018). However, considering the public health issues, this type of study is entirely inadequate to perceive the actual human health threat from fungal bioaerosol in Asian cities.

Viruses in Bioaerosols

Airborne viral stability and infectivity may be associated with the interaction with pollutants such as PM and may have public health implications for communicable infectious diseases. Ambient PM ($PM_{2.5}$) in the polluted air interact with viral aerosols and alter their infectivity (Groulx et al., 2018). It is, therefore, perceivable that the threat of viral toxicity has been heightened considerably by the presence of PM. In their study, Groulx et al. (2018) further showed that when $PM_{2.5}$ is treated with high-efficiency particulate air (HEPA)-filter, the infectivity of a specific virus is reduced.

The respiratory syncytial virus (RSV) is an airborne viral infection that showed an infection rate concerning PM. Dose-response, lag-time, cumulative effects of RSV infection positively correlated to the PM concentrations from January-May and October-December throughout the study period (Ye et al., 2016). RSV infection among infants and kids was positively correlated to atmospheric temperature and AQI (Ye et al., 2016). Very recently, it is proved that infective microdroplets ($>5-10\ \mu\text{m}$) and aerosols ($\leq 5\ \mu\text{m}$) of coronavirus in air-suspension can expose individuals as far as 2 m from the COVID-19 infected person (Guzman 2020; Morawska and Milton 2020; Prather et al., 2020a; Prather et al., 2020b). The airborne SARS-CoV-2 virus can stay longer in the atmosphere in bioaerosols and on inanimate objects increasing transmission to other people's hands and noses. The study already reported that the COVID-19 could survive on any inert surface for several hours to days (Kampf et al., 2020). There is a suspicion that pollen bioaerosols can also affect coronavirus survival (Khailwal et al., 2021). Data analysis on SARS-CoV-2 infection, airborne pollen, and meteorological factors such as humidity and temperature from 130 sites and 31 countries showed 44% infection rate variability (Damialis et al., 2021). Considering the recent incidence of coronavirus (COVID-19) pandemics, it shows that under suitable environmental conditions, simultaneous or co-exposure to SARS-CoV-2 (*via* other infected human carriers) and airborne pollen might promote viral infection. Therefore, we must detect their seasonal patterns of pollens and airborne viruses, including COVID-19, based on environmental factors. However, the drastic mutating nature of the virus makes it difficult to predict which mechanisms and ecological parameters affect its growth and prevalence.

EFFECTS OF ENVIRONMENTAL PARAMETERS ON THE DISTRIBUTION OF BIOAEROSOLS

Different environmental variables like humidity, relative humidity, temperature, wind speed, wind direction, presence of sunlight, specifically UV light at day time and absence at night time, seasonal variations, presence of pollutants $PM_{2.5-10}$,

dust particles, along with the gases related to air quality, haze and fog, precipitation affect the concentration, structure, and taxonomy of bioaerosols. There is a strong seasonal correlation that increases bioaerosol loads in fall, early winter, spring, and PM ($r = 0.75$, $p < 0.001$) (Bowers et al., 2012). The ambient bioaerosols community structure, in turn, is being affected by the seasons and terrestrial environments (Bowers et al., 2012). It further affects the community structure of the indoor bioaerosols (Zhou et al., 2021). The microbial ecology of the atmospheric ecosystems is evident for this correlation, and the exploration requires in-depth analysis. In the following subsections, we have discussed these variables.

Bioaerosols in Association With PM

Many Asian megacities are seriously affected by particulate matter pollution such as $PM_{2.5}$, PM_{10} , and other air pollutants. COVID-19 lockdown resulted in a significant reduction in $PM_{2.5}$, PM_{10} , NO_2 , and CO in all the Indian regions (Singh et al., 2020). In Delhi, the concentrations of PM_{10} and $PM_{2.5}$ have observed a $>50\%$ decrease compared to the pre-lockdown period (Mahato et al., 2020). For $PM_{2.5}$, 40–70% reduction was observed during the first week of lockdown. However, O_3 pollution remained high during the lockdown due to non-linear chemistry and dynamics under low aerosol loading (Dhaka et al., 2020). In China, similar results were also observed. The AQI in the locked-down cities was reduced to 19.84 points. $PM_{2.5}$ was reduced by $14.07\ \mu\text{g m}^{-3}$. In cities without lockdown, AQI was brought down by 6.34 points ($PM_{2.5}$ down by $7.05\ \mu\text{g m}^{-3}$) compared to 2019 (He et al., 2020).

The increasing number of bacterial colonies correlated to the PM concentrations has been identified (Amarloei et al., 2020). $PM_{2.5}$ and PM_{10} are significant AQI that hosts a load of secondary pollutants, including airborne microorganisms. PM's physical and chemical composition positively correlates with bacteria, especially pathogenic bacteria (Liu et al., 2018).

Ammonia (NH_3) emission develops secondary inorganic aerosol with a dynamic relationship with the concentration of urban $PM_{2.5}$. The contribution of ammonia in $PM_{2.5}$ is often ignored and undervalued compared to SO_2 and NO_x (Wu et al., 2016). Fan et al. (2019) identified that ammonia-oxidizing microbes significantly cooccurred with the prevalent bacterial and fungal groups and potential pathogens. It further proves the role of ammonia in the development of $PM_{2.5}$. Therefore, managing ammonia emission means minimizing $PM_{2.5}$ pollution rather than other $PM_{2.5}$ precursors, SO_2 , and NO_x , for instance (Fan et al., 2019).

However, the stimuli of PM_{10} and temperature on bioaerosols contrasted with the hazing intensity (Gao et al., 2016). In winter, on heavy pollution days, hub bacteria in $PM_{2.5}$ were abundant. In contrast, on less-pollution days in winter, hub fungi were dominant (Fan et al., 2019). However, Li et al. (2018) informed that in autumn and early winter haze days in Beijing, PM_{10} and relative humidity were the main reasons to alter the airborne bacterial load and community structure substantially. During the summer heatwaves, the size distribution of bioaerosol became single-mode while on average sunny days, the particle sizes of the total microbes showed two sets of distribution with one skewing at

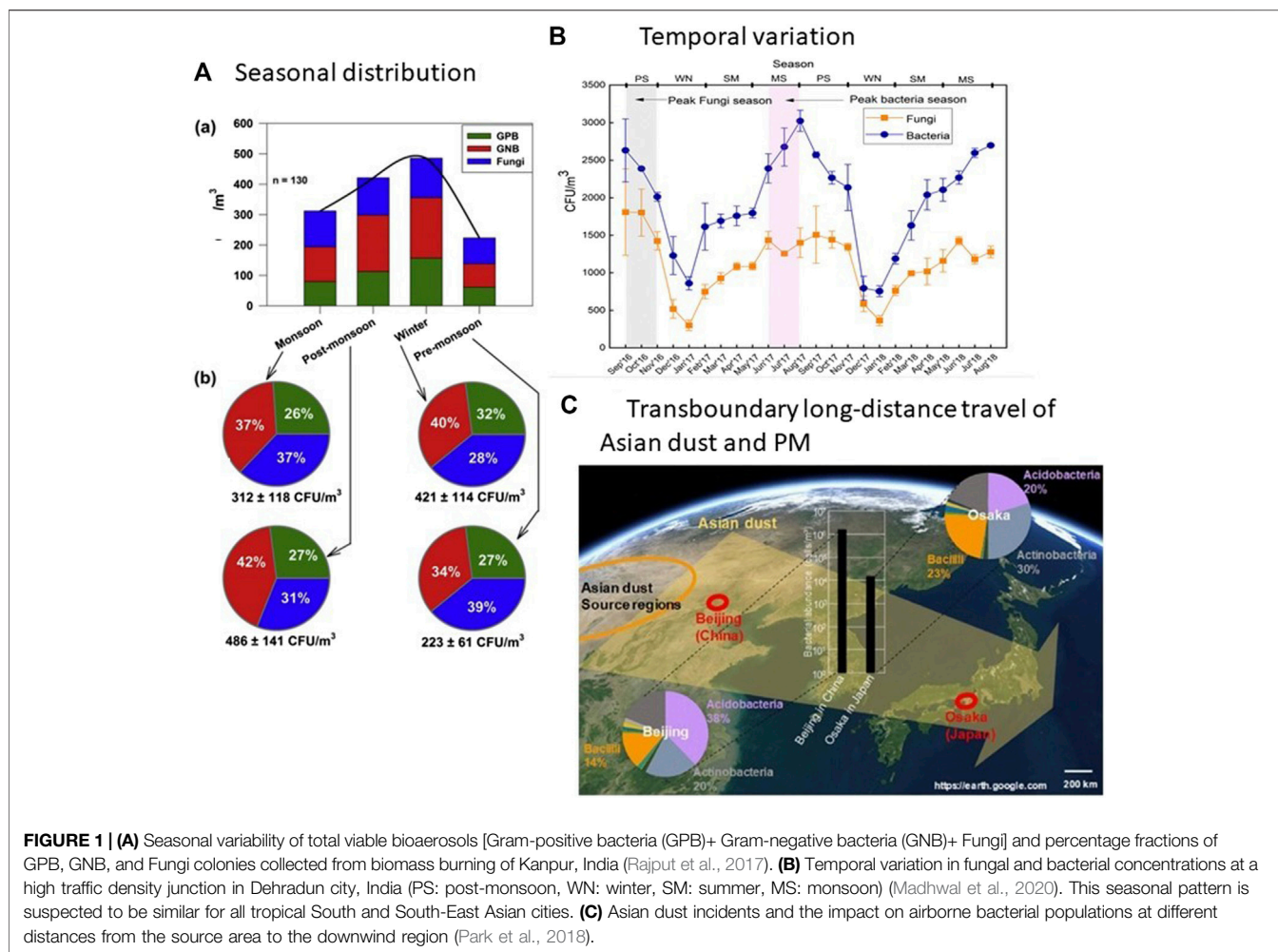


FIGURE 1 | (A) Seasonal variability of total viable bioaerosols [Gram-positive bacteria (GPB)+ Gram-negative bacteria (GNB)+ Fungi] and percentage fractions of GPB, GNB, and Fungi colonies collected from biomass burning of Kanpur, India (Rajput et al., 2017). **(B)** Temporal variation in fungal and bacterial concentrations at a high traffic density junction in Dehradun city, India (PS: post-monsoon, WN: winter, SM: summer, MS: monsoon) (Madhwal et al., 2020). This seasonal pattern is suspected to be similar for all tropical South and South-East Asian cities. **(C)** Asian dust incidents and the impact on airborne bacterial populations at different distances from the source area to the downwind region (Park et al., 2018).

1.1–2.1 μm and another at 4.7–7.0 μm (Dong et al., 2016) with average airborne fungi distributed towards 2.1–3.3 μm while bacteria skewed towards greater size (Gao et al., 2016). The tendency led to the development of a bigger size particle. Nevertheless, Lu et al. (2018) showed that the bacterial population structure in $\text{PM}_{2.5}$, PM_{10} , and total suspended particulate (TSP) did not vary much.

The overall characteristics depending on the load and size distribution of culturable airborne microbes are related to several environmental factors. The factors are AQI ($\text{PM}_{2.5-10}$), sampling times and seasons, diurnal temperature, relative humidity, dewpoints, wind pressure and speed, ground-level gases such as ozone, NO_x , and SO_x (Gao et al., 2016). Airborne microbe concentration had a substantial negative correlation with temperature and ozone concentration (Yan et al., 2019), while positive relationships with the AQI and ground-level SO_x , NO_x , CO concentration during the hazy days (Dong et al., 2016). Similar observations were found in the study of Yan et al. (2019). Gao et al. (2016) informed that the ratio of SO_x/NO_x showed a diurnal and chronological change in bioaerosol concentration (Gao et al., 2016). However, Lu et al. (2018) confirmed that atmospheric temperature, ozone, and NO_x

substantially affected bacterial communities compared to other atmospheric parameters (Liu et al., 2018; Lu et al., 2018). Consequently, the increased number of airborne microbes may affect the air quality on hazy days by different size distributions of bioaerosol (Liu et al., 2018; Fan et al., 2019), which might be abundant in pathogenic bacteria (Liu et al., 2018) mentioned in Table 4.

A Seasonal and Temporal Variation of Bioaerosols

The amount of bioaerosols present in winter and summer is comparable. For example, a study from the Seoul Metropolitan area confirmed significant fungal bioaerosols in winter compared to the very few bacterial bioaerosols (Uk Lee et al., 2016). Yan et al. (2019) further confirmed noteworthy differences in the concentration of culturable airborne bacteria and fungi in the winter season from Xinxiang, China (bacteria $4,595 \pm 3410 \text{ CFU/m}^3 >$ fungi $6,358 \pm 5032 \text{ CFU/m}^3$). Again, precipitation types (snowfall and rainfall) may have different effects on bioaerosols. Snowfall in winter seizes bioaerosols, while rains in summer aerosolize microbes from the ground into the air through

splashes and humidifying the immediate environments (Uk Lee et al., 2016).

Temperature affects the bacterial concentration while rainfall (1–4 mm) increases the fungal concentration in the environment (Rajput et al., 2017) (**Figure 1**). For tropical regions such as South Asia, the seasonal pattern of bioaerosol in the atmosphere is similar. During the monsoon and post-monsoon months, bacterial and fungal loads were the highest (Madhwal et al., 2020). Raindrop splashes caused microbial aerosolization on ground air and automobile movement, human microbial fluid from phlegm and coughs, lifted relative humidity in the air, and soil resuspension. Significant seasonality among the fungal bioaerosols in the tropical city of Chennai, India, was also confirmed (Priyamvada et al., 2017).

The maximum and minimum bioaerosol loads were documented at night time and mid-day, respectively, from the study of Yan et al. (2019). Temporal differences in bioaerosol explain the potential harms during hazy and non-hazy days as the UV radiation intensity varies (Gao et al., 2015). An example includes the rush-hour effect of PM₁₀ on bioaerosol varies at different times of the day. For instance, in the morning rush hour, 9:00 am, people go to work, while at midday, people could go for lunch outside. At approximately 6:00 pm, another rush hour occurs when people return home (Gao et al., 2016). Moreover, during rush hours, transport crossings are among the most populated locations where travelers are likely to acquire airborne and transmitted microbial pathogens due to increased exposure levels. Traffic/human-induced roadside dust resuspension and microbial aerosolization from commuters were the primary sources of bioaerosol emissions (Madhwal et al., 2020).

Effect of Haze Days Versus Non-haze Days on Bioaerosols

The presence of haze days varies bioaerosol loads in the atmosphere. The severity of haze days significantly impacts atmospheric bioaerosols composition and community structure (Li et al., 2018). The principal component analysis suggested that haze-level, sampling period, and seasons influence the bioaerosol sizes. Among hazy and non-hazy days, the size distribution of bioaerosols (Gao et al., 2016) and relative abundances of pathogenic bacteria rarely varied (Lu et al., 2018). Moreover, airborne bacteria inclined towards the larger particles, while airborne fungi showed a Gaussian distribution (Gao et al., 2015). Besides, total microbes increased in the finer portion on haze days, while on foggy days, it inclined towards coarse portions. As discussed in earlier sections that the microbial load was the sharpest in the winter and at a low level in the summer (Dong et al., 2016). However, Li et al. found a clear recurring association with the haze events and airborne bacterial load from Beijing in autumn and early winter (Li et al., 2018). Nevertheless, winter haze events can be a potential source of fungal bioaerosol infection risk, and people should be careful about these days (Zeng et al., 2019).

Bioaerosols in Association With Dust Storms and Asian Dust Events

Dust storms are a major global environmental problem, especially in Asian cities, due to high Asian monsoon variability. The deserts of the Middle East and Central and North East Asia are the primary sources of dust storm events in Asia. Dust from these areas can be distributed worldwide all year round with different concentrations and occurrences (Soleimani et al., 2020). Amarloei et al. (2020), from Ilam city, Iran, identified that increased dust storm events are correlated to the PM_{2.5} and PM₁₀ concentrations in the warm and dry months, subsequently increasing the bioaerosols. The chiefly detected bacterial colonies by Amarloei et al. (2020) isolated from AD events are given in **Table 4**. Asian dust events, also known as Kosa (Kobayashi et al., 2015), contain Aeolian dust particles. Aeolian dust is a crucial component impacting the atmosphere in dry and semiarid environments, which intimately affects the global biogeochemical and carbon cycle and energy exchange (Zhang et al., 2020). Aeolian dust particles are a critical media for the long-range transport of microorganisms (Maki et al., 2019). Usually, the bioaerosols are transported freely or attached to dust particles suspended in the atmosphere (Aalismail et al., 2020). Strong seasonal winds cause Aeolian dust from arid and semiarid Mongolia and northern China (Yoo et al., 2019). East Asian countries China, Japan, and Korea are disturbed mainly by Aeolian dust and the bioaerosols by air currents through the westerly winds (Kobayashi et al., 2015; Park et al., 2018). During the spring, the transit of air masses over continental and marine surfaces brings Kosa or Aeolian bioaerosols (Maki et al., 2019) that affect environments, public health, and agricultural production in the windward regions (Kobayashi et al., 2015).

Maki et al. (2019) reported that airborne bacterial diversity increased from the Chinese desert to the Japanese shore with dust scatterings and bacterial taxa, including desert microbial communities and pathogens related to humans and plants. During the travel of Aeolian air mass, it is also influenced by the local landforms, and microbial dispersal occurs even at high altitudes. The study further showed that on non-dust event days, the bioaerosols are usually dominated from the nearby shores.

Acute AD days raise bacterial richness 1000-fold times compared to the non-AD days. Prevalent bacterial phyla in the same AD dust events differed between regions. Aerosol bacterial communities closer to the dust origin region (Beijing, China) are altered by Aeolian dust highly than their outlying analogous areas (Osaka, Japan) is shown in **Figure 1C** (Park et al., 2018). As the 16S ribosomal RNA gene quantity increased, bacterial diversity expanded considerably into AD samples, and the PM₁₀ concentration was associated positively (Yoo et al., 2019). AD samples are usually abundant with the *Bacillus* species (almost 23.8%) than the non-AD models (almost 13.3%).

Effects of Aerodynamics and the Human Crowd on Bioaerosol

Aerodynamic size variation is a significant parameter in evaluating bioaerosol exposure during hazy and non-hazy days. The temporal variation of aerodynamic diameter (d_g) of microbial aerosol with $PM_{2.5}$ (AQI) varied from morning 9:00 to evening 21:00, suggesting their depositional pattern would fluctuate during a day (Gao et al., 2015). Moreover, climatological aspects, PM with d_g of $\leq 10 \mu m$, and altitude had sizable interactions per loads of fungal spore in the atmosphere (Kallawicha et al., 2015). Origin-tracking analysis by Lu et al. (2018) indicated that the airborne microbes could be transported to an entire city or region by airflow and aerodynamic characteristics.

The circulation of microbial aerosols associated with mass people such as fair, political meetings; religious gatherings is a less-researched area. A substantial number of airborne microbial aerosols were found throughout a trade fair period in central India contrasted to the no-fair period and no-fair sites. Furthermore, the antibiotic-resistant bacterial proportion was higher throughout the trade fair period and continued even after-fair period (Yadav et al., 2015). Considering the recent COVID-19 pandemic, the application of social distancing, home-isolation, and uses of face masks can decrease human transmission of the virus bioaerosols (Li et al., 2020).

Biomass Burning Effect on Bioaerosols

Biomass burning sources are firing grasslands, pine needles, forest woods, and hays during the harvest seasons. The crop harvest seasons are marked by open biomass burning and subsequently elevated $PM_{2.5}$ and other air pollutants. The broader range of particle-spectrum indicated growth of similar community structure for bacteria and fungi in $PM_{1.0}$ and $PM_{2.5}$ (Table 4) with a slight profusion in $PM_{2.5}$ (Wei et al., 2019). Biomass burning often originates locally or from cross-regional and transboundary airborne transportation by air masses. Urban haze days in Shanghai were traced from four regional transport sources: biomass burning (28%), pollen (25%), spores (24%), and emissions from fuel combustion (23%) (Li et al., 2016). In winter, biomass burning tracers peaked, while fungal spore tracers peaked in summer (Xu et al., 2019).

From Indo-Gangetic Plain Kanpur, India, the concentration of PM number associated with the finer portion of aerosol throughout the year while the high abundance of Gram-negative bacteria (GNB) dominated during large-scale biomass burning (Rajput et al., 2017). Peatland fire from Indonesian tropical peatlands is another haze and $PM_{2.5}$ pollution (Uda et al., 2019) in Southeast Asian countries. Every dry season is marked by peatland fires in Sumatra and Kalimantan Islands, leading to the transport of heavy smoke and haze that impacts public wellbeing, visual clarity, and the local climate of Indonesia, Malaysia, and Singapore (Fujii et al., 2017; Uda et al., 2019). Although loads of bioaerosols from peatland fire were not found during this review, we think this research requires in-depth exploration. Again, in South Asian countries, roadside wastes and biomass burning are common practices of waste

management. The generation of PM and the associated bioaerosols should be vividly explored in aerodynamics, seasonal, and spatial distribution.

PUBLIC HEALTH EFFECTS AND DEACTIVATION/INACTIVATION OF BIOAEROSOLS

The replication and dispersion of airborne bacteria, fungi, spores, viruses, and other bioparticles in different environments can transmit diseases to animals, plants, and humans (Fröhlich-Nowoisky et al., 2016). The effective cooccurrence and co-elimination mode of pathogenic microbes in $PM_{2.5}$ aggravates air pollution on public health and the ecosystem despite low concentrations (Fan et al., 2019; Wang et al., 2019; Amarloei et al., 2020). Aerodynamics of PM and size characteristics precede it to transfer over spaces from the source of their origin, which is an essential pathway of spreading diseases in different locations (Wang et al., 2019). Besides, smoke particles from biomass burning and microbial aerosols are likely to form ice nuclei and condense cloud nuclei. Subsequently, it can influence biochemical cycles and public health (Wei et al., 2019). An example includes Gram-negative bacterial endotoxins exposure to public health during large-scale biomass burning (Rajput et al., 2017). A substantial seasonal rise of asthma exacerbation and emergency medical department visit was found in Kyoto, Japan, in association with the ambient coarse particles, proteins, and endotoxin (Khan et al., 2018). It was observed that in the springtime, protein concentration in fine ambient particles increased while endotoxin concentrations in both fine and coarse particles rise in the autumn, and hence the risk of asthma increases.

The risk of human exposure to airborne pathogenic bacterial bioaerosol has primarily been related to air inhalation. (Lu et al., 2018; Yan et al., 2019). Many deadly diseases, such as pneumonia, tuberculosis, brucellosis, anthrax, and Q-fever, are connected to bacterial bioaerosols (Uk Lee et al., 2016). Moreover, frequent causes of asthma, respiratory allergies, hypersensitive rhinitis and chronic obstructive pulmonary disease (COPD), and others are associated with the airborne fungal pathogenic exposure owing to their omnipresence (Kallawicha et al., 2015; Uk Lee et al., 2016; Priyamvada et al., 2017). *A. fumigatus* is implicated in numerous wellbeing difficulties in people compromised by immune deficiencies or bronchopulmonary aspergillosis. *S. chartarum*, on the other hand, colonize in damp and produce mycotoxins. Fungal bioaerosols considerably influence the oxidative ability and chemical composition of the ambient PM in the presence of *A. fumigatus* spores (Samake et al., 2017). Also, bioaerosols accelerate reactive oxygen species (ROS) in human lungs in response to different microorganisms and concentrations. For example, fungal spores generated up to 10 times more ROS than bacterial cells (Samake et al., 2017).

The microbial organisms associated with the desert dust and AD events may cause several diseases such as respiratory, cardiopulmonary, and heart diseases (Soleimani et al., 2020).

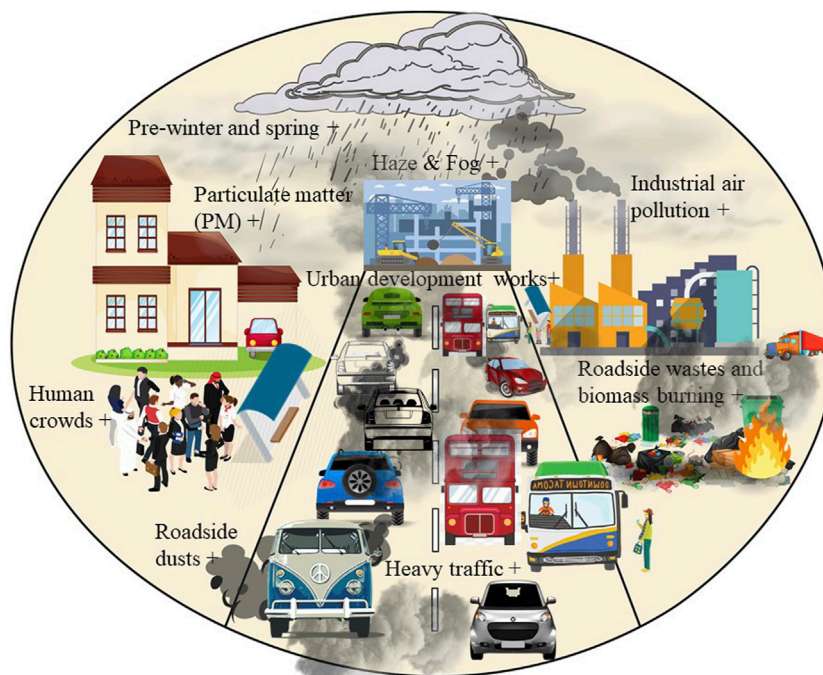


FIGURE 2 | Factors influencing bioaerosols load (indicated by +) in association with the development of particulate matter (>2.5–10 μm) in the outdoor urban/industrial environments of developing countries. This is suspected to be similar for all tropical South Asian and Southeast Asian cities.

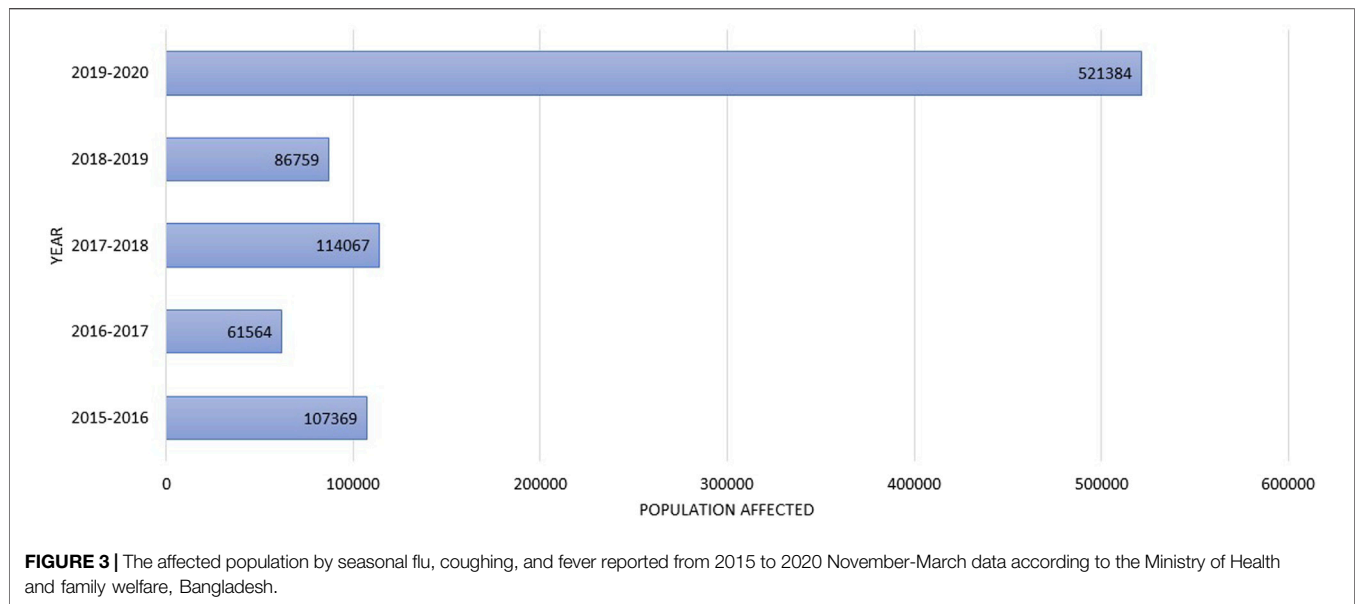
Moreover, the systematic characterization of airborne bacterial communities in Asian dust (AD) samples identified the presence of *B. cereus* that poses risks to public health (Yoo et al., 2019).

Children are susceptible to airborne pathogens and allergens (Shin et al., 2015). The annual RSV-prevalence among children was 10%, of which infants under 6.5 months represented 80% of all patients (Ye et al., 2016). Biodefense approaches, which include assessing, detecting, monitoring, responding to biological threats, can be established to avert/lessen the apparent exposure of bioaerosols. Displaying hourly or daily AQI level in color-code in public screens, endorsing alternative travel routes, face masks, prevention of spitting and littering in public places, and above all, maintaining environmental and personal hygiene through strict laws are required for the commuters' safety plan (Madhwal et al., 2020). COVID-19 lockdown shows that Indian cities with poor air quality correlated with higher COVID-19 cases and deaths. Conversely, low mortality was reported in cities with better air quality (Naqvi et al., 2021). The SARS-CoV-2 viral disease COVID-19 infectivity rate is higher in many developing and developed countries as the unaware population is not using masks properly and not maintaining social distancing. Wearing face masks in public is associated with a decline in the daily COVID-19 growth rate in many US states (Lyu, and Wehby 2020), requiring general public guidance (Leung et al., 2020).

Subsequently, mechanisms to deactivate or inactivate bioaerosols containing airborne bacteria, fungi, fungal spores, and virus bioaerosols are pressing research issues to protect the public at the hospitals, offices, homes, and institutional environments. Photocatalysis using titanium dioxide (TiO_2) is

a significant research area of bioaerosol deactivation or inactivation. Biological waste management processes are often the primary sources of bioaerosols in the cities (Valdez-Castillo et al., 2019; Valdez-Castillo et al., 2021). Valdez-Castillo and his colleagues (2019), in their earlier study, showed that photocatalytic systems based on Perlite-supported ZnO and TiO_2 significantly inactivated fungal/bacterial emissions up to 70%. In their later study (Valdez-Castillo et al., 2021), involving photocatalysis with ZnO and TiO_2 immobilized onto Poraver glass beads proved to inactivate 78% bioaerosols during the first two-hour. Both of these processes by bacteria and fungi were inactivated by cell death. In another study (Valdez-Castillo and Arriaga 2021), a photocatalytic system could entirely inactivate bioaerosols in indoor environments.

The application of nanotechnology can significantly contribute to the efficiency improvement of bioaerosol inactivation. Recent research on visible-light-activated (VLA) antimicrobial air filters equipped with TiO_2 -crystal violet nanocomposites shows <99.9% bioaerosol inactivation (Heo et al., 2021). Application of Iron Oxide nanowire-based filter significantly inactivated airborne bacteria. The inactivation of bacteria is related to the combined effect of the OH radicals, electroporation, and Joule heating that disrupts the bacterial cell walls. A single filter can capture 52% of the bacterial cells and inactivate them. The filter also has a long life (Wang et al., 2018). The application of plasma technology is also a novel approach to inactivate many bioaerosols, including SARS-CoV-2 RNA, in hospitals and other indoor environments (Bisag et al., 2020).



FUTURE RESEARCH PERSPECTIVES

It is evident that PM from urban development works, industrial activities, heavy traffic pollution, roadside wastes, and biomass burning, massive human crowds can increase the bioaerosols in the atmosphere (Figure 2). It is, therefore, essential to carry out regular bioaerosol assessments in the cities of developing countries, particularly in Asian cities, when the pollution levels are high. The literature review found that the higher prevalence of bioaerosols occurs in fall, early winter, late winter, and spring. Seasonally these are the tipping times for bioaerosols concentration in the outdoor environments. However, the seasonal effect of post-monsoon and pre-monsoon on bioaerosol load in tropical countries are still less-explored issues that need research.

- In many developing countries, detection and laboratory facilities are non-existent, leading to unreported cases of bioaerosols. For example, in Bangladesh, the exact bioaerosols concentration in the atmosphere is unknown. However, the hospital admission data on respiratory affected people show a drastically increasing trend in 2019–2020, according to the Ministry of Health and Family Welfare which was reported in the local Bengali daily Kalerkantha (Maruf, 2020) compared to the previous years (Figure 3). In February 2020, alone, 5,21,384 persons were affected in the November-March season of 2019–2020, which is considered winter months and post-winter months and possibly by airborne transmission. However, lack of research and enough evidence-based research is a pressing issue to infer exposure to airborne pathogenic microbes related to microbial infections such as asthma, allergy, or other respiratory diseases in the urban, industrial and institutional environment in relation to PM.
- Integrated research should be focused on rapid airborne bioaerosol detection, monitoring, early warning, and inactivation or deactivation of bioaerosol is required in association with PM.
- Since the research of airborne bioaerosol is integrated research, a network of environmental scientists, microbiologists, medical microbiologists, biochemists, computer engineers, and researchers from information technology can develop integrated ecological sensors for bioaerosols detection technologies. Kit-based rapid detection research and methods should be focused on detecting the nature of the bioaerosols in the urban atmosphere that may pose a serious public health threat. Fluorescence techniques can be used for the rapid detection of bioaerosols. In addition, research on low-cost real-time quantitative PCR (RT-PCR and qPCR) should be developed to identify which phylum is in the air.
- Artificial intelligence, deep neural networks, and machine learning can develop and test real-time bioaerosols sensors. Mobile apps can be created for city dwellers to inform them about the concentration of bioaerosols in the air, particularly of the pathogenic and allergens type. Similarly, like AQI a global real-time bioaerosol sensors and detection technologies can be developed to alarm the global real-time scenario of bioaerosols. Further exploration should focus on the uses and consequences of the internet of things (IoT) technologies for calculating the concentrations of bioaerosols and maps in real-time.
- For public warning, precaution and communication, and policymaking on bioaerosols, effective health policy research is needed for public health safety.

CONCLUDING REMARKS

This review is aimed to identify the current bioaerosol scenario in the Asian regions. The environmental quality of Asian megacities is composed of rapid industrialization, faster urbanization, and development, followed by very high PM pollution. In turn, PM, AQI, and the presence of associated gases significantly contribute to the abundances of airborne bioaerosols concentration during the hazy and foggy days, and the aerodynamics controls their floating behavior. Moreover, dense crowds, heavy traffic density, uncontrolled biomass burning also regulates the prevalence of bioaerosols in different concentrations in the outdoor atmosphere and the occurrences of human transmission. Subsequently, pathogenic bioaerosols in outdoor environments are responsible for various allergens and respiratory diseases among children and adults, and the response is not identical. For public health safety, it is essential to detect and control the pathogenic bioaerosol loads, along with the spatiotemporal distribution in Asian megacities. Particular emphasis should be given to developing on-site automated bioaerosol-

monitoring systems and bioaerosol deactivation or inactivation mechanisms. Although, in this review, we have emphasized bioaerosol formation and detection in the outdoor environment, to protect indoor spaces such as homes, offices, schools, and hospitals, should also be brought under strict and continuous monitoring of bioaerosols. Research should be more focused on devising bioaerosol's deactivation/inactivation mechanism.

AUTHOR CONTRIBUTIONS

MS planned, reviewed, and prepared the manuscript. MMR and SMT reviewed independently. All authors commented and contributed to the final manuscript preparation.

ACKNOWLEDGMENTS

The authors would like to acknowledge all the authors cited in the references.

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