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Chemical and Biological Compositions Associated with Ambient Respirable Particulate Matter: a Review

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Abstract Particulate matter (PM) is defined as a mixture of solid and/or liquid particles that remain separately dispersed in air. PM is not a pollutant by itself but a complex and dynamic combination of compound particles with biological and chemical origins. However, fine PM ($PM_{2.5}$) seems to be incriminated in the respiratory system and poses a severe threat to human health. Several reviews focused on chemistry segments because they mainly contribute to fine PM concentration. Biological elements in $PM_{2.5}$ should also be considered because they cause multiple allergies and respiratory illnesses. This review has selected articles by following predefined criteria and demonstrated that the biological and chemical parts of fine particles play a significant role in $PM_{2.5}$ concentration. In addition, justification on the origin or sources of biological and chemical compositions and their effects on health become a concern in this review. Lastly, this review can provide knowledge that can be a useful tool for researchers, designers, engineers and policymakers to consider for further action.

Keywords Bio-aerosols · Chemical component · High particulate event · Meteorological factors · Normal condition

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1 Introduction

Air pollution is one of the major environmental problems in several cities worldwide and the world's fourth leading cause of death (Bandpi et al. 2016) because it contains a complex mixture of thousands of pollutants. The mixture may contain particulate matter (PM) and different gases, such as carbon monoxide (CO), ozone (O_3), volatile organic compounds (VOCs) and nitrogen oxides (NO_2 and NO) (Lükewille et al. 2001). The composition of the mixture varies based on location and emission sources (Lonati et al. 2008; Jia et al. 2017). With the development of urbanisation and industrialisation, atmospheric particulate pollution has become of great concern especially with regard to public health (Baulig et al. 2004).

PM can damage human health (Amann et al. 2001; Khan et al. 2016). Individuals are damaged by air pollution based on their general exposure to pollutants as well as factors including length of exposure, concentration of pollutants and population vulnerability (Kalisa et al. 2019). However, children face severe risks from air pollution because their lungs are growing, they are active and they breathe much air (WHO 2014). Kim et al. (2018) asserted that children are highly vulnerable to any disease because of the premature development of their immune systems, lungs and other organs. PM is outlined as an advanced mixture of droplets, acids, organic materials, heavy metals and soil materials (Li et al. 2018). PM is classified into many classes: PM_{10}, $PM_{2.5}$ and ultrafine particles with aerodynamic diameters of less than 10 μm, less than 2.5 μm and less than

0.1 μm, respectively (Pope et al. 2002; Das et al. 2009; Tiwari et al. 2012).

At present, most countries focus on evaluation of air pollution on PM_{10}, which can be trapped in the nasopharyngeal tract, and $PM_{2.5}$, which can enter the lungs and reach the alveoli (WHO 2014). Exposure to high levels of PM_{10} and $PM_{2.5}$ can lead to asthma, cardiovascular pulmonary diseases, pulmonary fibrosis, cancer and immune responses (WHO 2014). The size of PM is related to its feasibility in causing health issues (Araújo et al. 2014), and Li et al. (2018) stated that small particles tend to cause serious health issues compared to coarse particles. Many researchers have found that PM is a complex mixture of air contaminants, including chemical and biological sources, such as biological organisms, nitrates, sulphates, heavy metals, organic compounds and elemental carbon (Sippula et al. 2013; Adams et al. 2015; Yoo et al. 2016; Morakinyo et al. 2016; Han et al. 2018). Maricq (2007) reported that the chemical composition of PM could provide information and reveal the sources of PM. Moreover, PM can act as a carrier of chemical and biological components according to time of sampling, location of sampling, seasons and climates (Kellogg and Griffin 2006; Gou et al. 2016; Maki et al. 2015).

Morakinyo et al. (2016) discussed that the chemical and biological compositions of PM could trigger negative health effects on humans because particles with toxic chemicals could carry other biological species and can deeply penetrate into human lungs, thereby enhancing asthma, lung cancer and cardiovascular pulmonary diseases. Thus, this review outlines the properties and sources of chemical and biological components of respirable PM and prescribes future centre regions for research and arrangement.

2 Methods

2.1 Database Sources

A literature review was conducted by database search in Web of Science and Google Scholar by using keywords such as chemical composition, biological composition, respirable particulate matter (RPM), fine particles, coarse particles, bacteria-associated PM, fungi-associated PM, polycyclic aromatic hydrocarbon, PAH and characteristics of bio-aerosols.

3 Chemical and Biological Compositions of RPM

3.1 Chemical Compositions of RPM

Ambient PM can absorb poisonous pollutants, such as heavy metals, VOCs and polycyclic aromatic hydrocarbons (PAHs), especially particles with an aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$) (Brüggemann et al. 2009; Cassee et al. 2013). According to Morakinyo et al. (2016), PM is profoundly unique. PM can be named carbonaceous parts, which comprise carbonate carbon, natural carbon, basic carbon and inorganic segments including crustal components, ionic species and trace metals. Raes et al. (2000) stated that chemical PM elements typically add an average of 20% to the overall PM mass load.

Snider et al. (2016) examined the background comparisons of $PM_{2.5}$ chemical compositions from 12 urban locations at Mammoth Cave in the USA. The results (relative contribution ± SD) showed that the samples were dominated by 20% ± 11% ammoniated sulphate, 13.4% ± 9.9% crustal materials, 11.9% ± 8.4% black carbon, 4.7% ± 3.0% ammonium nitrate, 2.3% ± 1.6% sea salt, 1.0% ± 1.1% trace element oxides, 7.2% ± 3.3% water and 40% ± 24% residual matter at 35% relative humidity. However, chemical compositions were not equally distributed based on size range but depended on their sources.

3.1.1 Organic Compounds

PAHs are a large group of organic compounds comprised of two or more fused benzene rings arranged in various configurations (Kim et al. 2013). As semi-unstable natural mixes, PAHs in air are available in vapour and molecular phases; lighter PAH species (i.e. usually two- and three-ring structures) were found to a large extent in the vapour phase, whereas heavier species (i.e. usually five-ring, atomic weight > 228) were found in the molecular phase and predominantly in the smaller respiratory size (i.e. $PM_{2.5}$), thereby increasing the risk of exposure (Lu et al. 2008). PAHs are mutagenic or carcinogenic toxic chemical compounds and are generated from the incomplete combustion of fossil fuel and organic materials (Bootdee et al. 2016). $PM_{2.5}$ sample was collected by Evagelopoulos et al. (2010) in the regions encircled with active opencast coal mining activities, and $PM_{2.5}$-bound PAH concentrations were found at levels many times higher than PM_{10}-bound PAHs.

In another study conducted in Tehran, total PAHs on PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ were collected indoor and outdoor in retirement homes and college dormitories. Complete PM-bound PAHs were predominant at 83–88% in $PM_{2.5.}$ This result is consistent with the statement by Duan et al. (2005); the levels of particulate PAH are extremely dependent on fine PM. In urban situations, the principal source is typically traffic, although traffic contamination might be secondary in exceptionally mechanical regions (Han and Naeher 2006). A study of PAHs in $PM_{2.5}$ in Spain considered the contribution of traffic and indicated the significant role of industrial emissions. Benzo(a)pyrene (BaP) concentration depended on the size of the population. The correlation of benzo(a)pyrene and complete amount of PAH (BaP/∑PAH) was greater during the cold season when observing variability in season and time (Villar-Vidal et al. 2014). A powerful correlation between PAH levels further confirmed that BaP is an appropriate marker compound to represent all PAH levels (Villar-Vidal et al. 2014). A previous study collected atmospheric PAH concentration to determine the seasonal variation of sources in Harbin, China and showed that the major source was coal combustion with 60%, followed by traffic emissions (34%) in heating season; in non-heating season, the main sources were traffic emissions (59%), ground dissipation (18%) and coal average (7%) (Ma et al. 2010). Yang et al. (2018) observed the PAH concentration in Chengdu, China from March 2015 to February 2016. The principal component analysis/multiple linear regression investigation distinguished the fundamental sources of PAH as coke (48%) and carbon burning (52%) with engine car smoke in spring; coke (21%), coal (52%) and engine car exhaust (27%) in summer; vehicle exhaust (34%), coal (47%) and coke (19%) in autumn; and vehicle exhaust (42%) and coal (58%) in winter.

3.1.2 Inorganic Compounds

Trace Metal Chemical composition of $PM_{2.5}$, especially trace metal components, plays a crucial role in the severity of the associated toxic effect (Wang et al. 2017). Samara and Voutsa (2005) stated the presence of trace metals in most airborne PM fractions of each aerosol volume. Cadmium (Cd), arsenic (As), chromium (Cr), copper (Cu), cobalt (Co), iron (Fe), nickel (Ni), lead (Pb), manganese (Mn), strontium (Sr), titanium (Ti), zinc (Zn) and vanadium (V) were reported to be widespread in $PM_{2.5}$ (Niu et al. 2010; Wang et al. 2017). Trace metals originated from soil dust formation, fossil fuel combustion, cremation and metal processing at high temperatures (Morakinyo et al. 2017). In a recent study of $PM_{2.5}$ at Nanjing China, anthropogenic exercises such as modern discharge, coal burning and traffic vehicle exercises resulted in the magnetic characteristics of particles strongly connected with trace metals; but those obtained from natural sources were inadequate (Wang et al. 2017). Pb mainly originated from coal emissions in summer samples, and the main sources were found to be smelting sector and coal emissions in winter samples. In a study on heavy metal in $PM_{2.5}$ in Kolkata published by an Indian–Singaporean team in Air Pollution Research, the high levels of Pb, Sr, Cd and Cd in $PM_{2.5}$ were related to industrial emissions, whereas high levels of Pb and Zn were linked to coal burning and non-ferrous metal melting (Das et al. 2015). Traffic emissions emit high levels of Cr, Ni and molybdenum (Das et al. 2015). Another study in Jharkhand, India reported that the main sources of airborne trace metals were coal mining and related activities, exhaust and industrial emissions from automobiles, resuspended soil and soil crust, burning of biomass, combustion of oil and flight emissions (Dubey et al. 2012).

Water-Soluble Ionic Species Water-soluble ions are chemical species that are readily soluble in water under certain circumstances in the reduced troposphere and are generally important elements by mass of atmospheric aerosols (Deshmukh et al. 2011). Ammonium (NH_4^+), calcium (Ca^{2+}), chloride (Cl^-), magnesium (Mg), nitrate (NO_3^-), potassium (K), sodium (Na), sulphate (SO_4^{2-}), organic carbon (OC), elemental carbon (EC) and metals are water-soluble ions usually found in $PM_{2.5}$ that comes from various sources (Ali-Mohamed and Jaffar 2000; Tsai et al. 2012; Salam et al. 2015). The major components of urban ambient $PM_{2.5}$ were SO_4^{2-}, NO_3^-, NH_4^+, OC and EC (Kothai et al. 2008; Chakraborty and Gupta 2010; Kim et al. 2011). A total of 60 to 70% of the absolute mass of suspended standard PM consisted of water-soluble ions. The water-soluble fraction of atmospheric aerosols is hygroscopic and contains many important compounds that can change the size, composition, number, density and lifetime of aerosols (IPCC 1995; Jacobson et al. 2000; Mariani and Mello 2007; Salam et al. 2015). Deshmukh et al. (2011) stated that

K^+, SO_4^{2-}, NO_3^- and Ca^{2+} were the most dominant species in $PM_{2.5}$, and the concentrations of NO_3^- and SO_4^{2-} were the highest in all size fractions. Tahir et al. (2013) conducted a research in Kuala Terengganu Coastal Suburban Area, South China Sea, Malaysia, and found that the average concentration of ions decreased as follows: $SO_4^{2-} > NH_4^+ > K^+ > Na^+ > NO_3^- > Cl^- > Ca_2^+$. The levels of ammonium (NH_4^+) and sulphate (SO_4^{2-}) were more than 70% of the water-soluble aerosol mass. Over 80% of $PM_{2.5}$-related ionic species originated from non-marine sources. The concentrations of sulphate and ammonium represented > 70% of the water-soluble airborne mass. Sea spray, crustal loading and biomass burning were found to be the main sources that influenced the ionic structure of $PM_{2.5}$.

Mineral Dust Peng et al. (2016) reported that Si, Ti, Al, Fe and Ca are dust-related compounds. Philip et al. (2017) classified them into three general categories: mineral dust normally windblown from dry desert regions (Prospero et al. 2002); anthropogenic windblown dust from human-disturbed soils due to changes in land use rehearses, deforestation and agriculture (Tegen et al. 1996, 2004); and anthropogenic fugitive, combustion and industrial dust (AFCID) from urban sources. Several studies stated that AFCID contains elements from coal combustion (fly ash) and industrial processes (for example iron and steel creation, cement production), mining, quarrying, farming activities and road–residential–commercial construction (McElroy et al. 1982; Watson and Chow 2000; Guttikunda et al. 2014). Table 1 shows the summary of dominant elements of chemical sources in respirable particulate matter.

3.1.3 Carbonaceous Species

Atmospheric PM carbonate species consist of organic, elemental and carbonate carbon (Yang et al. 2011). Organic carbon is a major component of ambient aerosols and constitutes up to 70% of the fine aerosol mass (Jacobson et al. 2000; Sharma et al. 2018). Studies in Beijing showed that the major contributor to the mass cooperation of fine atmospheric particles is carbonaceous species (Chen et al. 1994; He et al. 2001). Li et al. (2012) asserted that carbonaceous species can be divided into two main fractions: OC and EC (Turpin and Huntzicker 1995; Li et al. 2012). OC would be emitted either directly from the atmosphere (main OC) or from gas-to-particle reaction (Turpin and Huntzicker 1995).

Table 1 Dominant elements of chemical sources in respirable particulate matter

Location	Dominant elements	Sources group	References
Nanjing, China	As, Cd, Ca, Cr, Co, Cu, Fe, Mn, Ni, Pb, Sr, Ti, V and Zn As and Ni differ in summer and winter. Summer: As = 9.633 ± 1.986 ng/m^3 Ni = 8.637 ± 2.992 ng/m^3 Winter: As = 16.87 ± 3.409 ng/m^3 Ni = 29.14 ± 7.868 ng/m^3	Trace metal	Wang et al. (2017)
Kolkata, India	Cr, Ni, Zn, Mo, Sn, Sb, V, Co, Cu, Cd and Pb	Trace metal	Das et al. (2015)
Shanghai and Beijing, China	Shanghai: SO_4^{2-} = 46%, NO_3^- = 18% and NH_4^+ = 17% Beijing: SO_4^{2-} = 44%, NO_3^- = 25% and NH_4^+ = 16%	Water-soluble ionic	Yao et al. (2002)
Durg City, Chhattigarh, India	Total contribution in $PM_{2.5}$ = 11.57% (7.48% anions, 4.09% cations) SO_4^{2-} = 32.76%, NO_3^- = 13.38%	Water-soluble ionic	Deshmukh et al. (2011)
Dhaka, Bangladesh	Total contribution in $PM_{2.5}$ = 15% K^+ = 8.11 μg/m^3, SO_4^{2-} = 5.30 μg/m^3, NO_3^- = 7.75 μg/m^3, Ca^{2+} = 3.09 μg/m^3	Water-soluble ionic	Salam et al. (2015)
Huzhou, China	Si = 3.93 μg/m^3, Al = 6.03 μg/m^3, Ca = 2.65 μg/m^3	Mineral dust	Peng et al. (2016)

OC is a mixture of several natural compounds (with primary or secondary origin), such as PAHs, polychlorinated biphenyls, polychlorinated dibenzo-*p*-dioxins, dibenzofurans and other components with potential mutagenic and carcinogenic effects (Cao et al. 2003; Cao et al. 2005; Ram et al. 2008). EC is sometimes referred to as black carbon from incomplete carbon-containing combustion (Morakinyo et al. 2016; Turpin and Huntzicker 1995). EC is predominantly transmitted from anthropogenic burning sources and does not undergo chemical transformation (Li et al. 2012). Yang et al. (2005) revealed that OC and EC in urban Beijing exhibited higher weekly concentrations and variances in winter and much lower values in summer and spring.

3.1.4 Seasonal Variation of PM2.5 Major Component

The weather condition is a major driving force of air pollution concentration (Hsu et al. 2017). According to Bell et al. (2008), higher temperatures accelerate chemical reactions in the air; lower temperatures make particulate matter (PM) dissipate more slowly in the air than usual; and rain washes away water-soluble pollutants and PM. Furthermore, the temperature is seasonal and the concentration of PM varies according to area and season. Table 2 shows the concentration of $PM_{2.5}$ during two different seasons (Winter and Summer).

3.1.5 Chemical Properties of PM2.5 During Haze Episodes

Haze is a common phenomenon in Southeast Asia (SEA) and has occurred in the last few decades almost every year. Latif et al. (2018) stated that the particulate matter compositions can be divided into two categories: inorganic and organic compositions. On February 1 and March 31, 2011, at a South Area Supersite at Gwangju, Korea, Park et al. (2013) reported in their study that two pollution episodes are investigated. Hourly measurements of $PM_{2.5}$, organic and elemental carbon (OC and EC), inorganic ionic species and elemental constituents were measured during this study. Kim et al. (2004) used IMPROVE equation in their study. The measurement only can be used for $PM_{2.5}$ fine aerosol. The analytic method and composite equation are shown in Table 3. Table 4 shows the $PM_{2.5}$, organic and elemental carbon (OC and EC), inorganic ionic species and elemental constituents during winter and summer seasons with different categories of the station.

3.2 Biological Compositions of RPM

$PM_{2.5}$ is a mixture of liquid and solid particles including chemical and biological fractions. The significant $PM_{2.5}$ components in indoor and outdoor environments are bio-aerosols, bacteria, fungi, pollen and endotoxins. The characteristic size ranges of particles in the atmosphere and bio-aerosols are shown in Fig. 1.

3.2.1 Bio-aerosols

Bio-aerosols are emitted directly into the atmosphere from the biosphere and include living and dead organisms (e.g. bacteria, archaea and algae), dispersal units (e.g. fungal spores and crop pollen) and different fragments or excretions (e.g. crop debris and brochosomes) (Fröhlich-Nowoisky et al. 2016). Fröhlich-Nowoisky et al. (2016) also reported that the origin, profusion, structure and impacts of biological spray are not yet well categorised and represent an important gap in life science and atmosphere conditions, interaction and evolution in the Earth. The chemical composition of $PM_{2.5}$ provides useful data for identifying contributions from

Table 2 Concentration of $PM_{2.5}$ during summer and winter season

References	Location	Summer seasons (μg/m^3)	Winter season (μg/m^3)
Yao et al. (2015)	Beijing, China	78	105
Bagtasa et al. (2018)	Northwestern Philippines	11.9 ± 5.0	12.9 ± 4.6
Huang et al. (2018)	Beijing, China	64.1	135.6
Tolis et al. (2014)	Kozani, Greece	7.18–37.06	6.12–37.10
Hawkins and Holland (2010)	Carlisle, Pennsylvania	2.6–53.9	2.0–43.0
Ali et al. (2015)	Khanspur, Pakistan	118 ± 33.3	63 ± 49.3

Table 3 IMPROVE equation for fine particulate matter (Kim et al. 2004)

Site and period	Sources identified	Component	Mass (μg/m^3)	Component analysed and composite equation
Kwangju, Korea (22 March, 11–13 April and 25–26 April 2001	Asian dust storm event (mineral dust, sulphate, organic carbon, elemental carbon)	Elemental carbon (EC)	2.6	Thermal-CO_2 analysis 3[S] − 0.25[Na] ion chromatography analysis 2.20[Al] + 2.49[Si] + 1.63[Ca] + 2.42[Fe] + 1.94[Ti]
		Organic carbon (OC)	8.1	
		Non-sea-salt sulphate (nss-SO_4^{2-})	6.9	
		NO_3^- (nitrate)	3.0	
		FS (fine soil)	8.9	

particular sources and for understanding aerosol characteristics that could affect health, climate and atmospheric conditions (Snider et al. 2016).

In atmospheric processes, bio-aerosols are emerging as important but poorly understood players (Urbano et al. 2011). Bio-aerosols contain living organisms or are directly released from living organisms (Cox and Wathes 1995; Wolf et al. 2010). Bio-aerosols contain biological agents, including viruses, bacteria, bacterial endotoxins, allergens and fungi. This definition includes all airborne microorganisms regardless of the viability or capability of culture to recover; it also includes whole microorganisms as well as fractions, biopolymers and products from all varieties of living organisms (Chithra and Shiva Nagendra 2018). According to Morakinyo et al. (2017), pollen, microorganisms (bacteria, fungi and viruses) or organic microbial (endotoxins, metabolites, toxins and other microbial fragments) compounds are usually planted with bio-aerosols. Most bio-aerosols have sizes of 0.25–20 μm in bacteria, 0.003 μm in viruses, 1–30 μm in fungi and 17–58 μm in plant pollens (Stanley and Linskins 1974; Thompson 1981; Taylor 1988; Morakinyo et al. 2017).

Hargreaves et al. (2003) stated that bio-aerosol size distributions differ significantly by type. The sizes of pollens, fungal spores, bacteria and viruses are typically 5–100, 1–30 μm, 0.1–10 μm and less than 0.3 μm, respectively. Bio-aerosols span a broad variety of aerodynamic diameters (Da) from viruses, which are the smallest (Da 20–300 nm), to pollen, which have diameters of up to 100 μm. Other commonly studied bio-aerosol classes are bacterial and fungal spores, with typical Da values of 1–3 and 1.5–30 μm, respectively (Wolf et al. 2017). Liu et al. (2016) reported the positive correlation of the respirable fractions of bacteria with $PM_{2.5}$ and that of the respirable fractions of fungi with PM_{10}. Several variables, including temperature, relative humidity, wind velocity and physical characteristics of bio-aerosols, influence the transport of bio-aerosols and other air pollutants in the gas phase (D'Amato 2002; Woo et al. 2013; Kalisa et al. 2018; Kalisa et al. 2019). Bowers et al. (2011) reported a high diversity of bacteria in outdoor air; these bacteria sometimes originate from unexpected sources, such as dogs.

3.2.2 Bacteria

The levels of bacteria normally vary from 10^4 cells m^3 to 10^6 cells m^3 (Lighthart 2000) but may be higher in the

Table 4 $PM_{2.5}$, organic and elemental carbon (OC and EC), inorganic ionic species, and elemental constituents during winter and summer seasons with different categories of the station

	Stations	$PM_{2.5}$	Chlorine	Nitrate	Sulphate	Ammonium	Organic carbon	Elemental carbon	Aluminium	Silicon	Calcium	Iron	Lead
Winter													
Abu-Allaban et al. (2007) (Cairo, Egypt)	Urban	216.1 ± 11.0	22.4 ± 1.4	4.5 ± 0.3	9.1 ± 0.6	7.6 ± 0.5	32.7 ± 2.7	12.4 ± 1.5	0.9 ±0.1	5.4±0.3	5.5 ±0.5	4.2 ± 0.2	26.8 ± 1.4
	Rural	49.7 ± 2.7	10.3 ± 0.7	3.2 ± 0.3	4.8 ± 0.3	7.9 ± 0.5	10.2 ± 1.0	5.9 ± 0.7	0.1 ±0.0	0.1±0.0	0.1 ±0.0	0.1 ± 0.0	0.0 ± 0.0
	Traffic	84.6 ± 4.3	9.2 ± 0.6	3.0 ± 0.2	6.7 ± 0.4	6.8 ± 0.4	23.2 ± 2.0	13.0 ± 1.5	0.1 ±0.0	0.5±0.0	0.8 ±0.0	0.5 ± 0.0	1.6 ± 0.1
Cao et al. (2012) (Beijing, China)	Urban	115.6 ± 46.6	2.3 ± 1.8	13.1 ± 4.5	20.0 ± 4.2	9.4 ± 4.1	23.9 ± 12.4	6.2 ± 2.7	–	–	–	0.99 ± 0.32	0.28 ± 0.23
Summer													
Abu-Allaban et al. (2007) (Cairo, Egypt)	Urban	60.7 ± 3.2	1.6 ± 0.2	0.6 ± 0.1	9.6 ± 0.6	2.7 ± 0.2	22.2 ± 1.7	7.4 ± 0.8	0.1 ±0.2	1.9±0.1	0.4±0.0	0.7 ± 0.0	5.1 ± 0.4
	Rural	34.7 ± 1.9	0.3 ± 0.1	0.4 ± 0.1	5.5 ± 0.4	1.8 ± 0.2	14.9 ± 1.2	4.5 ± 0.6	0.2 ±0.0	0.7±0.0	0.3±0.0	0.3 ± 0.0	0.0 ± 0.0
	Traffic	59.3 ± 3.1	0.3 ± 0.1	0.6 ± 0.1	8.1 ± 0.5	2.6 ± 0.2	26.5 ± 2.0	16.3 ± 1.8	0.2 ±0.0	0.6±0.0	0.4±0.0	0.4 ± 0.0	0.3 ± 0.0
Cao et al. (2012) (Beijing, China)	Urban	131.6 ± 28.0	1.3 ± 0.6	13.7 ± 6.4	22.6 ± 9.2	9.8 ± 4.2	19.7 ± 4.7	5.7 ± 4.1	–	–	–	0.8 ± 0.24	0.18 ± 0.09

vicinity of point sources, such as composting crops, wastewater treatment plants and feedlots (Lange et al. 1997; Albrecht et al. 2007; Rinsoz et al. 2008). Table 5 listed the dominant species of bio-aerosols in ambient $PM_{2.5}$ and their concentration levels across the world. Rachna (2018) defined bacteria as prokaryotic microorganisms that are considered the first organisms on Earth and evolved around 3.5 billion years ago. Bacteria can be autotrophs (which can prepare their own food by photosynthesis or chemosynthesis) as well as heterotrophs (depends on others for their food). With the thriving human activities such as solid wastes and sewage transport, processing and favourable wetlands can enhance the abundance of cultured airborne bacteria in urban environments (Gangamma 2014).

Haas et al. (2013) reported that bacteria are associated with large particles in urban air. Cao et al. (2014) discovered that the depiction of pathogens recognised in the bacteria society as a whole is 0.017% in PM_{10} and 0.012% in $PM_{2.5}$ specimens; their concentration increased twice from an average of 0.024%. Proteobacteria are the most dominant bacterial components identified in $PM_{2.5}$ (Bowers et al. 2013; Liao et al. 2013; Cao et al. 2014; Du et al. 2018). To date, the features of most airborne bacteria, including pathogenicity, cell activity, resistance to adverse meteorological conditions and biotransformation, are not very evident. Research on the connection between pollutant concentration and bacterial community composition in $PM_{2.5}$ is restricted by several gaps in understanding and technology that could lead to contradictory results.

3.2.3 Fungi and Pollen Grains

Fungi are derived from natural activities (soil, plants and animals) and anthropogenic sources (Jacobson 2012; Kalisa et al. 2019). Zhang et al. (2010) stated that fungal spores are the dominant biological component of airborne particles. The spore concentrations of *Penicillium and Aspergillus* increased with the increase of fine particle concentrations (Haas et al. 2013; Yan et al. 2016). About 4 to 11% of the total mass concentration of RPM was contributed by fungal spores and pollen (Womiloju et al. 2003; Kalisa et al. 2019). However, the concentration of fungal spores in PM_{10} is greater than that in $PM_{2.5}$ (Kalisa et al. 2019); the concentration of specimens with dominant loads of microorganisms in PM_{10} is 4.5% greater than in $PM_{2.5}$ (1.7%). Fröhlich-Nowoisky et al. (2009) reported that the capacity of parasitic spores

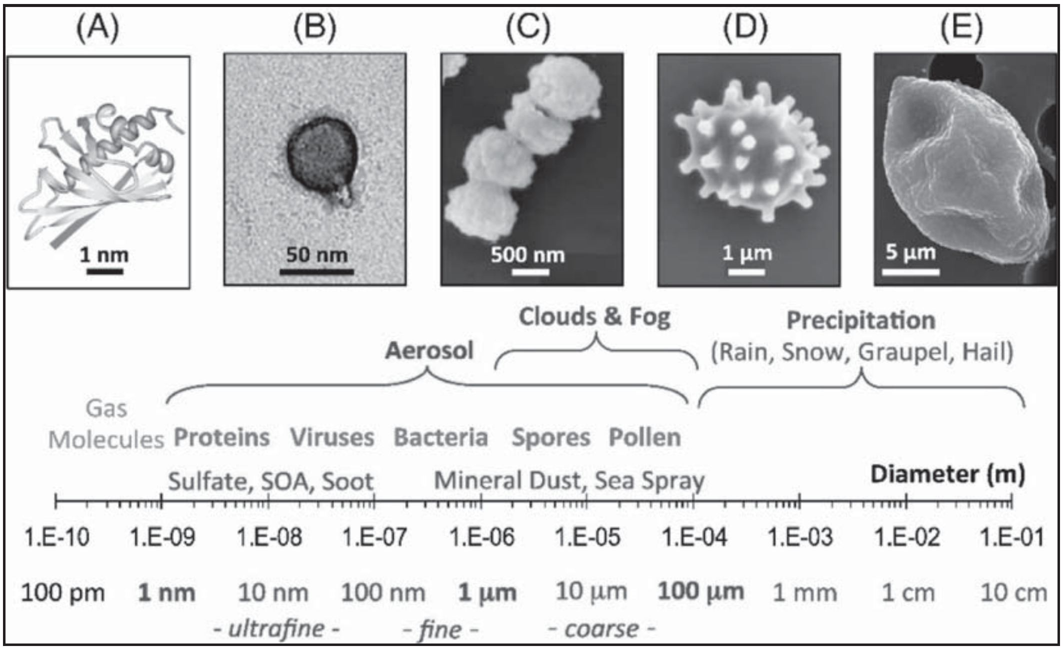

Fig. 1 Characteristic size ranges of atmospheric particles and bioaerosols (A) protein (B) virus, (C) bacteria, (D) fungal spore and (E) pollen grain (Fröhlich-Nowoisky et al. 2016)

under adverse ecological conditions (outrageous cold to hot) empowers them to be ever-present in the surrounding PM; they can comprise up to 45% of PM size portion and have normal streamlined distance across > 1 µm. Telloli et al. (2016) detected and identified fungal spores and pollen grains based on morphological properties. Organic particles were collected and examined by scanning electron microscopy with energy-dispersive X-ray spectrometer. *Aspergillus* spores, which could lead to allergies and aspergillosis to crop farmers, are the most common elements of organic particles sampled.

3.2.4 Endotoxin

Tim Sandle (2016) stated that bacterial endotoxin is the lipopolysaccharide component of the cell wall of Gram-negative bacteria. Endotoxin is ubiquitous in nature and has potent toxicity. Endotoxin is present in small amounts in environmental particles (Morakinyo et al. 2016) because it is stable under extreme conditions (Sandle 2016). Studies showed that the endotoxin levels in PM_{10} are 3–10 times greater than in $PM_{2.5}$ (Allen et al. 2011; Nilsson et al. 2011; Morakinyo et al. 2016). Other studies confirmed that $PM_{2.5}$ is correlated with airborne endotoxins (Carty et al. 2003; Mueller-Anneling et al. 2004; Morakinyo et al. 2016) and passes through the lungs after inhalation. Heinrich et al. (2003) distinguished surrounding airborne endotoxins in coarse and fine molecular portions; however, the level of such toxin is 10 times higher in coarse PM. The concentration of endotoxin was elevated in the atmosphere in locations where organic materials such as wastewater, composting equipment and farms are handled (Rolph et al. 2018). Ambient endotoxin is usually below 10 EU/m^3 in rural and urban regions but may exceed 100 EU/m^3 around enormous sources, such as manure centres, farms and sewage treatment plants. Based on the ambient sampling campaign of Rolph et al. (2018), endotoxin is mainly associated with coarse fragments because large quantities of endotoxins can bind to create larger particles.

4 Conclusion

PM, especially fine particles ($PM_{2.5}$), is a complicated heterogeneous mixture of gases and can adversely affect human health. The chemical and biological components of PM lead to various health problems. Studies on exposure to fine PM could provide basis for establishing operational regulatory rules to reduce outdoor air pollution and directly extend life. However, research on biological components is still lacking in many countries.

Table 5 Dominant species of bio-aerosols in ambient $PM_{2.5}$ and their concentration levels across the world

Locations	Site characteristics	Pollutant concentrations	Dominant species	Source group	References
Cincinnati, Ohio, USA	Intense motor traffic, industrial area, rich vegetation land	N/A	Total fungi, 184–16,979 spores m(− 3) Total pollen, 0–6692 pollen m(− 3)	Bio-aerosols	Adhikari et al. (2006)
Beijing, China	Red alert air pollution event	Bacteria = 329.47 CFU/m^3	Classes: *Alphaproteobacteria*, *Actinobacteria*, *Betaproteobacteria* Genera: *Rubellimicrobium*, *Microbispora*, *Paracoccus*, *Skermanella*	Bacteria	Guo et al. (2018)
China	Megacity, industrial urban, suburban, coastal site	Bacteria = 1.19 × 10^5 cell/m^3	Phyla: *Proteobacteria*, *Cyanobacteria*, *Actinobacteria*	Bacteria	Gao et al. 2016
Upper Silesia, Poland	City centre, compact building development	Bacteria = Summer, 355 CFU/m^3 Winter, 65 CFU/m^3	N/A	Bacteria	Bragoszewska et al. (2017)
New Delhi, India	Busy two-lane road, industrial area	Average = 6.3 × 104 ± 2.6 × 104 CFU/m^3	*Bacillus* sp. *Bacillus firmus*, *Bacillus licheniformis*, *Bacillus cereus*, *Bacillus pumilus*, *Acinetobacter* sp. and *Acinectobactor radioresistens*	Bacteria	Agarwal et al. (2016)
Beijing, China	Continuous hazardous haze days	Fungi = 168.66 CFU/m^3	Classes: *Dothideomycetes*, *Eurotiomycetes*, *Sordariomycetes* Genera: *Alternaria*, *Cladosporium*, *Phoma*, *Aspergillus*,	Fungi	Guo et al. (2018)
Jeddah, Saudi Arabia	Urban, traffic, barren, no vegetation and farmland	Fungi = 4–28 CFU/m^3	*Aspergillus fumigatus*, *Aspergillus niger*	Fungi	Alghamdi et al. (2014)
Taipei, Taiwan	Subtropical, densely populated area, residential, traffic, industrial	Average endotoxin = 1.05 ± 0.74 EU/mg	Endotoxin	Endotoxin	Huang et al. (2002)
Sachsen-Anhalt, Germany	Lower levels of air pollution, no sources of industrial emission	Average endotoxin = 1.10 EU/mg	Endotoxin	Endotoxin	Heinrich et al. (2003)

N/A not available

Further studies should focus on the biological components of PM that have not yet been fully understood. The results would be useful for designers, engineers and researchers who endeavour to undertake research in this area.

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