1.1 Atmospheric aerosols and bioaerosols

Atmospheric aerosols are very small colloidal particles of various sizes and shapes suspended in the atmosphere (Chow et. al., 2006). The size of the aerosols generally ranges from 1 nm to 100 µm in aerodynamic diameter (Seinfeld & Pandis, 2006). Due to its small size range, it can be easily suspended in the air and travel to local and long-range distances. There is a significant link between aerosols and various atmospheric processes, human health, and other socio-economic issues that have been observed in recent eras (Kumar & Banerjee, 2013). Atmospheric aerosols show a wider impact ranging from local to synoptic scales. In the localized impact, ambient air quality and visibility deteriorate, while regional and global scale precipitation, regional haze and climate forcing are common (Dey et. al., 2012). Due to small size of aerosols, humans can be easily exposed via inhalation or skin. Along with the physical properties (size), the chemical and biological properties can also alter their effect to a large extent. Not only on the local scale, the altered properties can influence the transboundary movement of aerosols from different regions of the world (Finlayson & Pitts, 2000).

The properties of the aerosols depend on their sources i.e. natural or anthropogenic sources. Natural sources include crustal dust, sea salt from oceans, biogenic emissions (like vegetation), and mineral dust from deserts. Natural sources are considered primary sources of aerosols, and they are relatively coarser in size range. Sources of anthropogenic emissions include biomass burning, wastewater treatment process, waste processing process, vehicular emission, fossil fuel burning, forest fire, vehicular emission, crop residue burning, industrial emission, etc. (Seinfeld & Pandis, 1998). These anthropogenic sources are the secondary sources of aerosols, mainly emitting a finer size range of particles.

Aerosols originated from biological sources are commonaly reffered as bioaerosols. For example pollen from plants (10-100 µm), microorganisms like bacteria, and fungi (1-10 µm), viruses (10-100 nm) from waste, parts of microorganisms/plants microbial substances (e.g., endotoxin, mycotoxin), excreta from alive and dead animals (cat, dog, mite, cockroach) (Kim et. al., 2018) etc. The size distribution of different bioaerosols and their comparison with other atmospheric particles are shown in Figure 1.1. Bioaerosols may be viable (can multiply) and non-viable (cannot multiply) in nature, found in both indoor and outdoor environments.

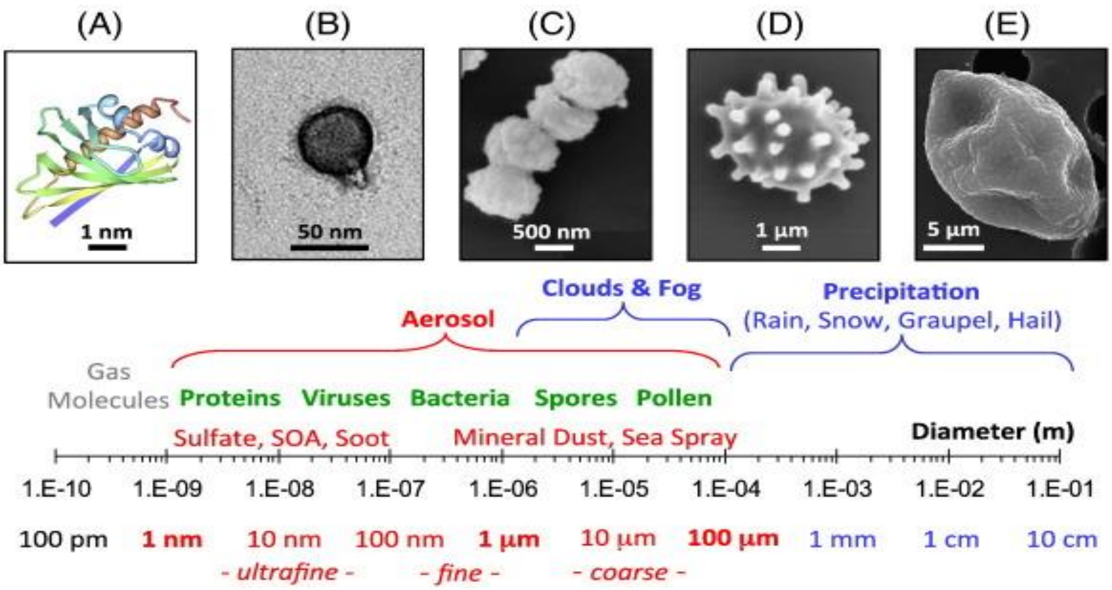

Figure 1.1 Size segregation of different bioaerosols and their comparison with other atmospheric particles (modified from Pöschl & Shiraiwa, 2015).

The concentration of the biological substances in the total particulate matter is about 28%, 22%, and 10% by volume proportionality in remote continental, populated continental and remote maritime environments, respectively (Matthias-Maser et. al., 2000). Therefore, the exposure level of the bioaerosols is different for the different regions. The biological sources contribute about 16 to 80% mass of the primary atmospheric aerosols (Jaenicke, 2005). The industrial process emits large amounts of bioaerosols in activities like agricultural production, food processing, organic waste collection, waste sorting, livestock raising, composting and wastewater treatment systems, the population working in this process have greater risk of exposure (Brodie et. al., 2007; Douwes et. al., 2003). In the upcoming decades, it must be considered that industrial activities will expand, which will create the challenge for exposure and control measures of bioaerosols.

Rapid expansion of the population needs rapid industrial development across the globe which leads to increase in the anthropogenic activities (food processing, organic waste collection, waste sorting, livestock raising, composting, wastewater treatment etc.) (Ghosh et. al., 2015). In the higher populated contries like India and China and other developing contries, bioaerosols are one of the primary concern for the health associated problems (Pearson et. al., 2015). Recent studies highlighted the concern of the health risk associated with the bioaerosols (e.g. allergies, respiratory issues etc.) in various indoor and outdoor environments (Ghosh et. al., 2015). In the recent COVID-19 pandemic, the exposure of bioaerosols in the form of virus-carrying particles or fungal bioaerosols in recovered patients or immuno-suppressed patients was a great concern (Vishwakarma et. al., 2022). It is reported that children have higher risk of exposure dose of bacterial and fungal bioaerosols than adults (Morakenyo et. al., 2019). Apart from humans pets and husbandry animals are also distressed by the increasing prevalence of bioaerosols exposure. The exposure of different fungal bioaerosols on crops has been the topic of attention in the agriculture field for many decades (Yadav et. al., 2020).

The Earth system depends heavily on biologically derived aerosols, especially when it comes to the interactions between the atmosphere, biosphere, and climate (Després et al., 2012; Fröhlich-Nowoisky et al., 2016). According to Fahlgren et al. (2011), aerosolized bacteria and fungus can be found in the troposphere at elevations of up to 10–20 km and in the stratosphere at elevations of up to 20–40 km above sea level. Changing environmental conditions can change the dispersion of microbes amount and distance from the source. This relation could increase the health risk due to pathogens and allergenic components from one place to another. Along with all these, the study of bioaerosols is very important in contributing to the defence system from biowarfare.

1.2 Bioaerosols and human health

In recent decades, exposures of bioaerosols to human beings have also been investigated, considering an increase in the number of asthma and allergy cases. These allergies and other associated diseases depend on the size of bioaerosol particles and their capability to penetrate the respiratory system (Madhwal et. al., 2020). The details of the bioaerosols penetration in the human respiratory system are shown in Figure 1.2.

Higher concentration dose of bioaerosols are more potent to cause several diseases (Osunmakinde et. al., 2020; Peter, 2014; Wei et. al., 2017). It was observed that unorganized buildings with poor ventilation and waste management could enhance exposure to dust and microorganisms, which can cause some diseases (Gerasymov, 2020). Sometimes health problem associated with buildings are (i.e., sick building syndrome) because of poor ventilation are good examples of bioaerosols-associated pollution in indoor environment (Eduard et. al., 2012; Huo et. al., 2020). It was recently observed that a moderate level of continuous bioaerosols exposure might significantly increase the symptoms of highly prevalent diseases in humans and animals (Eduard et. al., 2012).

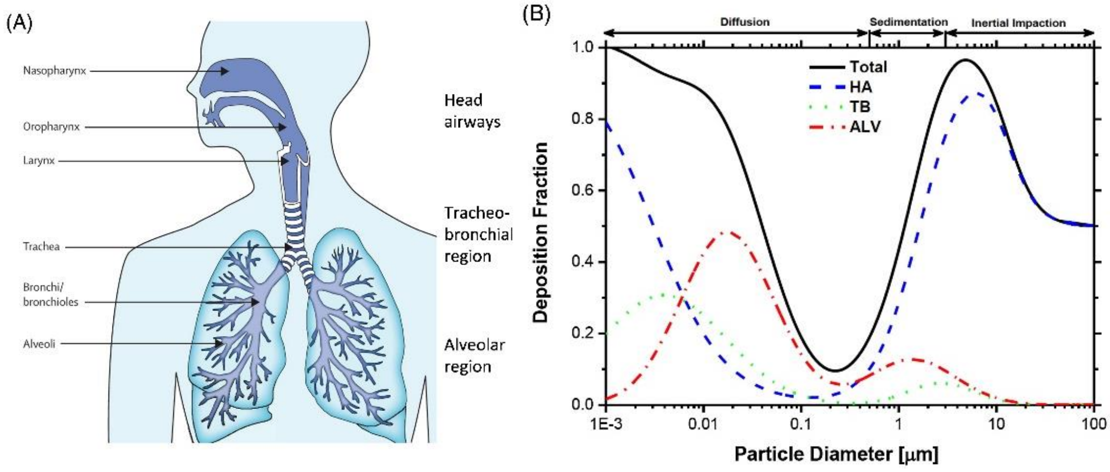

Figure 1.2 Deposition of inhaled particles: (A) human respiratory tract and (B) predicted total and regional particle deposition in relation to particle size, based on the International Commission on Radiological Protection (ICRP) deposition model for nasal breathing and light exercise and deposition mechanisms. HA: head airways; TB: tracheobronchial region; ALV: alveolar region (Guarnieri & Balmes, 2014).

Widespread use of antibiotics as a growth promotors of livestock, the worker of handling process are greater risk of the exposure of bioaerosols emitted from the source and process (Bonfoh et. al., 2010; Douwes et. al., 2003). In the last few decades, many countries and groups have been working on using pathogens like viruses, bacteria, fungi, etc., as biological weapons in the war (Shafazand et. al., 1999). Anthrax is one the famous example of bioweapon which was spread from envelop in USA during 2001, causing many deaths where *B. anthracis* spores were used (Anderson & Bokor, 2012). COVID-19 is a recent example of an infectious disease and its lethality associated with bioaerosols. The indoor bioaerosols effect on the post-COVID-19 patients, where the body was immuno-compromised, could be affected by indoor fungal bioaerosols exposure in the form of black fungus and others (Vishwakarma et. al., 2022).

1.3 Bioaerosols and food security

Bioaerosols, comprising diverse biological particles like fungal spores, bacteria, and viruses, play a significant role in agricultural ecosystems. Emerging fungal diseases (EFDs) pose a growing threat to global food security, particularly in India, where agriculture is a key economic sector (Fisher et. al., 2012). The fungal spores have the ability to travel long distances via air currents (Brown & Hovmoller, 2002), increasing their potential to spread diseases such as rice blast (*Magnaporthe oryzae*) and wheat rust (*Puccinia graminis*), leading to substantial crop losses (Fisher et. al., 2012). For example, rice has been reported to be affected by multiple fungal species, while wheat faces repeated infections from *Puccinia striiformis.* For instance, one outbreak eradicated up to 60% of wheat plantations in Himachal Pradesh, Late blight caused by *Phytophthora infestans* has resulted in up to 75% production losses in areas like Punjab and West Bengal. Diseases such as bud rot (*Phytophthora palmivora*) and Panama disease (*Fusarium oxysporum*) have reduced yields by 50–75% in southern states like Kerala and Tamil Nadu, guava wilt caused by *Fusarium oxysporum* led to 70–80% yield losses in Uttar Pradesh, severely impacting farmers livelihoods. Similarly, apple scab (*Venturia inaequalis*) resulted in over 70% harvest losses in Himachal Pradesh (Yadav et. al., 2020). A research conducted in 2008 suggested that *P. infestans* causes an estimated $6.7 billion in potato crop losses annually worldwide (Haverkort et. al., 2008). These diseases not only threaten food supply but also impose severe economic burdens on farmers. Sensitive ecosystems, including the Himalayan and Western Ghats regions, are at particular risk due to their unique topography and biodiversity. Approximately 48% of the 261 disease alerts reviewed over 20 years in India were attributed to fungal-related diseases, outstripping bacterial and viral alerts (Yadav et. al., 2020). The data reveals that the role of fungal bioaerosols is a growing challenge to food security, especially in climate-sensitive regions, and calls for immediate policy and research interventions to safeguard agricultural productivity.

1.4 Atmospheric interaction of bioaerosols

The environment near the earth surface is most affluent in the biological particles because most of the bioaerosols are released in this domain. The cumulative effect of the transport process influences species distribution, the rate of evolution and the emergence of new species, and the ability of species to adapt to shifting environmental conditions in the study of bioaerosols.The interaction of bioaerosols with the atmosphere is shown in Figure 1.3.

Atmospheric circulation and gravitational settling are essential for the atmospheric movement of suspended particles, both biological and non-biological in origin. Some of

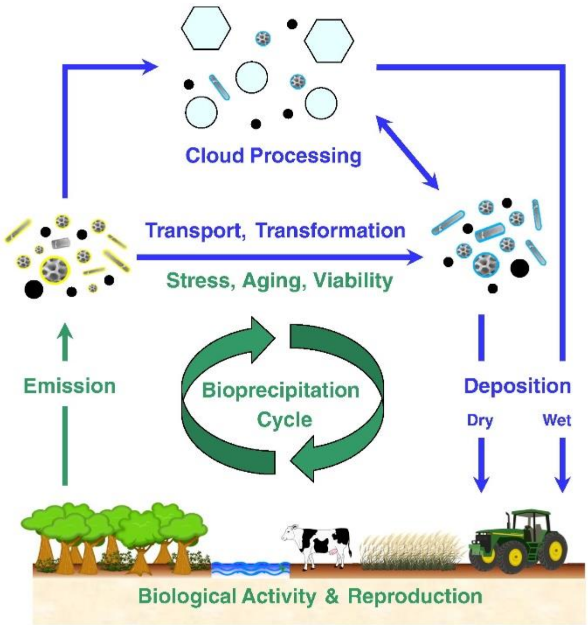

Figure 1.3 Interaction of bioaerosols with the atmosphere (Adapted from Pöschl & Shiraiwa (2015) and Pöschl (2005)).

bioaerosols can also be found within ice crystals or water droplets in the air. Depending on its aerodynamic diameter, this particle may remain in the atmosphere for a few hours to a few weeks. Furthermore, may scavenge by either precipitation or deposition on various surfaces (Després et al., 2012; Fröhlich-Nowoisky et al., 2016). Dry deposition (i.e., sedimentation or impaction onto the surface) effectively removes particles with an aerodynamic diameter of 10 µm or greater. Biological particles have complex structures, i.e., asymmetric shape, rough texture, and pores, and their aerodynamic size also vary significantly. Fungal spores and pollen, are examples of bigger particles that have evolved to be aerodynamically buoyant. Microorganisms can occasionally be discovered in the atmosphere in the form of clumps or linked to other particles, and their aerodynamic diameter can be more or less than their physical diameter (Lighthart, 2000; Reponen et al., 2001). Rain or drizzle effectively removes particles with a diameter of around 0.1 to 10 µm. According to reports, a tiny shower, even a light drizzle could effectively remove a higher proportion of airborne particles. (McDonald, 1962).

The buoyancy and ice nucleation (IN) activities showed minimal change, therefore they are addressed similarly in most model investigations of mineral dust occurrences. Desert dust is carried with bacteria-carrying particles during storms, and satellite observations can reveal this. The biological particle has the same width and buoyancy as the mineral or dust particle being transported through the air. These particles are transported together with the dust during dust storms, as evidenced by satellite data. Satellites are still unable to detect biological particles during dust storms (Wilkinson et al., 2012). Bioaerosol transport has been extensively studied using Gaussian plume models (up to ~100m) (Skelsey et al., 2008). For regional and global transportation, Lagrangian stochastic models (Sofiev et al., 2006) and Global climate and transport models (Wilkinson et al., 2012) are employed, respectively. The primary focus of bioaerosol investigations is the spread of illness (human, plant, and animal) on a regional and local scale (Isard et al., 2005).

Aerosols are an important factor in producing the nucleus that initiates the creation of cloud droplets, hence influencing the cloud's microphysical features. The active particles function as cloud condensation nuclei (CCN) based on their size, composition, and hygroscopicity. CCN is formed when biological particles' surfaces become wettable (Ariya et al., 2009). At lower supersaturation, the biggest biological particles (e.g., pollen grains) form bigger droplets known as 'giant CCN'. It can create cloud droplets and other aerosol particles, and it rapidly expands into larger droplets, encouraging rain formation (Pope, 2010).

Water's hygroscopicity is defined as the increase in diameter relative to dry diameter (also known as the diameter growth factor) or the mass of water taken relative to dry mass at a specific relative humidity (RH) below the saturation threshold. The diameter growth factors (GF) of bacteria and fungi range from approximately 1.05 to 1.3 at RH=98%, while those of inorganic salt particles, such as sodium chloride, have a growth factor of approximately 1.65 at RH=98%. Although pollen grains do not exhibit a significant increase in geometric size growth in response to relative humidity, they can hold up to three times their dry weight in water when RH=95% (Diehl et al., 2001). According to Bauer et al. (2003), bacteria have a more extensive range of GF, ranging from 0.07 to 2. Compared to artificial seawater without exudate, the algal exudate decreases the hygroscopicity and CCN activity of sea spray particles (Fuentes et al., 2011; Wex et al., 2010).

Even though cloud water droplets directly freeze at 0°C, they remain in a supercooled liquid condition in the atmosphere until the temperature drops to about -38°C. In order to promote ice formation by heterogeneous freezing, the particle needs ice nuclei as the atmosphere's temperature rises. Condensation freezing occurs when the cloud droplets'

CCN functions as IN during their development phase, while immersion freezing occurs when the ice nucleus freezes inside the cloud droplets. Another instance, known as "contact nucleation," occurs when the supercooled liquid and the aerosol particle collide and freeze. According to Augustin-Bauditz et al. (2014), the vapour phase is directly transformed into ice during the dry deposition phase. Freezing a fraction of the cloud droplets into ice causes glaciations, in which the entire fraction of the cloud or faction inside the cloud becomes ice. When RH goes below the water saturation level, glaciations are triggered by the variable levels of saturation pressure over supercooled liquid water and ice, resulting in the deposition of ice crystals (Storelvmo & Tan, 2015). This process also defined the creation of big crystals, which typically fall below water saturation. Ice multiplication takes place in the atmosphere as well. Ice crystals generated using pre-existing crystal examples may include the production of ice splinters during the riming of ice particles. Several investigations have shown that mineral dust particles can form ice nuclei. Soot particles can form a nucleus at lower temperatures. It is shocking to learn that the IN identified so far is of biological origin.

1.5 Sustainable development and bioaerosols

The main objective of many sustainability goals is to ensure the sustainability of cities and society. According to this perspective, it is vitally important to comprehend the significance of sustainability indicators. The three pillars of sustainability: social, economic, and environmental are currently the primary criteria used to evaluate it. A fourth pillar: the institutional dimension, becomes more significant as a result of increased understanding in this area. Addressing bioaerosol-related challenges aligns closely with the Sustainable Development Goals (SDGs), particularly in the areas of health, environmental quality, climate resilience, and sustainable urban development. The significance of sustainability indicators based on health, such as bioaerosols, must also be understood by the next generation. In order to guarantee the sustainability of diverse professional contexts, researchers might specifically focus on the fate of source-specific bioaerosols. Additionally, recent sporadic events indicate that newly discovered biologically derived pollutants may be far more harmful (Singh et. al., 2024). Integrating bioaerosol management into environmental policies, urban planning, and public health initiatives can directly support SDGs, particularly health (SDG 3), clean water (SDG 6), and sustainable cities (SDG 11). A proactive, multi-disciplinary approach will enable societies to mitigate bioaerosol risks while advancing toward healthier, cleaner, and more resilient environments.

Being a highly populated and agriculturally dominant region, IGP need to explore the exposure of the bioaerosols on humans and agriculture. Along with the emergence of pathogenic nature and antimicrobial resistant properties in microbes, there is a need to study them in various indoor, outdoor and in the process of various anthropogenic activities. How the atmospheric process and meteorological parameters affect the survival of the microbes. These are the central questions which thesis seek to answer. So, this study aims to characterise bioaerosols dynamics in the Indo-Gangetic Plain, integrating microbial composition, seasonal variability and health risk assessments to inform air quality policies and public health strategies. This is the first kind of work where a detailed investigation of particulate matter over the selected urban location in the middle IGP was carried out. For these various outdoor sites, such as agriculture fields, traffic, dumping sites and waste treatment sites, were selected where human involvement is prominent. Similarly, various indoor sites such as a cowshed, a poultry, a hospital, a laboratory, a library, an auditorium, and a canteen were chosen so that the exposure of bioaerosols on humans in indoor environments can be estimated. These sites can be representative sites for the various indoor and outdoor environments where humans are exposed for a longer time. Along with the humans, the bioaerosols study in the agriculture field has the potential to predict crop diseases. Seasonal bioaerosol analysis at various outdoor sites was performed to understand bioaerosol properties over the seasonal variation, and attempts were made to understand the variability of bioaerosol concentration and diversity during atmospheric events like fog. Some anthropogenic sources of bioaerosols were also investigated in detail using metagenomics analysis and antibiotic resistance properties. The health effect assessment was done using survey-based analysis. To understand the bioaerosol exposure at various indoor sites, various animal and human-dominant sites were also studied. Such findings will fill the existing scientific gap over the central part of IGP, mostly in terms of aerosol's biological properties, and it will help in developing suitable mitigation strategies for indoor and outdoor pollution over the region. This research has potential to make a significant contribution to environment and human health.