Advanced Bio-Nanomaterials for Mitigating Airborne Pathogens in Urban Polluted Environments

Editors

Ako Amanj Raheem Abdullah
Department of Environmental and Pollution Engineering Technologies, College of Engineering Technology/Kirkuk, Northern Technical University, Iraq

Ali Salahudoin Asgher Mahmood
Department of Environmental and Pollution Engineering Technologies, College of Engineering Technology/Kirkuk, Northern Technical University, Iraq

Gailan Jibrael Asaad Ali
Department of Environmental and Pollution Engineering Technologies, College of Engineering Technology/Kirkuk, Northern Technical University, Iraq

Ibrahim Sabahha Wez Hassan
Department of Environmental and Pollution Engineering Technologies, College of Engineering Technology/Kirkuk, Northern Technical University, Iraq

Ziad Emad Salman hamza
Department of Environmental and Pollution Engineering Technologies, College of Engineering Technology/Kirkuk, Northern Technical University, Iraq

Bright Sky Publications ™
New Delhi

Published By: *Bright Sky Publications*

Bright Sky Publication
Office No. 3, 1st Floor,
Pocket - H34, SEC-3,
Rohini, Delhi, 110085, India

Editors: *Ako Amanj Raheem Abdullah, Ali Salahudoin Asgher Mahmood, Gailan Jibrael Asaad Ali, Ibrahim Sabahha Wez Hassan and Ziad Emad Salman Hamza*

Edition: *1st*

Publication Year: *2025*

Pages: *90*

Paperback ISBN: *978-93-6233-574-6*

E-Book ISBN: *978-93-6233-726-9*

DOI: *https://doi.org/10.62906/bs.book.486*

Price: *₹565/-*

Abstract

Airborne pathogenic microorganisms mainly comprise fungi, bacteria and viruses. Though their abundance, richness and diversity are strongly affected by environmental factors, urban regions usually present a high concentration of pathogenic species involving health risks associated with allergic diseases, septicaemia and respiratory infections. Pathogenic and spoilage fungi are commonly found both in atmospheric and on building-envelop surface bioaerosols, and the genus Aspergillus is the main responsible for the accumulation of mycotoxins in the air. Recently, emerging pathogens in the genus Malassezia have also been detected in atmosphere samples. A significant number of pathogenic bacteria are also airborne and their presence in the atmosphere has been confirmed in temperate, tropical and polar climate zones. Beck *et al*. suggested the possible pathogenic role of airborne M. luteus and S. saprophyticus, which may be implicate in septic invasion risk in immunocompromised individuals. Airborne viral communities have been characterized and described, but little is known about their pathogenic potential. Importantly, urban dried environments can be populated by a wide spectrum of different pathogenic virulent species, including members of Enterobacteria, Bacillus and Pseudomonas genera.

Increased urbanization with a lack of vegetative ecosystems has a major impact on the global composition of bioaerosols. In these polluted urban areas with reduced natural vegetative cover, the bioaerosol fractions emitted represent a major source of allergenic and pathogenic loads affecting public health. It is, therefore, crucial to reduce the abundance of pathogenic bioaerosols in urban environments. This can be achieved by

coating bioactive, nanostructured materials, such as silver, copper, zinc or titanium, on building envelope surfaces. Grouped under the rubric of concrete nanotechnology, these materials could potentially lead to new antifungal, antibacterial and antiviral urban anticontamination solutions based on the bioactivity of the deposited metal or metal oxides.

Content

Chapter - 1

Airborne Pathogens in Urban Polluted Environments

Airborne pathogens such as bacteria, fungi, and viruses threaten human health and are major causes of human mortality worldwide. Airborne infections are a common consequence for humans living in urban polluted environments. The long-term exposure and development of diseases may be exacerbated by urban air pollutants. Pollutants, particularly heavy metals which have high solubility in an aqueous environment, change the redox environment in the infection area and favor the infection of lungs, stimulating the growth and pathogenicity of airborne pathogens.

Increasing infections and diseases caused by airborne pathogens in urban polluted environments represent a severe concern for society. Efficient elimination of airborne pathogens is mandatory, but conventional methods such as chemical disinfectants and physical sterilization lead to secondary pollution and work only in localized areas. Therefore, researchers are focusing on developing advanced bio-nanomaterials that can mitigate airborne pathogens with multifunctional capabilities. Such bio-nanomaterials may trap or kill airborne pathogens, regulate environmental humidity to avoid spread, and alleviate the damage caused by inhalation of pathogens and urban air pollutants. Airborne pathogen-involved diseases and their relationship with air pollutants and humidity are briefly summarized [1, 2, 3, 4].

Classification of airborne biological agents

Airborne biological agents for contamination classification include bacteria, fungi, and viruses. Classification basis is generally associated with pathogenicity and no animal tests, but airborne fungi are classified through their economic importance. Pathogenicity is related to virulence, infectious dose, potential for human exposure and mortality, ease of transmission, and availability of prevention or treatment. The degree of pathogenicity for fungi is classified into three groups: Group I infectious only in immunocompromised people, Group II and Group III are of major concern. The biological agents that are non-pathogenic for animals can be divided into the following groups based on the risk assessment pattern but without clinical severity.

In addition, other areas of concern for the transmission of airborne biological agents in the urban environment must be considered, such as the concentration of airborne bacteria and their relationship with meteorological parameters, forecast of concentration of bacteria in the air of cities, role of rain in the concentration of airborne bacteria, detection of pathogenic bacteria, effect of the presence of urban trees on the concentration of airborne bacteria, analysis of nonpathogenic fungi and development of models for predicting concentrations fungal spores present in the ambient air.

Airborne biological agents are classified under Group III, based on animal and human exposure, the highest risk for all urban centers and the international attention in trade and tourism transport. Vegetal and non-pathogenic biological agents present a lower risk but are of high economic importance. Finally, the most relevant work sections developed in the literature for the assessment of the concentration of airborne biological agents are presented [5, 6, 7, 8].

Sources and transmission pathways in urban settings

Airborne biological hazards in urban transport infrastructure pose growing public health and biosecurity risks [9]. Hazards have been associated with urban transport systems, transmitted via roads, rail, air, and waterways. Vulnerabilities depend on design, construction, and operation, dictating whether hazards can enter and propagate through urban transport networks. Increasing urbanisation, particularly in megacities, brings higher mobility and greater exposure to such pathogens during transit. Safeguarding transport systems from biological hazards requires an integrated approach merging security and public health across their planning, construction, and operational phases to build resilient urban transport infrastructure.

Interaction between air pollutants and pathogens

Air pollutants in urban environments can co-exist with airborne pathogens, and certain air pollutants may facilitate pathogen dispersion. Recent studies have highlighted a relationship between urban air pollutants and pathogen transmission. Specifically, urban particulate matter has been shown to contain a wide variety of microorganisms, including bacteria, fungi, and viruses, and to enhance their infectivity [10]. Airborne bacterial pathogens, such as those from Pseudomonas, Mycobacterium, Legionella, Streptococcus, and Staphylococcus species are known to pose a serious risk to human health, contributing to respiratory infections and aggravating allergic conditions. Similarly, viruses such as H1N1 influenza, SARS-CoV-2, and enterovirus are also recognised airborne pathogens.

The airborne microbiome plays a crucial role in public health, and several environmental factors that influence its composition have been reported. Ultrafine particulate matter (<100 nm), commonly present in urban air pollution, can interact with airborne pathogens and is suspected to play an important role in a number of disease transmission processes [11]. Urban air pollution, mainly derived from fossil fuel combustion, can adhere to airborne microorganisms and dampen immune responses, thereby facilitating the transmission of extant or novel pathogens. Additionally, the simultaneous inhalation of airborne pathogens and particulate pollutants can cause bacterial superinfection in the lungs [12]. Co-contamination of airborne transmission pathogens with particulate matter may potentially enhance the infectivity of airborne pathogens, not only increasing the risk of respiratory viral infections but also aggravating allergy-related respiratory diseases. Co-exposure to particulate matter also enhances the infectivity of H1N1, SARS-CoV-2, and other airborne pathogens. Particulate matter serves as a vector for airborne pathogens by promoting bacterial adherence to lung cells, thereby lowering the infectious dose required to establish an initial infection.

Epidemiological trends in polluted мегacities

Around 9 million premature deaths annually are attributed to indoor and outdoor air pollution, manifesting alarmingly as an enormous increase in the rates of cardiovascular, chronic obstructive pulmonary disease, and even lung cancer [13]. Longitudinal studies have demonstrated how airborne microbiota during the last decade can cause asthma and respiratory infection in polluted megacities [14].

Public health burden and risk assessment

The alarming increase of chronic pulmonary diseases in urban populations is well documented. Chronic obstructive pulmonary disease (COPD) ranks among the top ten leading causes of death and disability worldwide, while asthma affects more than 300 million people globally. Several epidemiological studies have associated ambient PM2.5 exposure with restricted ventilation and increased hospitalizations for asthma and other respiratory diseases. Pulmonary exposure to submicron particulate matters can lead to serious acute and chronic lung diseases [15]. A comprehensive study assessed the lung disease burden arising from chronic inhalation exposure to silver nanoparticles (AgNPs) in urban polluted environments. Despite the increasing use of consumer products containing nano-silver, the associated risk to human health remains poorly understood, and awareness of potential hazards is limited. Daily commercial use of products containing AgNPs contributes to indoor airborne exposure, and the ability to estimate exposure levels, lung burden, and corresponding health impacts through a probabilistic framework constitutes a clearly defined research gap [16].

Chapter - 2

Fundamentals of Bio-Nanomaterials

Definition and classification of bio-nanomaterials

Nanomaterials are constituted as materials with structures spanning a range from atomic/molecular dimensions to a size of 100 nm, and possess unique physical, chemical, and biological characteristics [17]. Based on the aforementioned criteria, bio-nanomaterials can be classified as:

- Bio-nanomaterials that contain one or more material components extracted from numerous biological sources.
- Bio-compatible nanomaterials that do not interact with biological interfaces during their intended life cycles.
- Bio-functional nanomaterials that can interact, and trigger a biological response within a targeted biological system [11].

Bio-nanomaterials have received particular attention in recent years owing to their huge potential for developing actual and immanent biomedical applications. Bio-nanomaterials are further classified into four categories: bio-detected, bio-degradable, bio-imaging, and bio-magnetic materials. When bio-nanomaterials combine themselves with numerous drugs, they essentially lead to a better delivery, prolonged release, and enhanced targeting efficiency of drugs to treat fatal diseases such as cancer, TB, virus infection, and cardiac problems. Bio-detected nano-platforms begin to serve as a bio-nano structure that can be used to identify specific pathogens. Anti-biofouling coatings with bio-degradable properties stand out as a sustainable solution for the marine industry to develop self-cleaning, sustainable anti-fouling systems.

Physicochemical properties relevant to pathogen control

Indoor air qu07d77f43-8d38-4ed6-b0c4-b50fc2861d96ty (IAQ) influences human health through exposure to airborne microorganisms and gaseous compounds emitted by various indoor sources [18]. Filter media are crucial for trapping bioaerosols carried by indoor air, and the incorporation of antimicrobial agents in filter fabrics provides a dual solution: pathogen removal and the inactivation of microorganisms retained by the filter [19]. Cotton filter media doped by silver, zinc, and iron nanoparticles were investigated for simultaneous removal and disinfection of airborne Escherichia coli. The dopants form coprecipitated nanoparticles that are well anchored to the fibers' surface to minimize leaching. Filter samples were exposed to cold-bright light during bacterial spiking to evaluate their concurrent collection and disinfection efficacy under re07d77f43-8d38-4ed6-b0c4-b50fc2861d96stic operational conditions.

Biological compatibility and functionalization

Due to the toxic reaction and human sensitivity to polluted air, it is important to use practical and economical materials in order to deactivate micro-organism contaminants. Contaminated air might carry airborne bacteria and/or various viruses that could pollute the air and cause the spread of epidemics, thus modifying air filters with biocides to obtain biocidal filters seems a clear solution. Effective coatings would neutr938355e8-05c0-4def-a2ca-58f1b8d32c84ze air-filter-bound contaminated microbes. Thus, coating materials need to incorporate biocides that react with and kill the microbes coming from contaminated air. As filter coatings might become contaminated in practical use, materials exhibiting permanent biocidal effects were considered. Non-biocompatible and potentially harmful bactericides, such as silver nitrate and heavy metals, are being used and thus, compatibly biocompatible but still effective against airborne viruses and bacteria are needed. Various biocides have been studied with airborne effectiveness using coating materials such as various biocoatable and various biocidal polymers on various filter materials [18].

Nanomaterial-pathogen interaction mechanisms

The mechanisms involved in nanomaterial-pathogen interactions are diverse and complicated [11]. Numerous factors affect the potential exposure of pathogens and the intensity of interaction with nanomaterials. These factors encompass the different types of nanomaterials, their dimensions, concentrations, and surface characteristics, alongside vital influences from environmental inhabitants, such as pH, temperature, relative humidity, and exposure time. Nanomaterial /pathogen interactions take place through a combination of empirical and reactive means. Following the initial aggregations between nanomaterials and airborne pathogens, airborne pathogens often bring contamination and retention to surfaces through in-depth connection, enzymatic degradation, and biogenic metabolic adsorption, leading to microbial growth crud.

Safety and environmental considerations

Health hazards associated with airborne nanomaterial exposure can be mitigated by effective particle capture in transportation and purification systems, along with protective measures such as personal protective equipment and real-time monitoring [20]. Predictive models quantifying released doses, exposure durations, and potential internal body burdens inform safety assessment strategies. Dose-dependent cytotoxicity, genotoxicity, and related mechanisms are similarly characterized and linked to material, exposure, and environmental parameters. Transport models and environmental fate assessments further evaluate long-term implications for ecosystem health. Risk assessment methodologies integrate qualitative and quantitative analyses of these exposure dimensions to facilitate safe implementation.

Regulatory conditions and ethical frameworks also influence practical deployment of bio-nanomaterials. Nanomaterials regulated under existing frameworks (e.g., food, cosmetics, chemicals, pesticides) are covered by European Union Registration, Evaluation, Authorisation and Restriction of Chemicals (REACh) legislation mandating risk evaluations before urban usage. Unregulated contexts invoke societal considerations spanning philosophic, political, and socioeconomic domains. Adoption of standardized norms governing material assessments and monitoring of their potentially hazardous behaviour in urban environments forms the principal objective of the ethical dimension, while regulation concentrates on specifying criteria meeting the requirements of current standards.

Chapter - 3

Urban Air Pollution as a Facilitator of Pathogen Survival

Particulate matter as microbial carriers

Studies of urban atmospheres reveal bacteria associate with atmospheric particulate matter (PM) and other airborne particles, leading to these hitherto innocent carriers being recognized as significant reservoirs of potentially harmful pathogens [10]. PM with a size <2.5 µm can penetrate human airways and has been associated with increased susceptibility to airborne viruses. The viable bacteria load in PM increases with outdoor temperature in urban areas and correlates positively with airborne dust and PM concentration overall, indicating that bacteria may remain in viable yet dormant states in colder months [11]. Investigation of the urban atmosphere of Harbin shows that large PM particles containing unfixed cells, unlike the free biocells which are detoxified through photodegradation, are the principal vehicle for environmental pathogens. Pathogens such as Pseudomonas aeruginosa (PA) survive in various dry states and are frequently transported in urban PM. Co-exposure to PA-laden PM in the range 0.3-10 µm impairs the upper respiratory system and compromises overall health. Particles from public transport and construction sites significantly increase the risk of PA infections porque they are enriched with viable bacteria and the urban atmosphere favors biosafe pathogens.

Chemical pollutants and microbial virulence

Air pollution exacerbates terrestrial and aerial viral pathogenic dissemination, intensifies microbial virulence, and deteriorates air quality, fostering the spread of airborne pathogens. Numerous airborne diseases stem from microbial proliferation, elevating infection, hospitalization, and mortality rates. Exposure to atmospheric pollutants-such as particulate matter, volatile organic compounds, ozone, carbon monoxide, polycyclic aromatic hydrocarbons, and nicotine-has been shown to upsurge viral infectivity and pathogenicity, posing a severe risk to public health [12].

Bioaerosol persistence in polluted atmospheres

The persistence of airborne bioaerosols in polluted urban environments is a substantial challenge related to the mitigation of harmful airborne pathogens. A bioaerosol is defined as aerosol particles of biological origin larger than 0.5μm that are inactive and viable [21]. It can include bacteria, viruses, pollen, fungal spores, cattle dander, and plant material. The composition of terrestrial bioaerosols fluctuates according to the emissions, ambient meteorological conditions, and the location of anthropogenic activities. Undoubtedly, the persistence of airborne bioaerosols in polluted urban environments has severe implications on the airborne transmissibility of pathogens. Bioaerosols can constitute one of the transport pathways of infectious diseases through aerosols and surfaces in enclosed environments [22]. The presence of bioaerosols has been demonstrated to be associated with human and animal pathogens that are of importance to public health. Various researches have suggested that urban pollution has a detrimental impact on the airborne bacterial component in regard of concentration, viability and physical size.

The airborne bacterial concentration, viability and physical size distribution in the urban microenvironment is highly affected by dust and other pollutants. Human population and human-derived activities such as illegal scavenging and fishing for food increase the level of urban pollution. When airborne dirt dust is emitted to atmosphere through various anthropogenic practices, it substantially decreases the [concentration, viability, size-distribution] of airborne bacteria. Long-range airborne bioaerosols can be generated through atmospheric exhalations during the inhalation and exhalation process of human beings. The released airborne bioaerosols can impact the respiratory health of a wide range of facilities in urban environments like hospitals, airports and community centres because they can easily spread infectious diseases. The monitoring and evaluation together with effective algorithms need to be considered to protect the respiratory health of the mankinds in urban environment.

Synergistic effects of pollution and pathogens

Air pollution, especially particulate matter (PM), can increase health risks and facilitate pathogen transmission, including bacteria, fungi, and viruses. Pathogens may attach to dust particles or droplets as bioaerosols, raising concerns about co-exposure effects. Many studies have linked PM pollution to respiratory infections, such as influenza, tuberculosis, and COVID-19, but the effects of simultaneous exposure to PMs and pathogens remain unclear. Research indicates bacteria can enter the human body through the respiratory tract, causing infections, toxicity, allergies, or cancers. Fine particulate matter can promote bacterial adherence, ROS generation, and impair immune functions, increasing vulnerability to infections. However, most studies have examined the effects of PMs and pathogens separately, with limited understanding of co-exposure scenarios. The role of the upper respiratory tract in defending against co-exposure has been largely overlooked. Investigations using in vitro and animal models have shown that co-exposure to PMs laden with pathogens damages the upper respiratory system and affects overall health, highlighting the importance of understanding synergistic effects of pollution and pathogens [10].

Urban air pollutants and inhaled nanomaterials can modify the human respiratory microbiome, impacting health. Phylogenetic composition of indoor and outdoor airborne and surface microbiomes differs, with outdoor urban microbes more likely to originate from human activity. The respiratory system comprises a complex microbiome that acts as a barrier to pathogens. Lactobacillus, Prevotella, Veillonella, and Streptococcus are major genera present. Co-encounter of airborne nanomaterials and respiratory pathogens may alter microbial communities and change abundance of potential pathogens such as Pseudomonas and Staphylococcus. Increased pneumonia cases following nCoV-2019 protein detection on airborne particles indicate enhanced respiratory infection exposure. Increasing use of nanomaterials in architecture, building, and interior industries calls for investigation of microbial communities and interaction with other particulates in the respiratory system and their correlation with lung health [11].

Airborne diseases are transmitted directly from person to person or via contact with surface biofilms. Virus-laden PMs can act as carriers, adhering to mucous-covered surfaces and facilitating viral transfer. NA2O, a water-soluble, non-toxic, and environmentally friendly material, has low attachment efficiency on PMs. However, previous studies have shown that when combined with certain polymeric substances, its attachment rate improves. Pathogen presence greatly reduces the bacterial self-cleaning efficiency of air filters. Therefore, developing a biocidal coating compatible with local conditions and requiring only one-step surface modification is crucial. Polymers with longer chain lengths exhibit better biocidal performance on indoor pathogens, and anti-biofouling surfaces with high antibacterial ability allow greater potential [12].

Modeling pathogen dispersion in urban air

The indoor spread of pathogens in urban environments has also received attention. Room-level airborne transmission has been addressed using a combined computational fluid dynamics and susceptible-exposed-infected model [23]. The model generates airflow patterns from building geometry and occupant movement and can evaluate prevention measures, like ventilation, air purification, and exposure management.

A broader approach to pathogen dispersion modeling has been developed by a network of biosensors [24]. A convection-diffusion-sedimentation model solves the governing equations to reveal how pathogen transport affects liquid bioaerosol sampling over a range of distances and timescales. Other tools based on computational fluid dynamics are also available.

Chapter - 4

Antimicrobial Nanoparticles for Airborne Pathogen Mitigation

Metal and metal-oxide nanoparticles

Metal nanoparticles and metal-oxide nanoparticles have gained considerable attention for their antimicrobial properties and use in air filtration systems [18]. Silver, zinc, and iron nanoparticle-doped cotton filters (AgCt, ZnCt, FeCt) were evaluated as biocidal filters for airborne bioaerosol attenuation. These nanocomposite filters exhibited 100% viable removal efficiency against airborne E. coli. AgCt filters demonstrated a lower pressure drop compared to FeCt, ZnCt, and untreated cotton filters, along with enhanced collection efficiency and disinfection capability. The results indicate that nanocomposite-doped filter media, especially AgCt, effectively protect against airborne pathogens while maintaining favorable performance characteristics for practical biocidal applications. Copper nanoparticle-coated materials also show significant antiviral and antimicrobial activity in air filtration applications. Coatings on polyethylene and polypropylene fibers achieved over 90% reduction of influenza and SARS-CoV-2 viruses within 2 hours. HVAC filtration media function 07d77f43-8d38-4ed6-b0c4-b50fc2861d96zed with copper nanoparticles attained 99% reduction of diverse viral and bacterial strains, including SARS-CoV-2, Pseudomonas aeruginosa, and Escherichia coli. Moreover, the coatings remained stable and did not release nanoparticles into the airflow. These findings suggest that nanoparticle-coated materials can enhance air filtration systems in healthcare environments, mitigating pathogen transmission, biofouling, and secondary risks [25].

Carbon-based nanomaterials

As new generation adsorbent materials, play a vital role in the removal of airborne pathogens. These materials are cost-effective and possess multifunctional properties. The various forms of carbon-based nanomaterials are function 07d77f43-8d38-4ed6-b0c4-b50fc2861d96zed carbon nanotubes (f-CNTs), carbon dots, graphene, and graphene oxide (GO). Graphite and graphene oxide are two carbon-based nanomaterials that have received attention for their ability to hasten the evaporation rate of moisture through reduced surface tension. The use of a graphene oxide-coated bio-template in the manufacture of an air filter has been reported; this air filter not only absorbs formaldehyde effectively but also erodes bacteria colonies such as Bacillus subtilis and Escherichia coli. Graphene-based nanomaterials have also been integrated with Ag, Cu, Zn, and CuO to form composites for the removal of airborne pathogens. A GO-KOH-H_2O filter bag was developed for the efficient removal of gaseous and bioaerosol formaldehyde. The GO-KOH-H_2O filter bag displayed efficient removal of gaseous and bioaerosol formaldehyde through the formation of an abundant number of oxygen-containing functional groups. The inside and outside of the GO-KOH-H_2O filter bag can be considered flexible framework die for maintaining a uniform dispersion of the target compound and accelerating the removal process. GO-KOH-H_2O filters also showed a removal ratio of ~99% available for various bioaerosols such as Bacillus cereus, E. coli, and Staphylococcus aureus [18].

Polymer-based antimicrobial nanostructures

Environmentally friendly, polymer-based, ready-to-use antimicrobial coatings for air-purifying filters or surface coatings of contaminated places such as walls and door handles are being developed. Widespread development of conventional biocidal coatings for air-purifying filters or other contaminated surfaces such as transparent glass walls for urban dust removal is hindered by several drawbacks. These include complex time-consuming and expensive multi-step synthesis procedures, high human toxicity of biocidal agents such as Ag, Cu, and hazardous cross-linkers needed to improve water resistance, direct release of airborne nanoparticles, and relatively low bacterial inactivation rates requiring repeated spraying of coatings [12]; Singh *et al*., 2023 [26].

Protector-dispensing water-soluble copolymers are being synthesized through a very simple one-pot polymerization procedure, and polymeric biocidal compounds such as chitosan, gelatine, and P(DMAEMA) can be readily added in situ through water-resisting cross-linking. A highly transparent and highly porous epoxy-based biocidal hybrid with aggregation-induced emission (AIE) capability, which possesses excellent protection against airborne bacteria, is also being developed, enabling bioimaging and theranostics [27].

Bio-inspired and biomimetic nanoparticles

Airborne infectious agents pose a threat to public health in urban areas, and their persistence on environmental media is a significant risk factor for disease transmission indoors. The development of sustainable and scalable air-cleaning materials that can control airborne pathogens, especially when used in conjunction with pollution-removal active materials, is a pressing need for society. Bio-inspired and biomimetic copper- and silver-based materials that incorporate a particle size of approximately 9-20 nm significantly reduce the viability of airborne viruses, bacteria, and fungi [25]. Antiviral copper-based coatings capture airborne viruses and markedly reduce their survival, and copper-oxide nanoparticles of approximately 10 nm coated on polyethylene and polypropylene textile fibers dramatically decrease the viability of aerosolized influenza virus and SARS-CoV-2. Mechanism studies reveal that copper inhibits the synthesis of the viral genome through interaction with the viral genome. Silver-embedded biocompatible polymeric filters capture particles greater than 3 µm and from an initial concentration of 1.0×10^3 to 2.85×10^4 CFU/mL dramatically reduce the bacterial aerosol concentration, stabilizing silver colloids on substrates for a long time without significant leaching in solution. Other materials such as bio-inspired and biomimetic nanoparticles that were derived from Euscaphis japonica were significantly less toxic to human cells and exhibited a stronger antimicrobial activity toward Bacillus cereus, Bacillus subtilis, and Escherichia coli than nickel chloride, which is classified as a human carcinogen [20]. Three other research groups also report the effective long-term of bioinspired nanoparticles for indoor pathogen mitigation. Thus, bio-inspired and biomimetic nanoparticles could lead to environmentally friendly bioaerosol control systems suitable for indoor environments. [1, 28, 29, 30]

Comparative efficacy against airborne microbes

In vitro studies were carried out to determine their comparative efficacy against airborne microbes during summer and winter months utilizing glass slides as passive collectors. In summer, Nylon mesh coated with nano copper oxide and zinc oxide exhibited 100% activity against E. coli, 86.666% against S. aureus, and 90% against B. subtilis whereas uncoated mesh was ineffective against all the bacterial airborne pathogens. During winter season when the microbial count was low, cobalt oxide proved to be the best bio-nanocomposite against E. coli and S. aureus while the activity against B. subtilis was shown by cobalt oxide, iron oxide, and zinc oxide.

The design of feasible inhibitory nanocomposite through a simple and economic route enables the potential application of the developed nanocomposites as a coating material on textile, hospital bed sheets, carpets, vehicle seat covers, and passenger cabin interiors. Life expectancy of the developed products can be enhanced through proper encasement. In polluted-bacterial-infested urban environments developed protective meshes can be utilized as passive bio-aerosol samplers for monitoring bacterial pollution. Further bacterial-fungal synergy spread by air transport can be tackled through using prepared bio-nanocomposites into ceramic tiles, cement, and concretes. Additional research for tackling the microbial pollution transfer of the synergy via soil has also been described. The role of agama lizard in climate control has been focused. [31, 32]

Chapter - 5

Nano-Enabled Air Filtration Technologies

Airborne pathogens such as bacteria, viruses, and fungi are widely prevalent in polluted urban environments. The presence of these pathogens in polluted urban air poses heightened exposure risks under ongoing global urbanization. Urban pollution sources such as transportation, construction, and industry could contribute to the loading of airborne pathogens. Pollutants like particulate matter (PM) and various chemical species also play significant roles in pathogen deposition and virulence. Aerosolized pathogens released from diverse sources tend to persist for longer duration and travel longer distances in polluted cities. Accordingly, exposure to airborne pathogens is likely greater in polluted urban environments than in non-urban settings. The expected health burden and resource constraints associated with deteriorating urban air qu938355e8-05c0-4def-a2ca-58f1b8d32c84ty are detailed by [18]. Cities regularly experience outbreaks of airborne infectious diseases (Kadam, 2018), along with the associated health impacts and economic ramifications.

Nanofiber-based filtration systems

Particularly in urban polluted environments, there is a growing interest in combatting airborne pathogens using biogenic nanofibrous materials. A prospective research line is to develop highly efficient (...), biogenic nanofibre-based HEPA filters that reduce both airborne pathogens and fine particulate matter in polluted environments. Available techniques to fabricate vertically aligned nanofibres in bulk are mass-production-amenable, and there are hospitals in urban landscapes that can provide bulk bio-inoculum to develop practical biogenic operational HEPA filters on-site, thereby reducing airborne pathogens.

The ability of ultrafine nanofibres to act as a HEPA filter for bioaerosol removal has been demonstrated. As the statistically packed HEPA filter was composed of biodegradable and biocompatible nanofibres, it could be operated as a biocaptor under low-survival conditions. Through an increased surface-area-to-volume ratio, and because of the fineness of the fibres, the statistically packed HEPA filter caged bioaerosols more effectively than conventional PP-based HEPA filters. In addition, dead honeybee and butterfly bodies tested positive for the presence of pathogenic fungi. Observations indicated that statistically packed bioinspired HEPA filters could capture significant quantities of airborne pathogens in an urban polluted environment [33, 34, 35, 36].

Functionalized filters with bioactive coatings

Many particulate matters in polluted urban environment or PM can carry pathogens infecting respiratory system. Filters can be made antimicrobial with the low-cost polymer, chitosan, synthesized from dried, powdered shrimp shells. Samples were made of a sintered polymer using silica space-holders that were leached by water when the polymer was set. The filters were modified with chitosan either growing a layer of live bacteria around (Paracoccus sp.) the pore openings or as a coating over the entire filter surface to trap the PM. A water-insoluble chitosan derivative enhanced with tryptanthrin (a natural alkaloid isolated from the fruit of the plant), found to have a strong bactericidal effect on E.coli and Staphylococcus sp, was applied over a polyester filter. The antimicrobial coated filter was tested in an experimental set-up that revealed a reduction in the bacterial load over filter and air. In a biological device for recycling polluted air, the chitosan-coating process yielded a lower concentration of dead colonies in the aerosol, the lower concentration of FK20 in the medium and a slower proliferation rate of the Bacillus mycoides colonies. Under this scenario, the die-off rate of the Gammaproteobacteria was higher when the concentration of FK20 was lower.

The approach offers an ecological, cost-effective, and easy-to-control method for the biocidal treatment of filters. Since it can be undertaken in situ or ex situ, it also has application for air ventilation systems, being suitable for recirculation. Chitosan can be obtained from many natural sources, such as crawfish and cassava waste. Because of its natural origin, it is biocompatible and can therefore be applied in a food-corner for the treatment of the air in an area with high concentration of a pathogenic fungus (Aspergillus sp.) in the aerosol. Since the concentration of the fungus in the aerosol is reduced by 43% over the biogenic filter when compared with a plain one, it can be defined as a filter with a chitosan treatment for a specific pathogen (Aspergillus) [37, 38, 39].

Electrospun membranes for pathogen capture

In urban polluted environments, diseases are rapidly spreading through contaminated aerosols emitted from exhalation and far-infrared devices. Capturing airborne pathogens has emerged as a major challenge and using electrospun nanofiber membranes in personal protective equipment can assist in addressing this challenge. Electrospun nanofibers themselves are as thin as a few nanometers and can provide high surface area that facilitates the infiltration of aerosols. Therefore, they can function as a platform for efficiently capturing airborne pathogens [40, 41].

Smart and self-sterilizing air filters

Air pollution represents a serious public health issue that paradoxically favors immunization of the exposed population due to the greater circulation of foreign inhaled antigens. The air quality, however, also depends on the presence of airborne pathogens, such as viruses or bacteria, that when inhaled can lead to serious lung diseases. Recent reports argue that retained airborne viruses could persist on fly screens originating an increase in the infection rate in the trapped areas.

Airborne pathogens could therefore affect the health of around 80% of the world's population not directly exposed at the onset of the infection. To counteract the risk associated with exposure to these environmental pathogens, the use of filters impregnated with antiviral agents, e.g., filters coated with different nano-materials (TiO_2, ZnO) that assured a bactericidal effect under radiation exposure, has been proposed. Here, self-sterilizing air filters incorporated in polymer nanocomposite have been developed. Nanocomposites added with either TiO_2 and graphene oxide (GO) or TiO_2 combined with ZnO exhibit a long-lasting activity against airborne pathogens and could constitute a significant step forward in the development of pollution-resistant materials. [1, 2, 3, 42]

Performance evaluation in polluted environments

Urbanization is increasing almost exponentially. Rapidly evolving cities with improper development influence their populations and health outcomes, with considerable and lasting effects for both society and the economy. Industrial growth and domestic activities bring together pollutants, gases, and toxic dust with small particle sizes that are unsafe to inhale directly. Alongside particulates, allergens, and pollutants, airborne microbes in urban areas contaminate indoor environments and damage human health. Surfaces and filters can help with air cleaning; however, infected people are still sources of airborne diseases, with microorganisms emitted. Consequently, there is a need for efficient filters to minimize airborne exposure and mitigate health risk from bioaerosols [18].

Chapter - 6

Bio-Nanomaterials in Indoor Air Quality Control

Indoor bioaerosol dynamics in urban buildings

Indoor bioaerosol dynamics involve the processes governing the concentrations and fates of biological particles such as bacteria, fungi, and viruses in indoor air. These particles are readily released through indoor activities and outdoor infiltration and persist in the air for long periods before settling. Understanding the dynamics is essential for designing effective controls to reduce exposure, thereby improving indoor air quality and human health.

Sources of indoor bioaerosol include ventilation of outdoor air, emissions from indoor sources such as occupants and moldy materials, and still water that provides liquid water for survival [43]. Removal mechanisms include ventilation out of the building, surface deposition on floors, walls, and furniture, and recapture through room- and building-scale filtration. The size-dependent behavior of bioaerosols governs their deposition within the respiratory tract and thus potential health impacts.

Nanomaterial-based purification systems

Air pollution represents one of the greatest threats to public health worldwide [18]. Polluted air leads to several adverse health effects such as allergies, influenza, sick building syndrome, and respiratory infections. The possibility of bioterrorism by pathogenic agents such as anthrax or the emergence of future airborne pandemic diseases raises concerns about the presence of dangerous microorganisms in the air. Nanocomposite-coated biopolymer materials such as cellulose, starch, and chitosan are being explored as efficient and eco-friendly materials for the preparation of air-filtering devices due to their biodegradability and chemical versatility [12]. The incorporation of metal oxide nanoparticles, such as silver, zinc, or iron oxide, into these biopolymeric matrices has also been examined, affording materials with well-documented biocidal properties. Recent studies have demonstrated the preparation of filters made of cotton impregnated with metal (silver and zinc) or metal oxide (iron) nanoparticles for the control of bioaerosols, which were subsequently tested against aerosolized E. coli to evaluate the physical and viable removal efficiencies as well as the survival rates of bacteria at different humidity levels.

HVAC integration of bio-nanomaterials

In urban polluted environments, significant research effort is focused on portable bio-nanomat echnologies and their filtration efficiency against airborne pathogens to improve air qu938355e8-05c0-4def-a2ca-58f1b8d32c84ty. Ventilation systems, such as heating, ventilation and air-conditioning (HVAC) systems, significantly influence indoor air qu938355e8-05c0-4def-a2ca-58f1b8d32c84ty. In 2015, the United States Environmental Protection Agency (EPA) reported in a publication that indoor occupants spend approximately 90% of their time in enclosed spaces. Air-hygiene in enclosed spaces is a crucial issue; however, the current air-hygiene technologies still do not ensure elimination of airborne pathogens at designed efficiency. To improve [20]

Antiviral and antibacterial indoor coatings

Airborne viruses and bacteria are the predominant agents of infectious diseases, significantly increasing the risk for immunocompromised individuals. These pathogens mainly exist in prefabricated buildings with limited natural ventilation and are airborne in freshly expelled moist droplets from infected individuals. Traditional antibacterial coatings and surface materials can kill bacteria on contact, but they do little to inactivate pathogens in the air. To mitigate the risk of airborne pathogens, the development of coatings or materials with integrated antiviral and antibacterial property has thus become important. In a recent study, an indoor coating that inactivates viruses and bacteria in the air and on surfaces at room temperature has been demonstrated.

By virtue of its extremely low density and large surface area, the novel bio-nanocomposite material can kill >99.99& of both Escherichia coli and Staphylococcus aureus bacteria when coated on solid surfaces, while inactivate >99.99% of airborne influenza A viruses within 30 min (7.7-PLog reduction). This capability relies on its unique combination of hydrophilicity and electrostatic properties allowing effective capture and retention of virus-laden droplets, while the fluorescent dye-assured exposure of 3D porous structure to the droplets ensures fast inactivation of viruses under indoor illumination conditions. Such materials, surfaces, or coating paints with dual functions of inactivating airborne viruses and killing surface bacteria may help significantly reduce the risk of airborne virus-borne diseases indoors or in other locations with limited natural ventilation [44, 45, 46, 47].

Case studies in hospitals and public spaces

Active transmission of pathogens is recognized as one of the most important routes for pathogen spreading in hospitals, contributing to cross-infection among patients and healthcare professionals. In Taiwan, an electronic-record system developed in 2004 monitors patient history, and actively manages patients with multidrug-resistant organism (MDRO) infection and colonization. The contaminated wellbeing faucets in intensive care units played an important role related to the colonization by Acinetobacter, Klebsiella, Pseudomonas, and Enterobacter species. The pathogenic ventilator-associated Acinetobacter baumannii was admitted by two patients on the same day; both patients shared the same ventilator pipelined with an internal humidifier system. Hospital privacy curtains, heavily touched and easily stained, were contaminated rapidly with pathogenic bacteria. In isolation rooms, prior isolation of a patient with another MDRO remarkably increased the risk of acquiring multidrug-resistant Gram-negative bacilli by subsequent patients. Clogging hospital surfaces may play a role in the extensive transmission of Clostridium difficile or norovirus in healthcare settings. Implementation of environmental cleaning measures has been shown to reduce the prevalence of healthcare-associated infections caused by these bacteria in acute-care hospitals. Environmental decontamination of hospital rooms using hydrogen peroxide vapor reduced patient acquisition of resistant organisms following discharge of infected or colonized patients. Strategies comprising information technology assistance (Traffic Control Bundle) were effective for limiting the spread of nosocomial SARS among healthcare workers. Antimicrobial stewardship programs aimed at reducing inappropriate antimicrobial utilization may decrease the selection pressure imposed by antibiotics and combat the global threat of antimicrobial resistance. The antimicrobial activity of differently structured copper and silver nanofilms on simulated hospital surfaces against various nosocomial pathogens has been demonstrated [48, 49, 50, 51].

Chapter - 7

Photocatalytic and Light-Activated Nanomaterials

Photocatalytic mechanisms for pathogen inactivation

Involve processes like UV photocatalysis and plasma treatment to effectively eliminate airborne viruses, bacteria, and fungi. These methods generate reactive oxygen species that damage microbial DNA, cell walls, and vital biomolecules, leading to inactivation. Photocatalytic inactivation can also prevent reactivation of pathogens, providing safer air purification. Studies have shown that photocatalysis using materials like TiO2, sometimes with metal deposits, effectively inactivates bacteria spores, bacteriophages, and pathogenic fungi, including Fusarium species. The efficiency depends on factors such as irradiation time, wavelength, and catalyst properties [52].

Photocatalytic mechanisms for pathogen inactivation involve using photocatalysts such as ZnO and TiO2 to generate reactive species under light irradiation, which can effectively deactivate bacteria and fungi. These processes are applied in air and water purification systems to reduce bioaerosols and bioaerosol contamination in waste treatment plants, indoor environments, and during chemical degradation. Photocatalytic inactivation also reduces chemical pollutants like hexane vapors and bioaerosol emissions, contributing to improved air quality. The efficiency depends on factors such as catalyst composition, particle size, loading, and irradiation conditions [53].

Titanium dioxide and doped nanomaterials

Titanium dioxide (TiO) and TiO doped with metal or semiconductor ions are nanomaterials of great interest in multilayer antireflective coatings because they can photodecompose both organic and inorganic materials in the presence of UV light and catalyze several reactions. In on-doped TiO and TiO doped with alkaline earth metal ions, the UV light elevates the lattice temperature, driving the sintering process, which is mediated by diffusion and desorption. Antimicrobial agents based on TiO, such as coatings used in hospital environments, have become commercial products because the ultraviolet light is sufficient to inactivate airborne pathogens. TiO doped with Fe, Cu, Mg or Ca ions by sol-gel or mechanochemical methods is promising for the preparation of bioactive ce-ramics. Photocatalytic destructors based on TiO are useful for indoor air treatment; how-ever, the harsh environmental conditions and aging degrade their effectiveness. The op-timization of TiO with the inclusion of metallic dopants or metal oxides improves the per-formance for photodecontamination.

The deposition of TiO on glass substrates leads to multilayer coatings with antireflective properties. TiO and TiO:NiO films have been prepared by dip-coating processes using precursor solutions containing titanium(IV) isopropoxide, isopropanol, acetic acid and ethyl-nectar. A solution containing titanium (IV) isopropoxide, titanium(IV) butoxide and a trace of a diphosphonate surfactant has been employed in the preparation of TiO oxide thin layers. Clean glass coverslips were immersed for 5 s in the precursor solution and, after exposition to a natural UV-light source reflecting the solar spectrum ($\lambda \geq 290$ nm) for 40 h, the TiO layers became superhydrophilic. The effective detachment of dried-on pollen particles from the TiO surface has been attributed to its superhydrophilic character and its photocatalytic activity. The superhydrophilicity and photocatalytic activity are promoted by sintering treatments at 450 °C [54, 55, 56, 57, 58].

Visible-light-responsive bio-nanomaterials

Anoxia in the action zone of the bio-nanomaterials system is steered under visible-light irradiation via coupling of different functionalities in a composite containing disapproved glucosamines and L-tyrosine composites providing: absorption of infrared rays-enabling bio-enhancement and an easy reduction of potassium dichromate within the composites; visible-light-responsiveness-generating heat and reactive oxygen species; in-situ carbonization-forming hyperthermophilic and geosmin-destroying agents; and graphene where the conjugation, quenching and confinement effect enhances the catalytic property. The composite provides an ecologically benign and efficient system for mitigating potential pathogens in crowded urban polluted environments. Airborne pathogenic fungi and Ultraviolet irradiation irradiated Escherichia coli in a prototype system producing anoxia just beneath the composites produce no detectable geosmin in broth media.

The highly polluted biosphere and an increasing number of people living in mega-cities, particularly in impoverished developing countries, encourage the spread of airborne infectious diseases. Airborne pathogens pose the highest risk during rapid proliferation and transit when nutrient supplies are close to depletion. coupled with the anti-zoosporic capability provide an ecogreen method for the relatively short-term mitigation of airborne pathogens, particularly when nutrient media supply is limited in crowded urban settings. Nevertheless, the long-term reduction of airborne pathogens, particularly at locations where maternal nitrogen products pollute nearby water bodies, necessitates other approaches. [2, 59, 8, 60, 61]

Integration with air purification devices

Hybrid bio-nanocomposites based on a polymeric matrix containing bio-inorganic nanoparticles display particular properties suitable for their integration into air purification devices. The essential requirements for such applications are high stability under humid conditions, low cytotoxicity, and the ability to react efficiently with the infective pathogens. A water-resistant hybrid bio-nanomaterial based on polyhydroxyethylmethacrylate copolymerized with a phenolic resin and containing Cu and Znsulfide-cadmium sulfide nanoparticles is prepared. The nanoparticle formation takes place within the nascent network and, therefore, adds extra stability to the polymeric matrix without deteriorating the initial properties of the organic components. The biogenic nanocomposites exhibit pronounced microbiocidal activity against viruses and Gram-negative and Gram-positive bacteria as well as nontoxic behavior as established on the model of Eukariotic cells.

A novel hybrid formulation is designed for the production of a bioactive bio-pesticide against fungi and bacteria showing synergistic combination of components effect. The formulation is a complex of polyunsaturated algal and rhizobial fatty acids, mannitol and Cu- and Zn-containing bionanomaterials. The natural-composite bioinsectofungicide is stable under storage for more than a year. [62, 63, 64, 65]

Challenges in real-world urban applications

With urban pollution being a prime precursor of respiratory disease the use of air purifying masks has become ubiquitous. However, masks can suffer from rapid deactivation, a factor that can reduce their effectiveness and even introduce a risk of airborne infection. Enhanced photocatalytic nanomaterials can be incorporated into protective textiles in a sustainable way to actively combat a variety of airborne pathogens, therefore warranting investigation into their activity under real-world urban conditions. Notably, photothermal heating due to sunlight absorption can complement the direct photocatalytic effect by enhancing their activity and stability as well as inactivating pathogens on their surface.

Urban pollution is known to facilitate the growth of pathogens in the environment. For example, sources of nitrogen oxide have been shown to support the growth of bacteria such as Escherichia coli and Kocuria rhizophila, and airborne infections have been shown to coincide with high levels of nitrogen oxide. Similarly, heavy metals such as copper and zinc are known to function as micronutrients for bacteria and these metals can be present in significant concentrations in polluted air. Furthermore, heavy metal exposure is suspected of supporting natural transformation, which allows pathogens to acquire virulence factors. Enhanced degradation of airborne pathogens in polluted environments can therefore help mitigate the risk of airborne infections. Photocatalytic air purifying masks have emerged as a promising strategy in this regard. However, rapid deactivation can compromise their effectiveness and even pose a risk of airborne infection. [66, 67, 68, 69]

Chapter - 8

Bio-Nanomaterials for Viral Aerosol Neutralization

Characteristics of airborne viral particles

Airborne viral particles can be transmitted through breathing, coughing, sneezing, talking, and laughing. They are smaller than 10 µm and thus are ubiquitous both indoors and outdoors [25]. They represent an emerging public threat that has been exacerbated during the COVID-19 pandemic. Copper nanoparticle-coated materials used in air filtration systems demonstrate significant antiviral and antibacterial properties, reducing the presence of SARS-CoV-2 and influenza virus by over 90% within two hours and also effectively mitigating bacterial strains Pseudomonas aeruginosa and Escherichia coli. The coatings are biocompatible, environmentally friendly, and firmly attached to the fibers without being released into the airflow, making them suitable for air filtration systems crucial for combating current and future pandemics.

The COVID-19 pandemic highlighted that aerosol transmission of viruses poses a serious threat to public health, with the airborne human coronavirus responsible for the disease surviving for hours and having been detected in various indoor environments. Controlling the spread of biological aerosols containing viruses like SARS-CoV-2, adenovirus, and rhinovirus capable of causing upper respiratory disease and highly pathogenic avian influenza virus, is therefore critical. Wearing protective clothing and masks, increasing indoor ventilation, and chemical disinfection are common control measures, but the first two are impractical in many scenarios. Nanomaterials with reasonable cost and broad-spectrum antiviral capability offer the potential to inactivate airborne viruses and improve control of aerosol transmission [70]. Nanostructured filters coated with silver nanoparticles exhibit virucidal activity against SARS-CoV-2, adenovirus, and influenza A virus. Incorporating an epoxy-embedded silver nanocluster-silica composite coating onto fiber-based filters also enhances antiviral activity against adenovirus and influenza A virus without hindering the filtration performance [71].

Nanomaterial-based viral adsorption mechanisms

Nanomaterials are recognized as effective sorbent agents for adsorbing and inactivating various viruses due to their high surface area, strong electrostatic interactions with positive-site viruses, abundant functional groups and intrinsic viral-surface affinity. They also act as water electrolyte or aqueous strong acid and catalyse viral acidic degradation through the proton-transfer reaction of Lewis acid-base pairs. The high dipole moment of these materials enhances the local electric fields, draws surrounding water molecules and electrolyzes them into oxidizing $HO\cdot$ and H_2O_2 in the presence of oxygen, resulting in virucidal effects on the surface of viral-associated aerosols. The wide-spectrum inactivation of viruses from various families, including coronavirus, influenza virus, bacteriophage, Aichivirus and duck-hepatitis virus, suggests a mechanism-based research exploration roadmap.

Virus structure, charged morphology and epitopes dictate the suitable nanomaterials responsible for virus interception and deactivation. Positively charged nanomaterials can successfully adhere negatively charged viruses on their high-surface-area but low-mass carriers for effective enrichment, while negatively charged nanomaterials are responsible for electrostatic adsorption of airborne cationic viruses. Viral adsorption utilizes the non-covalent interaction-based assembly design via hydrogen bonding or other secondary forces such as hydrophobicity, coordination and π-π stacking. The Lewis acid-base pair mechanism of ensuring acidity is critical to support virus destruction, while the dipole-enhanced catalytic effect is recognised as a supplementary factor for strong virucidal effect. Overall, the combination effect of several units supported by different functions from versatile nanomaterials establishes an appropriate platform for successful airborne-surface-bioaerosol killing [72, 73, 74, 75, 76].

Antiviral peptides and bio-functionalized nanostructures

Polyatomic cationic complexes of nucleic acid bases and their derivatives with organic dyes, quaternary ammonium salts, and some other compounds reveal high and - for nucleic acid bases - selective antiviral activity against the cytopathic actions of HIV-1, HHV-1, and HHV-2 in vitro. These polycationic compounds are combined with DNA-synthesizing cells and peptide copolymer carriers to form new biomimetic systems for the delivery of antiviral nucleic acid base-like cationic polyquaternium preparations to blood cells. These hemogeneous preparations exhibit a long-acting antiviral effect on HMC-3 and C8166 cells infected by the type-1 AIDS virus, without HIV-1 dependencies. The peptide copolymer carrier used is also applied to the fucoidan-containing polysaccharide fraction from Fucus evanescens, which is explored as an antiviral agent against HSV-1.

Nanostructures functionalized with hepatitis B virus (HBV) surface proteins and bempehtide exhibit an anti-HBV effect, and bempehtide biosafety properties are determined in culture on human placenta Danice cells. Polyelectrolyte complexes containing anionic and polycationic polymer components in a ratio that ensures charge compensation can be used to create HBV motif-functionalized materials capable of preventing viral attachment to hepatocytes. Sepiapterin synthase-peptide nanostructures and bempehtide also exert an antiviral effect in mouse models. Nanoconjugates containing the able-2-cystathionine γ-lyase Δ297-H2N-rscsvsp-fc, adenylate kinase-2 number-reduced poly-N-α-benzoyl-Δ4-piperidine-containing polypeptide prolin-enriched allergen of Pampas grass, and Chicken α-lysozyme-F8-aspartic acid. [77, 78, 79, 80]

Application against respiratory viruses

Whenever respiratory viruses invaded or infected human hosts, they caused serious diseases. The encapsulation of drugs in nanomaterials provides the possibility to maintain the therapeutic concentration and the targeted drug delivery. The lipid bilayer provides many advantages for inorganic nanoparticles for drug delivery. Controlled drug release can be achieved by regulating lipid-bilayer degradation in response to shear force. Phospholipid-stabilised silver nanoparticles targeting respiratory viruses are prepared by a two-step method. The prepared phospholipid-modified silver nanoparticles show similar UV-Vis absorbance peak to the unmodified silver nanoparticles. More importantly, the colour of phospholipid-modified silver nanoparticles solutions gradually changed with solution delivery and reached a colourless state during repeat delivery. Stability observation indicates that phospholipid-stabilised silver nanoparticles can keep stable before the maintenance time during targeted delivery under bad environment and can be delivered freely.

These phospholipid-stabilised silver nanoparticles can target respiratory viruses. The total time of the encapsulated silver nanoparticles for being invisible is much shorter than that of free silver nanoparticles. Strong evidence supports that the phospholipid-stabilised silver nanoparticles can effectively inhibit respiratory viruses. When the anticancer drug doxorubicin encapsulated in modified silver nanoparticles, the delivery system would target, inhibit and treat cancer. The proposed phospholipid-stabilised silver nanoparticles featuring the virus-targeting property provide a bio-nanomaterial that can target, inhibit and kill respiratory viruses in polluted environments. This method may shed new light with brightness on targeted delivery of drugs and nanomaterials to viruses [81, 82, 83, 84].

Future pandemic preparedness strategies

Vaccines remain the most important solution to reduce the incidence and pathogenicity of human coronaviruses. However, the production of a vaccine may take several months, if not years, following an outbreak. Rapid surveillance of pathogens present in the environment and mitigation measures to decrease the virulence of airborne pathogens in urban polluted areas can play an important role in ensuring pandemic preparedness. Several microorganisms, including Gram-positive and Gram-negative bacteria, fungi, and viruses, are distributed in the air and are known to contribute to pathologies affecting the respiratory system. Increased concentrations of airborne pathogens are correlated with the occurrence of respiratory diseases in susceptible populations exposed to urban polluted areas.

Airborne pathogenic microbiota require different control strategies from muscle or vegetable crops. The latter are treated with pesticides while bacteria, viruses, and fungi are removed through curative or preventive disinfection, frequently with copper-based products. In contrast to the application of copper salts, which generate resistance problems in the treated areas, the use of copper nanoparticles, given their minimal flow rate and absorption by plants, represents a promising solution. The bio-nanostructured nanomaterial CuO-graphene-lactic acid is produced with a low environmental impact and is capable of not only decreasing the airborne pathogenic microbiota but also lowering the toxic effects of pollution in urban areas where it is applied. Ag-graphene doped with chitosan resins represents another innovative approach in mitigating the risk of airborne diseases in polluted urban areas.

Chapter - 9

Smart and Responsive Bio-Nanomaterials

Stimuli-responsive antimicrobial systems

The traditional methods of antimicrobial treatments are usually based on their biocidal properties, which aim to kill, deactivate or inhibit the growth of pathogenic microorganisms. The increasing resistance of numerous pathogenic microorganisms to these agents is leading to a concern in the public health sector. Using these methods may also generate secondary pollutants, such as biocide residues and other toxic chemicals such as halogenated organic compounds. This has prompted the search for alternative approaches in the treatment of contaminated surfaces. A new innovative option is the application of high-efficiency coatings able to inactivate or remove pathogenic microorganisms from their surfaces without appreciable biocidal action and without generating secondary pollutants. In these novel alternatives the main disinfection mechanisms are based on the passive or active stimulation-response and/or the consequent reduction of humidity in the contact area of the microorganism, fibers or substrates.

Interestingly, stimulator-response coatings based on together an ecofriendly antimicrobial agent, such as chitosan, and silicate materials can have a very important novel technology. Besides contributing to the preservation of air quality, lowering the concentration of airborne microorganisms, these new materials also play an important role as stimulus-responsive materials able to inactivate pathogenic microorganisms. These systems combine the passive action of lowering the humidity concentration around the microorganisms that can be reflected in the room air quality and the active dysregulation of the microorganisms and/or the consequent general deterioration of the microorganisms and/or fibers.

Self-adaptive nanomaterials in polluted air

For mitigating the harmful effects of airborne pathogens released into urban polluted environments, self-adaptive nanomaterials capable of simultaneous capture of particulate matter and degradation of gaseous pollutants were developed. Electrospun nanofibrous membranes functionalised with β-cyclodextrin for the adsorption of volatile organic compounds were engineered with approaches to create beaded nanostructures and bilayer membranes from a single polymer. These modifications reduced pressure drops while maintaining high filtration performance. Non-contact laser microscopy enabled accurate measurement of membrane thickness. The obtained PAN/β-CD membranes captured aerosols and volatile organic compounds simultaneously, with evaluated cytotoxicity supporting their use for respiratory protection [40]. All these innovations contributed to the formulation of effective low-resistance nanomaterials that prevent airborne transmission of pathogens in urban and industrial settings [12].

Real-time pathogen detection and response

Drone systems have been a promising technology for the designing of devices able to detect and mitigate airborne pathogens. Drones equipped with specific detectors could monitor urban environments and detect local pollution peaks to initiate an immediate release of bio-nanomaterials able to mitigate the risk of infections. In this framework bio-nanomaterials synthesized by a new green technology are already functional for the capture and neutralization of Gram-positive and Gram-negative bacteria responsible of airborne infections are available. The green synthesis, realized by simple physical mixing of aqueous protein extracts from the non-pathogenic edible mushroom Leucopaxillus gentianeus and potassium permanganate in an optimized metal ion composing ratio, leads to a metal-enriched material with oxygen and nitrogen-enriched functional groups.

The antioxidant activities of these bio-synthesized nanomaterials are concurring to the protective roles during infection propagation. Several bio-synthesized nanomaterials mixtures have been realized modifying composition, temperature and time. At present, bio-synthesized nanomaterials showing the capacity to capture and kill both Gram-positive and Gram-negative bacteria, and also to mitigate respiratory infections during their growth, are under evaluation by the Health Ministry for their inclusion in hospitals for their high efficiency against airborne infections before people to maintenance the respiratory mask.

AI-assisted smart nanomaterial design

The emergence of artificial intelligence (AI) has generated immense interest in material design, facilitating the rapid discovery of advanced materials [85]. An AI-augmented approach for developing smart nanomaterials for filtration applications is proposed based on hybrid molecular dynamics simulation combined with deep generative model. An artificial intelligence-assisted computational framework predicts pressure drop during airflow through nanomaterials, one of the most critical filtration parameters. Building on these predictions, a generative model of structural polymers produces candidate structures that fulfil the required filtration conditions. The framework enables rapid exploration of enormous design space to discover advanced materials and supports objective-directed intelligent design of nanofibers for improving the overall filtration performance further [41].

Integration into smart city infrastructures

Airborne pathogens have an important role in the transmission of airborne diseases and respiratory infections [41]. Additionally, other bio-aerosols that can be found in the urban environment include pollen, spores, wood dust and toxins are the cause of human allergies and present an important problem for asthmatic patients. One possibility of bio-aerosol interception is the application of bio-inspired nanofibrous membranes with a high surface area due to their 3D structure along with bioactive surface modification materials. This is an important factor for urban environments as high concentrations of airborne biocontaminants have been linked to great changes in climate conditions (ex: Summer 2022). A vital technical challenge for protecting urban environments and human interactions is the development of highly efficient materials in order to mitigate pathogens in the air [86]. Current capture technologies such as electrostatic filters, and HVAC systems require significant energy consumption and continuous maintenance. This effort complements the permeated approaches of capturing pollutants present on the surface of leaves and other naturally occurring surfaces.

Chapter - 10

Toxicological and Environmental Impacts

Human inhalation exposure to nanomaterials

Despite the widespread use of engineered nanomaterials, potential exposure risk in humans after inhalation and subsequent reactions in the body remain largely unexplored. To identify and characterize the various sizes and biological origins of nanomaterials in human lung tissue, a recent study employed a non-targeted approach. Male smokers and non-smokers underwent surgery for lung cancer, and lung tissue specimens were preserved. High spatiotemporal resolution investigational methods equipped with energy-filtering transmission electron microscopy-a highly sensitive analytical technique-allowed for the observation of elemental distributions across two-dimensional detection of nano-sized materials in/near tissues. Engineering nanomaterials smaller than 100 nm can enter the lung and bloodstream after inhalation.

Since the lungs act as the first barrier for inhaled air from external sources, it is expected that lung tissues contain large amounts of engineered or natural nanomaterials (i.e., particles that reflect and scatter lights) and that their whole-body distributions depend on the sources of these nano-sized particulates. Drug development or nano-biomaterials to combat multifunctional diseases can be optimized using natural materials that have already been displayed in organs, tissues, and at the cellular level. Airborne bio-nanoparticles derived from biological sources such as bacteria, fungi, viruses, and pollens for example can enter the human respiratory system via inhalation and promote numerous diseases such as viral infections, allergies, respiratory infections, cardiovascular disorders, and even cancer.

Cytotoxicity and genotoxicity considerations

The increasing use of nanomaterials gives rise to potential cytotoxic effects, especially when exposed to mammalian or aquatic cells. Nanomaterials, including various compounds such as metals, semiconductors and oxides induce cytotoxicity when exposed to cells. The effect is governed by various parameters such as characteristics of the nanomaterial (size, shape, coating), exposure conditions (concentration, time) and type of exposed cells. Hence varying cytotoxicity may be expected for nanomaterials whose characteristics are designed to promote biocompatibility. Cytotoxic studies reveal that oxide compounds like FE2O3 or Sb2O3 exhibit negligible cytotoxicity while water-soluble organic molecules like polyhedral oligomeric silséthoxysilicate (POSS) furnished a cytotoxic profile.

The evaluation of the cytotoxic effect of various materials is typically performed on cultured cell line using standard protocols such as MTT assay or neutral red uptake (NRU) assay. These assays probe cell viability and morphology after a fixed incubation period in the presence and absence of a compound. Genotoxicity of nanomaterials includes strand breaks on the DNA of an organism, the induction of micronuclei in the daughter cells, toxicity to an developing embryo and alteration of the reproduction process. Cobalt oxide, Alumina, ZnO and TiO2 materials were shown to induce genotoxicity and micronuclei in the daughter cells of cultured human cells. Induction of micronuclei further proliferates mutation and embodies a hazard, and further investigation on such behaviour is essential to develop safer nanomaterials.

Environmental fate of released nanomaterials

Transportation of nanomaterials released directly in the environment or originated from other sources (directly environmental sources e.g. waste-water or atmospheric deposition) are a lively field of research. It is also understood that environmental transformations alter their original characteristics and the consequent biological interactions. Biological systems represent a key knowledge area but currently gaining even more interest is the investigation of the impact on the atmospheric behavior with a special emphasis on the oxidative-dissolved fraction. Various types of biological and abiotic systems were described with special regards to the cell toxicity of soot or the production of reactive oxidative species (ROS) in the nanomaterial release. Methodologies evaluating the atmospheric ability of various types of nanoparticles through non-environmental atmospheric dispersions but at the same time focusing on the oxidative potential evaluation in relation with the carbon urban soot were also presented. For the first time, the rainfall water from individual urban cities was simulated

The investigation provided information on the atmospheric ability of uncoated and aged Core-Coupled, Core-Shell and Patchy-Shell nanoparticles through a non-environmental atmospheric dispersion, while the presence of the atmospheric dissolved iron fraction of soot highlighted its role for inducing the generation of reactive oxide species. An innovative test bench was also developed in order to estimate the influence of a polluted rainfall episode on soot properties with the final purpose to correlate biological results with atmospheric chemistry. Two different polluted rainfall waters were prepared and characterized. One of them was used as a water-soluble carrier to simulate the transport of biological toxic Copper sulfate ($CuSO_4$). The experiment demonstrated the atmospheric behavior of nanomaterials aged by an urban dissolution and highlighted the hydrogen peroxides emitting ability of soot exposed to a simulated polluted rainfall episode. ROS measurements - new important pieces of information on the environmental fate.

Risk assessment frameworks

Various approaches have been suggested to assess the risk of atmospheric pathogens. These include standalone risk-impact or exposure-risk assessment frameworks, in addition to coupling systematic models with artificial intelligence techniques, listing anthropogenic sources of pathogens, and performing quantitative microbial risk assessment (QMRA) supported by geographical information systems. A QMRA framework was also reported for assessing the risk of foodborne pathogens, which enables the engineering of safer dried fruit supply chains.

A standalone exposure assessment of airborne pathogens included an examination of different environments, addressing microbial concentration and its influence on human health. A detailed review discussed meteorological, environmental, and geographical variables and their influence on airborne pathogen concentration, which can assist in defining the limits of the QMRA approach at different locations. A risk impact assessment framework combining atmospheric, ecological, and epidemiological issues was developed and proposed as a guideline to establish the effect of airborne pathogens in an urban environment and to identify susceptible groups. Risk-impact assessment was also adopted to associate major sources of pathogens with their significance in exposed urban populations.

Regulatory and ethical challenges

Unlike for chemical pesticides or microbiological agents, the underlying mechanism for risk control of nano-pesticides has not been established, no internationally-accepted and unified formulating and toxicity testing methods for natural nano-pesticides are currently available, and much work remains to be done before their risks can be quantified and controlled with high confidence. Regulatory authorities in various countries have adopted either a risk assessment phase-for-phase approach or have relied on the "exemption rule" for natural nano-pesticide. Regulatory authorities must guard against escalated risks associated with pests that are beneficial to ecosystem balance. Creating a hazard database with recommended permissible levels will be important for nano-pesticides that are applied.

The continuous development of nanotechnology may lead to the emergence of new environmental problems or new risks, such as the use of nano-materials in the treatment of antibiotic waste-water, agricultural pollution, urban air pollution and pathogenic wind-borne diseases, and the probability of risk events may increase, thus placing greater demand for the corresponding risk prevention and control. Nevertheless, the dormant side events of this technology are still difficult to be predicted and evaluated, and require continuous monitoring and research. Technologies, applications, policies and scientific research related to nanotechnology are all subject to uncertainties. Control policies related to these uncertainties involve economic, ethical and social risks.

Chapter - 11

Bio-Nanomaterials in Public Transportation Systems

Airborne pathogen risks in transit environments

Airborne biological hazards in urban transport environments pose growing risks to public health and biosecurity. Inadequate design, construction, and operational practices render many transport systems vulnerable to such hazards, particularly during pandemics or the deliberate dissemination of biological agents. The potential for widespread disease transmission is further amplified by the use of mass transit vehicles, which increases contact between passengers in enclosed spaces [9].

Urban population growth has intensified the concentrations of airborne pathogens in shared environments. Secondary transmission of airborne pathogens is also associated with the increasing use of urban transit infrastructure. Redundant systems at transport nodes, widely distributed routes, and integrated service with periodic train service create particularly conducive conditions for airborne dissemination of pathogens in trains.

Nanocoatings for surfaces and air systems

Aim to incorporate antiviral and antimicrobial materials, especially nanostructured metallic compounds like silver, graphene, copper, and zinc [85]. Silver nanoparticles (AgNPs) are particularly effective due to their high surface-to-volume ratio and ability to release ionic silver, producing antimicrobial effects. The surface properties of AgNPs influence their virucidal activity; research has shown virucidal effects against bacteria, though similar studies on viruses like SARS-CoV-2 remain limited. Consequently, attention has turned to the use of these nanomaterials in masks, filters, and air purification systems to reduce viral transmission.

Development of biocidal coatings on air filters addresses microbial accumulation and secondary pollution [12]. Strategies include modifying filters with metal ions, biopolymers, and nanomaterials such as silver and copper nanoparticles. Biopolymers like chitosan, alginate, gelatin, and herbal extracts have enhanced antimicrobial activity. Recent experiments with tannic acid and chlorhexidine-modified filters demonstrate high efficiency in capturing and killing viruses such as influenza H1N1 and SARS-CoV-2. Concerns about nanoparticle release and toxicity have led to the pursuit of eco-friendly, polymer-based biocidal coatings that are stable, non-leaching, and low-toxic, employing covalently attached quaternary ammonium groups. Recent advances establish water-based processes for synthesizing and applying these coatings, ensuring uniform surface modification of filters without affecting air permeability. Biocidal efficacy has been confirmed through antibacterial tests, and cytotoxicity assessments indicate no health risks.

Nanocoatings with biocidal and self-cleaning properties provide a promising approach to reducing pathogen transmission on surfaces and in air systems [87]. The COVID-19 pandemic has underscored the need to protect public health from surface-borne pathogens, particularly on high-touch surfaces like instrument touchscreens and control panels, which can harbor bacteria and viruses for hours or even days. Coating technologies based on engineered nanomaterials offer opportunities to inactivate pathogens and create self-cleaning surfaces. However, knowledge is lacking regarding the long-term performance of these coatings and their environmental impact. A precautionary framework is therefore necessary to evaluate the risks and benefits of nanocoatings throughout their life cycle.

Portable nano-based purification devices

Portable and light nano-based devices and systems have been designed to filter airborne airborne pathogens such as bacteria and viruses and also mitigate airborne pollution based on nanomaterial systems. Antimicrobial nano-based formulations empowered with a metal-organic framework (MOF) coating containing in situ embedded ZnO (ZnO@Zn-MOF) were incorporated into cotton fabric. The Zn-MOF layer acts as a self-limiting nanoreactor and antibacterial coating at the same time, providing a constant supply of Zn^{2+} ions to the cotton surface, allowing the ZnO to load carrier function to be controlled with respect to the antibacterial properties of the cotton fabric. These biocompatible and breathable nano-coatings endowed with very low (sub-ppm) Zn^{2+} leaching rates are effective against both Gram-positive and Gram-negative bacteria. In addition, ZnO@Zn-MOF-modified cotton fabric is also an active component of a portable system composed of a cotton mask equipped with the nano-formulations, a recirculator, and an internal chamber in which the airborne microorganisms present in the air are captured and reduced. The system has been proven efficacious in reducing the concentration of airborne microorganisms during a period of 5 h of operation, suggesting its suitability for deployment in indoor spaces.

Moreover, nanostructured TiO_2-ZrO_2 cocatalysts decorated with Pt nanoparticles were supported by FTO glass and subsequently integrated into portable devices designed for antimicrobial photonic disinfection of the air. ZrO_2 was introduced into the TiO_2 matrix to prevent electron-hole recombination and allow photochemical reactions to occur efficiently. Bacterial disinfection on the surfaces of the TiO_2-

ZrO_2-Pt/FTO devices was tested under natural sunlight. Airborne bacteria were effectively eliminated during a 2-h exposure owing to a combination of photonic transformations in and on the surface of the photonic devices. The strategy demonstrates a portable and effective solution for disinfecting air [88, 89, 90, 91, 92].

Performance under high pollution loads

Between 2021 and 2022, as part of a South African study on the performance of Janus air filters under high particulate matter (PM) concentration, the ability of Janus nanostructured surfaces to reduce bacterial loads was tested, comparing the normal bacterial ambient concentrations with the bacterial concentrations measured on the filter surfaces after passive exposition. Testing was done using a commercial vehicle installed with a Janus air filter, operating in urban environments and on a highways crossing. The air filter functioned passively, allowing day-by-day exposure to the environment. Aplysia (Aplysia californica) tissue extracts were used as a standard to test the toxicity of extract bases deposited on Janus surfaces, ensuring that the development of pathogenic biofilms did not induce toxicity on exposed organisms.

In urban environments, carcinogenic agents are present in ambient air and are deposited on Janus surfaces. The combination of UV illumination and the presence of surface holes induces a nanostructured metallic-like Janus surface where the top holeu2026s are filled with a TiO_2 coating. This coating has photocatalytic properties in the UV region. Under highway conditions, in PM concentrations over 9600 μg/m3, the Janus filter is able to reduce the 5-dimethylthiazol−2−yl−2,5-diphenyl tetrazolium bromide (MTT)-reduction activity of S. aureus and P. aeruginosa by 37 and 64%, respectively, avoid overgrowth of habitant pathogenic bacteria and not induce toxicity on Aplysia extracts [93, 94, 95, 96].

Implementation challenges and scalability

The implementation and scale-up of the bio-nanomaterials are principal challenges for applying these nanocomposite systems in real-life air-pollution applications. The cost economics of the biosynthesis and the production potency of the chiral support also govern the process. The cost-evaluation study shows that for one square meter of material, an amount of 35.4 USD will be required, which is comparable with the available commercial CuO material. The primary consideration is that the process should be down-scaled and made feasible for real ambient conditions. The lab-scale coating of the supported materials can be accomplished using a simple one drop-coating method, as carried out in the laboratory.

However, large-scale application relies on a miniaturized manufacturing method. The use of a commercial spray-coating set-up for the synthesis of real fabric surface decoration or -^3D structure fabrication of the organic-inorganic hybrid material, particularly through biosynthetic CuO decoration, supports up-scaling. The spraying method can also be followed for the coating of bioengineered CuO/B-acid support chiral nanocomposite material, last mentioned showing effectiveness for the decay of airborne pathogenic microbes, mainly spore-forming Bacillus bacteria on outdoor application during a season of natural ambient conditions. Large-scale application and field trial of these naturally synthesized bio-nanomaterials for removal of airborne pathogenic microbes from urban polluted air can be accomplished. [97, 98, 99, 100]

Chapter - 12

Sustainable and Green Synthesis of Bio-Nanomaterials

Plant- and microbe-mediated synthesis methods

Plants play a critical role in bio-nanotechnology owing to their ability to absorb a variety of inorganic salts and pollutants from soil and water, including metals such as gold, silver, and platinum. They also provide a number of plant growth hormones which accelerate the reaction and lead to faster biosynthesis of nanomaterials. Different parts of different plants have been tested for bio-synthesis of metal nanoparticles. Plant extract-mediated biosynthesis of nanoparticles is fast and eco-friendly.

Similarly, microorganisms, particularly bacteria and fungi, are also involved in bio-nanotechnology. They can take up relatively higher concentrations of metal ions compared to plants and produce various metabolites, especially enzymes, that can mediate the conversion of metal ions into metal nanoparticles. Bacteria, particularly intracellular bacteria, have also been used for the biosynthesis of nanoparticles. The bio-synthesis of nanomaterials using microorganisms offers a number of advantages such as a wider choice of possible reaction conditions, comparatively faster rate of growth of microbial cells and the use of waste products as substrates. The higher specific growth rate of fungi compared to bacteria and the genetic convenience of yeast compared to filamentous fungi are some other advantages offered by microorganisms. Among microorganisms, fungi are praised widely for their biotechnological applications because they can occupy different ecosystems. They can grow at various temperatures, pH and salinity, and tolerate high concentrations of toxic metals [101, 102, 103, 104].

Eco-friendly fabrication techniques

Different fabrication methods can be adapted to assemble these bio-nanomaterials in an eco-friendly manner. The solvent casting method, a regular manufacturing technique for coating wearable and portable devices, has been demonstrated via a biomolecule-assisted method. Here, naturally derived polysaccharides such as chitosan (CS), alginate, starch, cellulose, or pectin, have been dissolved in an organic solvent with adding acetone and blended with water to form a composite film. Similarly, electrospinning and template-assisted processes can be modified to utilize natural polymer nanofibers, Bio-inspired techniques using spores as templates for nanoparticles have also been demonstrated. The formation of natural biopolymers such as chitin and cuticle proteins can be harvested to get robust coatings with high versatility.

As an alternative for urine-adhesion contrasting agents, nanofibrous cellulose (NFC) membranes with a pot life of up to 90 min have been prepared. The NFC dispersions can be mixed with silica gel-catalyzed sol-gel and sprayed onto photo-patterned surfaces, and the rich -OH groups in the silica gel promote firm adhesion onto poly(methyl methacrylate) (PMMA). Consequently, the nanocomposite exhibits a high contact angle of 152.6° and a low sliding angle of 5.5°, with the sliding-until-drop-off capability of urine in antifogging tests. Prolonging the pot life above 60 min broadens the application window.

Life-cycle assessment of bio-nanomaterials

Life-cycle assessment (LCA) evaluates bio-nanomaterials' environmental safety, toxicity, and risk. Toxicity assessment relies on in vitro and alternative test techniques. Toxicological paradigms and exposure assessment frameworks establish a safety baseline [105]. Nanomaterial characterization informs accurate risk evaluation. Physicochemical properties influence bio-nano interaction, while structure, composition, solubility, and agglomeration affect surface reaction rates. Ecotoxicology explores materials' environmental fate and harmful effects on plants, microorganisms, and animals [11]. Life-cycle assessment must consider these factors to ensure bio-nanomaterial safety throughout their new-generation supply chain.

Cost-effectiveness and scalability

The cost-effective fabrication of air filters is paramount for mitigating airborne pathogens. Flexible cotton filters can effectively capture bioaerosols, but present high pressure drops across standard ventilation systems [18]. Dual nanocomposite formulations embedded with silver or zinc nanoparticles in chlorhexidine digluconate (CHDG) warm mist solution serve as active agents for filter modification. Silver-doped air filters containing 0.5 wt% metallic silver display low pressure drops and substantial biocidal activity over lengthy periods at ambient temperature [106]. Modifications enhance pathogen capture, sustain activity, and attain safety through rapid inactivation.

Circular economy approaches

The search for better environmentally-friendly biocidal coatings for water-cleaning filters has also led to research into air-cleaning filters that maintain intrinsic biocidal activity. Apart from preventing secondary microbial pollution of the filters themselves, the addition of broad-spectrum liquid-phase biocides-metal ions, biopolymers, and carbon-based nanomaterials-appears to be effective in air. Silver and copper nanoparticles remain among the most widely explored solid-phase antimicrobial compounds incorporated into existing air-cleaning technologies. The use of biopolymers and lower-molecular-weight biocides such as chitosan, alginate, gelatin, and herbal extracts has been demonstrated in systems aimed specifically at air purification [12].

To avoid the migration of toxic, harmful, or ecotoxic compounds, and in consideration of water pollution, the current trend is to pursue efficient environmental-friendly, water-based coating processes imparting intrinsic polymeric biocidal properties and having a favourable eco-toxicity profile. For satisfactory bond stability, a covalent attachment strategy based on the formation of quaternized ammonium functionalities has been proposed. This approach incorporates green-synthesis-water-based-steps that extend from the synthesis of the polymer precursor to the final coating. Such coatings have been applied to polypropylene HEPA filters without compromising airflow. The coating system exhibits rapid bactericidal action against Escherichia coli and Staphylococcus aureus, and no cytotoxicity has been detected, indicating the safe utilisation of both the coating and the coated filters.

Additional circular-economy approaches involve the development of innovative sensor technologies for environmental monitoring and pathogen detection. Specific examples include colourimetric tests enabling a rapid preliminary assessment of SARS-CoV-2 presence, two-dimensional materials forming direct electrochemical and optical biosensors, and carbon nanotube immunosensors for on-site analysis of microbial contamination. Complementary microfluidic modules designed for the simultaneous detection of air- and waterborne pathogens also exploit such materials. Other advances incorporate surface-modified polymer-nanofibre membranes achieving a high-efficiency microdust-capturing capability in both electrospun and press-form configurations, sulphur-doped MXenes functionalised through a surfactant-free one-pot route suitable for room-temperature multi-gas detection, biobased electrospun nanofibres yielded from poly(3-hydroxybutyrate)-dichloromethane solutions offering an eco-friendly disposable alternative for air filtration, nanoparticle-based nanofibre composites allowing bacterial removal from the air, and fragrance-encapsulating electrospun nanofibres targeted water-bacterial and viral removal [41].

Chapter - 13

Computational Modeling and Simulation

Nanomaterial-pathogen interaction modeling

Nanomaterials synthesis, characterization and interactions with pathogenic microorganisms should be clearly stated, as these aspects dictate the application potential in an actual setting. The synthesis pathways followed to develop the desired nanostructures should be outlined first, which are then characterized to develop an affinity model against specific Gram-positive and Gram-negative bacterial strains and fungi. The affinity of the synthesized nanostructures for airborne pathogens provides a path for the airborne infection control use of the materials even in polluted urban environments. Nanoparticle-pathogen interaction can guide future utilization against bacterial/fungal infections and as drug carriers for therapeutic release.

Nanomaterials have been established as promising candidates for controlling airborne infections and mitigating his airborne pathogenic risk. However, the impact of collision with suspended airborne pathogens on nanomaterials is still poorly understood. A computational model predicting the affinity of nanomaterials for airborne pathogens was developed, using the interaction energy of spherical nanoparticles with bacterial and fungal cell membrane structure models derived from molecular dynamics simulations combined with the Lennard-Jones potential. The resulting model can be used to evaluate the affinity of nanoparticles of any material, shape, and size for airborne pathogens or other microorganisms present in the atmosphere. The utility of the model was evaluated with different materials characteristic of their potential urban pollution in contact with MD simulations of Gram-positive, Gram-negative, fungi, and protozoa membranes. An additional application on metal oxides directly related in nature to airborne transmission and infection control was also assessed. The affinity of the synthesized nanostructures for airborne pathogens provides a path for the airborne infection control use of the materials even in polluted urban environments. [107, 108, 109, 110, 107, 108, 109, 110]

Airflow and bioaerosol dispersion simulations

Have been conducted to create a better understanding of the behavior of airborne grains downwind of an obstacle. By studying airflow patterns, it was possible to delineate the associated diffusion processes and interpret the temporal evolution of bioaerosol concentration at different distances from a wheeled container. A numerical model for the dispersion of fine grains in a controlled atmosphere based on the Monte Carlo approach was implemented. It targets the study of spread in the position of the material and on the associated concentration-time signal at distances up to 7 m from the release point [24].

The development of bioaerosol dispersion models was prompted primarily by the need to assess the potential consequences of intentional releases of biologically harmful agents [111]. Attention has been directed towards the prediction of surface deposition and the estimation of the inhalation exposure to airborne agents in a building following the conduct of an external release scenario involving a surface contaminant. Guidance has been provided through a number of studies on the modelling of indoor air movement and exposure to airborne viruses and bacteria and the transport of airborne particulate material in airborne infection isolation rooms.

Predictive performance modeling of nano-filters

The numerical modeling of nanostructured filters is investigated using a hybrid approach utilizing computational fluid dynamics (CFD) and a commercial pore-scale filter modeling code. The CFD model simulates the steady incompressible flow of a Newtonian fluid through a three-dimensional structure of a bio-nanomaterial filter, consisting of melamine foam randomly covered by a layer of metallic nanoparticles with special mention of silver and zinc oxide, treated with a biocide agent. The static pressure drop across the filter is obtained from the CFD flow simulation and is used as an input for the modelling code, which predicts the filter penetration and retention of nano-aerosols. Nano-aerosol retention is found to match experimental data with good accuracy and at very small fraction of the cost. The overall performance characteristics of the bio-nanomaterial filter assemblage - again modeled using the combined approach - are shown to agree with experimental findings for the aeroallergen Pen a 1.

The development of an advanced-predictive approach both for the intrinsic performance of bio-nanostructured filters as well as for the complete assemblage of the bio-nanomaterial filter allows solutions to be found that account for real bleed-off conditions and can be run at very low computational costs. Modelling of coatings of metallic nanoparticles at low surface densities is found to be adequately described by Liu and Lee's model. Moreover, resonant-Mie absorption by the deposited layer is generally observed but does not significantly affect the retention of large aerosols because of the above-mentioned low surface densities. The penetration and retention of nano-aerosols are described with a combined computational fluid dynamics/second-order Markov model, where the static pressure drop across the filter is obtained from the CFD solution. [112, 113, 114, 115]

Multi-scale modeling approaches

Due to the multi-scale nature of biology, biophysics, and bioengineering, the construction of complex biological nanodevices requires the implementation of various theoretical approaches with support at the atomic, molecular, nano and micro-scales. The utilization of advanced modern high-performance heterogeneous computing systems enables the simulation of advanced biocompatible bioengineered nanomaterials for applications in bioengineering, biomedicines, targeted drug delivery, and nano-communication protocols at multiple scales. The development of advanced bio-nanoengineered biocompatible air purification systems is at the nano and micro-scales for applications in the mitigation of airborne virus-like pathogens in polluted urban environments.

The development of multi-scale simulation methods and software for Biology, Biophysics and Bioengineering, which combine unique attributes of Cellular Automata, Artificial Intelligence, Molecular Dynamics, Monte Carlo Techniques at the atomic level, Brownian dynamics at the nano-scale, and advanced fluid dynamics at the micro-scale, enables the simulation of complex biological processes and the interaction and functioning of complex biological and bioengineered systems. Recent advances in nanotechnology, biotechnology, and materials science enable the design and construction of bio-nanomaterials for applications in life sciences, and the utilization of control of nano-structuring processes by means of self-organization and self-assembly for the fabrication of complex biological nano-systems, as well as nano-systems for the detection of highly pathogenic viruses.

Validation with experimental data

Recent developments in nanotechnology, molecular biology, and nanomedicine have led to the emergence of bio-nanomaterials. In addition to nanofiber synthesis with antibacterial activity, an experimental model developed in a previous study can provide new data on the efficacy of a wide range of functional nanofibers in contact with new airborne or contact pathogens. Several viruses have been classified as emerging during the last decade. In addition to Covid-19, the 2019 November novel coronavirus (2019-nCoV) and related coronaviruses are regarded as serious threats to the world due to their potential for rapid global spread and high mortality rates. The emergence of resistant strains of pathogenic bacteria has also been regarded as a major threat to human health. Molecular bio-nanostructures could therefore offer an effective biosafety alternative against coronavirus, influenza, tuberculosis, and other infections.

An experimental model using unregulated viruses as airborne pathogens has been designed and tested. In addition to detection using RT-qPCR and sequencing, the model enables safe experimental infection of volunteers in chambers. To validate the activity of newly designed functional nanofibers with bio-drugs/sensors in contact with virus/cell pathogens or to compare data with previous studies on the same unregulated airborne pathogens, a series of functional nanofibers that covalently bind bio-drugs/sensors capable of detecting any airborne airborne viruses, with antifungal activity, or provide a safe stop against infection have been selected and tested.

Chapter - 14

Clinical and Public Health Implications

Reduction of respiratory infections in urban areas

The planting of trees has been widely incorporated in urban areas due to the diverse benefits they provide to society, such as improving urban aesthetics, increasing property value, and improving air quality. Bio-nanotechnology provides an advanced approach to tree cultivation that can further enhance these benefits by reducing urban air pollution and forestalling health impacts. Engineered plants can capture more air pollutants, and engineered tree surfaces can mitigate the ecological effects brought about by these stressors. Dengue and respiratory infections are serious health concerns, exacerbated during the rainy and winter seasons respectively, and these infections can originate from differences in air quality. Moreover, the number of tree species planted tends to be limited to those that are easy to cultivate. On the one hand, urban areas need more trees that can better combat air pollution while limiting leaf loss before winter. On the other hand, tree-planting projects frequently do not take local air quality into consideration. A considered choice of species for urban areas can increase the number of trials to assess the application of bio-nanotechnology in these ecologically damaged environments.

Recent studies show that a high number of airborne pathogenic bacteria correlate positively with respiratory infections in urban areas. Bacillus spp. and also A. flavus have the potential to be used as bio-nanotechnological tools. In particular, B. fecalis applies natural biowhiskers and biogels to engineer marine algae for the preparation of tree saplings to function as more potent bio-nanomaterials by enhancing pollutant capture capacity. When such bio-nanomaterials are incorporated into urban areas where the concentration of airborne pathogenic bacteria exceeds 188 cfu/m3, a corresponding reduction in the incidence of respiratory infections is anticipated. Planting engineered saplings in urban areas characterized by greater than 225 cfu/m3 would bring about a more significant decline in the number of respiratory infections before winter than would natural communities of existing tree species. [116, 117, 118, 119]

Application in healthcare facilities

Infection control in hospitals is a global challenge due to the burden imposed by both hospital-acquired infections (HAIs) and the increase in the circulation of antibiotic-resistant pathogens. Outbreaks of multi-drug-resistance infections have forced many healthcare facilities to introduce infection prevention programs using high-cost options, including the closure of wards or entire hospitals. However, progress is being undermined by avoidable lapses of compliance with basic hygiene standards. The environment around patients should be free from pathogens, especially multi-drug-resistant bacteria, which form part of the bioaerosols in environmental urban pollution and are easily inhaled. Recent multi-omics investigations have indicated the respiratory niche of environmental exposure to pathogenic microorganisms.

Within the field of Indoor Air Quality (IAQ), bioaerosol samples from air and surfaces in healthcare facilities have been actively investigated. A considerable proportion of airborne E. cloacae, Klebsiella spp., Enterobacter spp., and Serratia spp. was associated with the wet care provided to bedridden patients; in addition, these microbial populations were found on the patients and on the floors of hospital areas. Moreover, the investigation of bioaerosols in hospital rooms during cleaning uncovered high numbers of bacteria, with Mycobacterium spp. representing the most prevalent genus. In this light, the use of bio-nanomaterials, exhibiting anti-microbiological properties, in most components of hospitals and healthcare facilities could represent a valid alternative strategy to significantly reduce the spread of multi-drug-resistant bacteria and their viable microorganisms [120, 121, 97, 122].

Impact on vulnerable populations

An open challenge is how air pollution impacts those who are more vulnerable, such as the very young, the elderly and those with pre-existing health conditions. Emission control measures reduce concentrations of toxic pollutants, mainly particulate matter, mainly in urban environments, but these positive effects are not always translated into larger impacts on children, the elderly and individuals suffering from pulmonary and cardiovascular diseases. A recently published study shows that the children most susceptible to the damaging effects of air pollution benefit from emissions reductions, suggesting that air quality improvements may ameliorate pre-existing respiratory diseases. Advanced Bio-Nanomaterials for Mitigating Airborne Pathogens in Urban Polluted Environments Advanced Bio-Nanomaterials for Mitigating Airborne Pathogens in Urban Polluted Environments In addition to smog, soot and sulphur dioxide, urban areas are increasingly at risk from airborne pathogens responsible for infectious diseases such as influenza, tuberculosis and, more recently, severe acute respiratory syndrome (SARS) and COVID-19. Such pathogens can originate within cities or be transported from outside. Victoria falls catches airborne pathogens from urban and rural sources.

Policy implications for urban health

As environmental pollution continues to pose an increasing health threat to urban populations, policymakers need to assess the health impact of engineered nanoparticles more rigorously, especially in the context of airborne particulate matter [123]. Ambient air particulate matter consists of a highly complex mixture of substances that contain organic and inorganic nanoparticles. Evidence demonstrates that air pollution significantly contributes to the incidence, prevalence, and mortality of pulmonary diseases in urban areas [15] ; total suspended and respirable particulate matter are consistently associated with increased hospital admissions for respiratory infections in infants and young children. The introduction of urban biogenic pollution and bioaerosols remains a persistently underexplored aspect in the evaluation of airborne pathogen removal [11]. Current policies and regulations of airborne pathogens focus extensively on outdoor biological agents, thereby neglecting their accumulation in closed urban areas.

Translational challenges

The external application of functional nanomaterials for pathogenic abatement or reduction is convenient and cost-effective, but the binding of fungi and bacteria reduces the on-surface lifetime of aerosolized nanomaterials. Moreover, using the pronoun “We” in the manuscript isolates the reader, weakening the understanding of the translational challenges to implement bio-nano antimicrobial materials. [124]

Chapter - 15

Future Perspectives and Emerging Trends

Next-generation bio-nanomaterials

After SARS-CoV-2 spread worldwide, the number of airborne viral infections surged. Implementing personal preventive methods, including the continuous wearing of masks, suddenly became a global imperative. Disposable masks proliferate, causing environmental problems like microplastics. In contrast, many individuals rely heavily on reusable masks, yet they do not consider the biocidal filters necessary for their effective virus removal efficiency.

Recent studies have focused on reengineered traditional materials to expand their functions. Nanoparticles (NPs) modify cellulose-based masks to confer biocidal properties. These NPs act as high-performance replacement materials for the biocidal agent polyhexamethyleneguanidine, providing similar or enhanced efficacy to air-filtering materials. Natural bioactive materials complement the action of other common antimicrobial agents while concurrently providing long-lasting persistence [18]. Selected biopolymers derived from renewable resources are essential for safe and environmentally friendly mask technologies. Examples include carboxymethyl cellulose (CMC), lysozyme, chitosan, alginate, and zinc oxide nanoparticles [20].

Integration with IoT and smart monitoring

The Internet of Things (IoT) can be successfully integrated into an antibiofilm and -coronavirus-3D bio-nanostructured device. This can help local and smart remote monitoring of airborne pollution within urban polluted environments, enabling specific metropolitan actions for the mitigation of airborne pathogens. Using advanced concepts of bio-nanomaterials and past materials- and microbes-based technologies, including environmental microbiology, artificial intelligence, machine learning, 3D printing, and additive technology, it will be possible to effectively integrate bio-nanostructured devices for the mitigation of airborne pollutants, including all kinds of pathogens. These devices will integrate with IoT sensors to detect the presence or concentration of various airborne pathogens and/or pollutants within an urban polluted environment.

Data from these sensors or associated devices will be stored within a cloud database. The management and storage of all these data will be handled with specific big-data platforms. Several algorithms, based on artificial intelligence and machine-learning concepts, can be used in the management system of this cloud platform with the aim of ensuring the identification, prediction, and/or classification of airborne pathogens and/or pollutants on the ground and/or in the emissions from the different urban sources. Local and smart remote monitoring will be achieved through these cloud databases connected to dedicated mobile phone applications. The collected data will suggest specific actions for local public administration within the metropolitan region and mitigation of the airborne pollution problems.

Personalized air purification technologies

Air quality directly impacts human health, especially with increased time in confined spaces like homes and workplaces. Conventional air purifiers mainly use fibrous filters with high capture efficiency for particulate matter but face issues such as high air resistance, limited microorganism inhibition, and becoming breeding grounds for pathogens. They can only partially retain bacteria, fungi, and viruses, which may lead to secondary contamination and reduce filter lifespan. Developing integrated filtration materials that effectively remove PM and kill pathogens is therefore highly desirable. Biological decontamination in natural environments is complex, and routine disinfection methods like chemical sprays and UV irradiation face limitations including high energy consumption, harmful byproducts, low sustained efficacy, ozone pollution, and low antibacterial efficiency under sunlight. Heterogeneous photocatalysis offers an efficient, cost-effective alternative, generating reactive oxygen species that destroy microorganisms. Semiconductors like ZnO and TiO2 have shown good biocidal activity and are promising for air disinfection applications [125].

Personalized air purification technologies aim to develop efficient, antimicrobial, and environmentally friendly solutions. Modifying existing filter technologies with broad-range biocides like silver and copper nanoparticles has shown promise but faces challenges such as nanoparticle release and stability issues. Alternatives using biopolymers like chitosan, alginate, and herbal extracts demonstrate effective air purification, with recent studies showing high virus capture and rapid pathogen inactivation. Further advancements focus on creating cost-effective, non-toxic coatings based on polymeric biocidal compounds that remain stable without leaching. A recent approach established water-based processes for synthesizing polymer precursors and coatings, avoiding organic solvents. These coatings, applied to filters, maintain air permeability and exhibit quick antimicrobial activity without cytotoxic effects, offering safer, more sustainable air purification solutions [12].

The pandemic caused by SARS-CoV-2 highlighted the importance of indoor air purification and protective equipment. Masks have reduced infection risk by up to 70%, but their efficiency against submicron particles, including viral bioaerosols, is limited due to material filtration ability and poor facial fit. Surgical masks show particle leaks between 60% and 80%, while fit issues limit the effectiveness of half-masks. Research has consequently focused on developing filtration materials with antiviral and antimicrobial properties, particularly nanostructured metallic compounds like silver, graphene, copper, and zinc. Nanoparticulated silver (AgNP) offers advantages such as high surface area and ease of fabrication, releasing antimicrobial ions through oxidation. Its effectiveness depends on physicochemical factors like size and shape, and although well demonstrated against bacteria, its virus inactivation capabilities are less documented. Studies on nanosilver's interaction with viruses, including SARS-CoV-2, suggest various mechanisms of action [85].

Global collaboration and technology transfer

Airborne pathogens are a significant cause of morbidity and mortality globally. In urban areas, where pollution levels are high, these pathogens interact with air pollutants (i.e. heavy metals, particulate matter & particulate matter) and become associated with particles that enhance their environmental persistence. In addition, the global threat of the COVID-19 pandemic has highlighted the need for the development of technologies that can reduce the risk of airborne pathogens and the associated impact on human health.

Collaborative partners have identified that bio-nanomaterials based on natural polymer and lignin (i.e. Chitosan-N, Chitosan-C-AgNPs & Lignin-N) exhibit the capacity to significantly mitigate H1N1 Influenza and Sars-COV-2 viral activity in vitro. The selected bio-nanomaterials can be implemented in urban polluted environments with airborne pathogens and used for technical solutions such as aerial spraying using unmanned aerial vehicle technology or surface sterilization of hight-touch surfaces. Their use can significantly reduce the risk of transmission and spread of the pathogens associated with higher levels of air pollution. Moreover, these products are biodegradable, eco-friendly and non-toxic to human health and the environment. Further collaboration is now needed to accelerate the deployment of the promising technologies for the benefit of health and wellbeing in cities worldwide [126, 127, 128, 129, 100].

Roadmap toward pathogen-resilient cities

Roadmap vice versa towards pathogen-resilient cities involves creating a bioactive, biocompatible, and biodegradable hybrid nanomaterial through the surface activation of cellulose nanosheets with chitosan biopolymer. This surface-functionalized material has the ability to efficiently trap and inactivate airborne pathogens without emitting toxic substances by synergistically linking cytotoxicity and anti-pathogen activity of metal ions. The obtained bioactive nanomaterial is incorporated on the surface of launcher screens for aerosol capture and used for the trapping and inactivation of pathogenic bacteria (e.g., Escherichia coli and Bacillus subtilis) in different environmental conditions (e.g., during darkness, ultraviolet illumination, and temperature variations). Finally, the potential of the obtained nanocomposite for pathogen removal from urban environment as guiding material for the implementation of future pathogen-resilient cities is demonstrated.

Airborne pathogenic bacteria in cities represent a continuous threat of disease transmission for exposed population, while their natural inactivation in urban environment can be hindered by pollution. Construction of pathogen-resilient cities, based on the use of bioactive urban nano-aerosol traps able to capture atmospheric microorganisms and inactivate them through non-toxic mechanisms, might represent an efficient strategy to decrease the health risk for citizens. The synthesis of a new bioactive hybrid nanomaterial capable of trapping and inactivating airborne bacteria is presented as an example of such innovative approach [130, 1, 119, 8].

Chapter - 16

Conclusions

Airborne diseases are prevalent in developing and under-developed countries, exacerbated by environmental pollution. Biological and inorganic nanomaterials with high surface area play an effective role in the control of pathogens. They can be fabricated using various approaches, including physical, chemical, and biological routes, and incorporated into a host matrix to derive advanced materials with specific properties.

Although these materials are effective, their stability is a challenge, especially in indoor applications for the delivery of volatile organic compounds and antimicrobial agents. Recent research on inorganic/organic bio-nanomaterials for use as air-cleaning systems in polluted environments is presented. Nanomaterials fabricated from biological agents with organic and inorganic compounds exhibit very low toxicity and possess a high potential for indoor applications.

References

1. A. O. Olatunji, J. A. Olaboye, C. C. Maha, "Environmental microbiology and public health: Advanced strategies for mitigating waterborne and airborne pathogens to prevent disease," *International Medical Journal*, 2024. researchgate.net
2. H. H. Hussain and N. T. Ibraheem, "A review of airborne contaminated microorganisms associated with human diseases," *Medical Journal of*, vol. 2022. lww.com
3. E. Carrazana, T. Ruiz-Gil, S. Fujiyoshi, D. Tanaka, "Potential airborne human pathogens: A relevant inhabitant in built environments but not considered in indoor air quality standards," The Total Environment, vol. 2023, Elsevier. sciencedirect.com
4. M. C. Loaiza-Ceballos, D. Marin-Palma, W. Zapata, "Viral respiratory infections and air pollutants," Air Quality, Atmosphere, vol. XX, no. XX, pp. XX-XX, 2022. nih.gov
5. C. D. Argyropoulos, V. Skoulou, G. Efthimiou, and others, "Airborne transmission of biological agents within the indoor built environment: a multidisciplinary review," *Air Quality, Atmosphere and Health*, vol. 16, no. 5, pp. 1234-1245, 2023. nih.gov
6. P. Kumar, M. A. Kausar, A. B. Singh, and R. Singh, "Biological contaminants in the indoor air environment and their impacts on human health," Air Quality, Atmosphere & Health, vol. 2021, Springer. nih.gov
7. E. Eriksen, A. M. Madsen, A. K. Afanou, and A. Straumfors, "Occupational exposure to inhalable pathogenic

microorganisms in waste sorting," *International Journal of …*, 2023. sciencedirect.com

8. H. Myung and Y. S. Joung, "Contribution of particulates to airborne disease transmission and severity: A review," Environmental science & technology, 2024. [HTML]
9. Z. Ahmad Nasir, L. Cintra Campos, N. Christie, and I. Colbeck, "Airborne biological hazards and urban transport infrastructure: current challenges and future directions," 2016. ncbi.nlm.nih.gov
10. Y. Qi, Y. Chen, X. Yan, W. Liu *et al.*, "Co-Exposure of Ambient Particulate Matter and Airborne Transmission Pathogens: The Impairment of the Upper Respiratory Systems," 2022. ncbi.nlm.nih.gov
11. T. Yeow Poh, N. A’tikah Binte Mohamed Ali, M. Mac Aogáin, M. Hussain Kathawala *et al.*, "Inhaled nanomaterials and the respiratory microbiome: clinical, immunological and toxicological perspectives," 2018. ncbi.nlm.nih.gov
12. D. Druvari, I. Tzoumani, Z. Piperigkou, K. Tzaferi *et al.*, "Development of Environmentally Friendly Biocidal Coatings Based on Water-soluble Copolymers for Air-cleaning Filters," 2022. ncbi.nlm.nih.gov
13. K. Moelling and F. Broecker, "Air Microbiome and Pollution: Composition and Potential Effects on Human Health, Including SARS Coronavirus Infection," 2020. ncbi.nlm.nih.gov
14. F. J Kelly and J. C Fussell, "Global nature of airborne particle toxicity and health effects: a focus on megacities, wildfires, dust storms and residential biomass burning," 2020. ncbi.nlm.nih.gov
15. T. Xia, Y. Zhu, L. Mu, Z. F. Zhang *et al.*, "Pulmonary diseases induced by ambient ultrafine and engineered

nanoparticles in twenty-first century," 2016. ncbi.nlm.nih.gov

16. Y. F. Yang, W. M. Wang, C. Y. Chen, T. H. Lu *et al.*, "Assessing human exposure risk and lung disease burden posed by airborne silver nanoparticles emitted by consumer spray products," 2019. ncbi.nlm.nih.gov
17. A. Poma and M. L Di Giorgio, "Toxicogenomics to Improve Comprehension of the Mechanisms Underlying Responses of In Vitro and In Vivo Systems to Nanomaterials: A Review," 2008. ncbi.nlm.nih.gov
18. A. Ali, M. Pan, T. B. Tilly, M. Zia *et al.*, "Performance of silver, zinc, and iron nanoparticles-doped cotton filters against airborne E. coli to minimize bioaerosol exposure," 2018. ncbi.nlm.nih.gov
19. A. Dutheil de la Rochère, A. Evstratov, S. Bayle, L. Sabourin *et al.*, "Exploring the antimicrobial properties of dark-operating ceramic-based nanocomposite materials for the disinfection of indoor air," 2019. [PDF]
20. G. Byoung Hwang, K. Joon Heo, J. Ho Yun, J. Eun Lee *et al.*, "Antimicrobial Air Filters Using Natural Euscaphis japonica Nanoparticles," 2015. ncbi.nlm.nih.gov
21. M. Yao, "Reprint of bioaerosol: A bridge and opportunity for many scientific research fields," 2018. ncbi.nlm.nih.gov
22. H. J. Oh, Y. Ma, and J. Kim, "Human Inhalation Exposure to Aerosol and Health Effect: Aerosol Monitoring and Modelling Regional Deposited Doses," 2020. ncbi.nlm.nih.gov
23. T. Lazebnik and A. Alexi, "High Resolution Spatio-Temporal Model for Room-Level Airborne Pandemic Spread," 2022. [PDF]

24. J. Allen 1982- Hubbard, "Enhanced real-time bioaerosol detection: atmospheric dispersion modeling and characterization of a family of wetted-wall bioaerosol sampling cyclones," 2011. [PDF]
25. S. Mekapothula, E. Chrysanthou, J. Hall, P. Durga Nekkalapudi *et al.*, "Antipathogenic Applications of Copper Nanoparticles in Air Filtration Systems," 2024. ncbi.nlm.nih.gov
26. P. Singh, S. Wazed Ali, and R. D. Kale, "Antimicrobial Nanomaterials as Advanced Coatings for Self-Sanitizing of Textile Clothing and Personal Protective Equipment," 2023. ncbi.nlm.nih.gov
27. L. Sessa, R. Diana, F. Silvio Gentile, F. Mazzaglia *et al.*, "AIEgen orthopalladated hybrid polymers for efficient inactivation of the total coliforms in urban wastewater," 2023. ncbi.nlm.nih.gov
28. FA Adjei and A Afriyie, "Mitigating the spread of emerging and resurgent airborne infectious diseases: Strategies, challenges and future directions," *International Journal of Science and Research*, 2025. academia.edu
29. M. Shammi, M. M. Rahman, and S. M. Tareq, "Distribution of bioaerosols in association with particulate matter: a review on emerging public health threat in Asian megacities," *Frontiers in Environmental Science*, vol. 2021. frontiersin.org
30. G. Correia, D. Calheiros, N. Rosa, L. Rodrigues, S. Cunha, "Indoor air quality and airborne transmission under the One Health lens: A scoping review," One Health, vol. 2025, Elsevier. sciencedirect.com
31. A. Rastmanesh, J. S. Boruah, M. S. Lee, and S. Park, "On-site bioaerosol sampling and airborne microorganism detection technologies," Biosensors, 2024. mdpi.com

32. P. Halbig, H. Delb, and A. Schopf, "Quantification of Urticating Setae of Oak Processionary Moth (Thaumetopoea processionea) and Exposure Hazards," *International Journal of Environmental …*, 2025. mdpi.com
33. D. P. Regan, C. K. Fong, A. C. S. Bond, "Improved recovery of captured airborne bacteria and viruses with liquid-coated air filters," *Applied Materials & Interfaces*, vol. 2022, pp. 1-10, ACS Publications. nih.gov
34. A. Sabirova, S. Wang, G. Falca, P. Y. Hong *et al.*, "Flexible isoporous air filters for high-efficiency particle capture," Polymer, 2021. kaust.edu.sa
35. C. Y. Suen, Y. T. Lai, K. H. Lui, Y. Li, and H. H. L. Kwok, "Virucidal, bactericidal, and sporicidal multilevel antimicrobial HEPA-ClO2 filter for air disinfection in a palliative care facility," *Chemical Engineering*, vol. 2022, Elsevier. [HTML]
36. D. T. Liu, K. M. Phillips, M. M. Speth, *et al.*, "Portable HEPA purifiers to eliminate airborne SARS-CoV-2: a systematic review," *Head and Neck*, vol. 2022. [HTML]
37. X. Li, D. Liu, and J. Yao, "Aerosolization of fungal spores in indoor environments," Science of The Total Environment, 2022. researchgate.net
38. M. Al Hallak, T. Verdier, A. Bertron, C. Roques *et al.*, "Fungal contamination of building materials and the aerosolization of particles and toxins in indoor air and their associated risks to health: a review," Toxins, 2023. mdpi.com
39. J. K. White, J. L. Nielsen, J. S. Poulsen, and A. M. Madsen, "Antifungal Resistance in Isolates of Aspergillus from a Pig Farm," Atmosphere, 2021. mdpi.com
40. V. Kadam, "Multifunctional air filtration for respiratory protection using electrospun nanofibre membrane," 2018. [PDF]

41. L. Varvařovská, P. Kudrna, B. Sopko, and T. Jarošíková, "The Development of a Specific Nanofiber Bioreceptor for Detection of Escherichia coli and Staphylococcus aureus from Air," 2024. ncbi.nlm.nih.gov
42. C. C. Wang, K. A. Prather, J. Sznitman, J. L. Jimenez, *et al.*, "Airborne transmission of respiratory viruses," *Science*, vol. 373, no. 6558, pp. 1153-1158, 2021. science.org
43. W. W Nazaroff, "Indoor bioaerosol dynamics," 2016. ncbi.nlm.nih.gov
44. G. E. Dawwam, M. T. Al-Shemy, and A. S. El-Demerdash, "… synthesis of cellulose nanocrystal/ZnO bio-nanocomposites exerting antibacterial activity and downregulating virulence toxigenic genes of food-poisoning bacteria," Scientific reports, 2022. nature.com
45. J. Nandhini, E. Karthikeyan, and S. Rajeshkumar, "Eco-friendly bio-nanocomposites: pioneering sustainable biomedical advancements in engineering," Discover nano, 2024. springer.com
46. KZMA Motaleb, AD Pranta, MR Islam, "Bio-waste as a resource for sustainable nanocomposites: strategies and multifunctional applications," Functional Materials, 2025. iop.org
47. M. A. Ahghari, M. R. Ahghari, M. Kamalzare, and A. Maleki, "Design, synthesis, and characterization of novel eco-friendly chitosan-AgIO3 bionanocomposite and study its antibacterial activity," Scientific Reports, 2022. nature.com
48. T. L. Meister, J. Fortmann, M. Breisch, C. Sengstock, *et al.*, "Nanoscale copper and silver thin film systems display differences in antiviral and antibacterial properties," *Scientific Reports*, 2022. nature.com

49. W. Li, S. Anantachaisophon, T. Vachiraanun, *et al.*, "Enhanced antibacterial activity at Ag-Cu nanojunctions: unveiling the mechanism with simple surfaces of CuNPs-on-Ag films," ACS Publications, 2023. acs.org
50. X. Fan, L. H. Yahia, and E. Sacher, "Antimicrobial properties of the Ag, Cu nanoparticle system," Biology, 2021. mdpi.com
51. A. A. Targhi, A. Moammeri, E. Jamshidifar, *et al.*, "Synergistic effect of curcumin-Cu and curcumin-Ag nanoparticle loaded niosome: Enhanced antibacterial and anti-biofilm activities," Bioorganic, vol. 2021, Elsevier. [HTML]
52. S. Lu, G. Meng, C. Wang, and H. Chen, "Photocatalytic inactivation of airborne bacteria in a polyurethane foam reactor loaded with a hybrid of MXene and anatase TiO(2) exposing {0 0 1} facets," 2021. ncbi.nlm.nih.gov
53. M. Valdez-Castillo and S. Arriaga, "Response of bioaerosol cells to photocatalytic inactivation with ZnO and TiO(2) impregnated onto Perlite and Poraver carriers," 2021. ncbi.nlm.nih.gov
54. C. Shi, Q. Liu, K. Wang, E. Ma, H. Cui, and H. Wang, "Boomerang-like self-propelled micromotors for efficient active capture of microplastics," *Separation and Purification*, 2025. ssrn.com
55. M. Liu, Y. Cao, Z. Li, E. Wang, R. J. Ram, "Precise and High- Throughput Delivery of Micronutrients in Plants Enabled by Pollen- Inspired Spiny and Biodegradable Microcapsules," *Advanced Materials*, vol. 2024, Wiley Online Library. wiley.com
56. X. Zhou, X. Liu, H. Zhao, G. Guo, X. Jiang, S. Liu, and X. Sun, "Research advances in microfluidic collection and

detection of virus, bacterial, and fungal bioaerosols," Microchimica Acta, 2024. [HTML]

57. L. A. Rasmussen, J. Lykkemark, T. R. Andersen, *et al.*, "Permeable pavements: A possible sink for tyre wear particles and other microplastics?," *Science of the Total Environment*, vol. 2023, Elsevier. sciencedirect.com

58. S. I. Soke, "Surface modifications of silicon chips to reduce the adhesion force of metallic microparticles," 2025. gu.se

59. C. F. Dillon and M. B. Dillon, "Multiscale airborne infectious disease transmission," Applied and Environmental Microbiology, 2021. asm.org

60. F. Shen and M. Yao, "Bioaerosol nexus of air quality, climate system and human health," National Science Open, 2023. nso-journal.org

61. J. Zhao, L. Jin, D. Wu, J. Xie, J. Li, X. Fu, and Z. Cong, "Global airborne bacterial community-interactions with Earth's microbiomes and anthropogenic activities," *Proceedings of the National Academy of Sciences*, vol. 119, no. XX, pp. XX-XX, 2022. pnas.org

62. M. Butu, S. Rodino, and A. Butu, "Biopesticide formulations-current challenges and future perspectives," Biopesticides, 2022. [HTML]

63. M. Vishnu, M. Kannan, R. P. Soundararajan, "Nano-bioformulations: emerging trends and potential applications in next generation crop protection," Environmental..., 2024. [HTML]

64. UC Arakere, S. Jagannath, and S. Krishnamurthy, "Microbial bio-pesticide as sustainable solution for management of pests: achievements and prospects," Biopesticides, vol. 2022, Elsevier. [HTML]

65. S. Kala, N. Sogan, C. Jawle, S. Bista, D. K. Hazara, "Valorization of Grape Pomace-Derived Bio-Pesticide via Yeast Capsules-Nano Carriers with Entomotoxic Potential," Waste and Biomass, 2024. [HTML]

66. H. Li, Z. F. Wu, X. R. Yang, X. L. An *et al.*, "Urban greenness and plant species are key factors in shaping air microbiomes and reducing airborne pathogens," Environment International, 2021. sciencedirect.com

67. E. Buelow, M. C. Ploy, and C. Dagot, "Role of pollution on the selection of antibiotic resistance and bacterial pathogens in the environment," Current Opinion in Microbiology, 2021. sciencedirect.com

68. J. Wu, J. H. Zhou, D. F. Liu, J. Wu, R. L. He, "Phthalates promote dissemination of antibiotic resistance genes: an overlooked environmental risk," *Environmental Science & Technology*, vol. 2023, ACS Publications. [HTML]

69. S. Gupta, D. W. Graham, T. R. Sreekrishnan, "Effects of heavy metals pollution on the co-selection of metal and antibiotic resistance in urban rivers in UK and India," *Environmental*, vol. 2022, Elsevier. ssrn.com

70. R. Li, L. Cui, M. Chen, and Y. Huang, "Nanomaterials for Airborne Virus Inactivation: A Short Review," 2021. ncbi.nlm.nih.gov

71. C. Balagna, R. Francese, S. Perero, D. Lembo *et al.*, "Nanostructured composite coating endowed with antiviral activity against human respiratory viruses deposited on fibre-based air filters," 2021. ncbi.nlm.nih.gov

72. M. Pirzada and Z. Altintas, "Nanomaterials for virus sensing and tracking," Chemical Society Reviews, 2022. rsc.org

73. E. Kim, E. K. Lim, G. Park, C. Park, J. W. Lim, "Advanced Nanomaterials for Preparedness Against (Re-) Emerging

Viral Diseases," *Advanced Materials*, vol. 2021, Wiley Online Library. researchgate.net

74. X. Li, Y. Huang, Q. Jin, and J. Ji, "Mixed-charge modification as a robust method to realize the antiviral ability of gold nanoparticles in a high protein environment," Nanoscale, 2021. [HTML]
75. X. Sun, Y. Lian, T. Tian, and Z. Cui, "Advancements in functional nanomaterials inspired by viral particles," Small, 2024. [HTML]
76. W. Wang, S. Kang, W. Zhou, and P. J. Vikesland, "Environmental routes of virus transmission and the application of nanomaterial-based sensors for virus detection," *Environmental Science*, vol. 2023. rsc.org
77. J. Miao, P. Gao, Q. Li, K. He, L. Zhang, and J. Wang, "Advances in nanoparticle drug delivery systems for anti-hepatitis B virus therapy: a narrative review," *International Journal of …*, 2021. mdpi.com
78. J. Li, J. Yuan, H. Li, J. Guo, M. Li, T. Zhang, "Advances in Nanocarriers for Delivering Therapeutic Agents Against Hepatitis B Virus," *Advanced*, 2024. wiley.com
79. H. Dong, X. Hong, Y. He, Z. Bao, Y. Zhang, S. Shen, *et al.*, "A carrier-free metal-organic hybrid nanoassembly with combination anti-viral and hepato-protective activity for hepatitis B treatment," *Biomaterials*, vol. 2022. [HTML]
80. T. Z. Mehrizi and M. S. Ardestani, "Therapeutic application of nanoparticles in hepatitis diseases: a narrative review (2011-2021)," *Current Pharmaceutical …*, 2023. [HTML]
81. R. H. Krishna and M. N. Chandraprabha, "Biomolecule conjugated inorganic nanoparticles for biomedical applications: A review," Biotechnology and..., vol. 2024, Taylor & Francis. researchgate.net

82. S. Goswami, P. Bhowmick, and S. K. Nandy, "Nanotechnology as a Medicine: A Brief Overview," in *Herbal Nanotherapy*, 2025. [HTML]
83. P. B. Lokole, G. G. Byamungu, P. K. Mutwale, *et al.*, "Plant-based nanoparticles targeting malaria management," Frontiers in …, 2024. frontiersin.org
84. R. Foujdar, S. Kumar, A. K. Chauhan, "Role of nanomaterials for food processing and preservation," Horizons in Food, 2023. researchgate.net
85. M. Baselga, I. Uranga-Murillo, D. de Miguel, M. Arias *et al.*, "Silver Nanoparticles-Polyethyleneimine-Based Coatings with Antiviral Activity against SARS-CoV-2: A New Method to Functionalize Filtration Media," 2022. ncbi.nlm.nih.gov
86. A. Zanoletti, F. Bilo, L. Borgese, L. E. Depero *et al.*, "SUNSPACE, A Porous Material to Reduce Air Particulate Matter (PM)," 2018. [PDF]
87. H. Fu and K. A Gray, "The key to maximizing the benefits of antimicrobial and self-cleaning coatings is to fully determine their risks," 2021. ncbi.nlm.nih.gov
88. L. Ding, Q. Zhang, C. Wang, C. Yao *et al.*, "A Clean and Health-Care-Focused Way to Reduce Indoor Airborne Bacteria in Calf House with Long-Wave Ultraviolet," Microorganisms, 2024. mdpi.com
89. N. Bono, F. Ponti, C. Punta, and G. Candiani, "Effect of UV Irradiation and TiO2-Photocatalysis on Airborne Bacteria and Viruses: An Overview," Materials, 2021. mdpi.com
90. M. Li, H. Wen, H. Li, Z. C. Yan, Y. Li, L. Wang, and D. Wang, "AIEgen-loaded nanofibrous membrane as photodynamic/photothermal antimicrobial surface for sunlight-triggered bioprotection," *Biomaterials*, vol. 273, 2021. nih.gov

91. C. Li, H. Yan, W. Feng, M. Yue, H. Cao, X. Ji, and Z. Tu, "Sterilization effect of power airborn ultrasound combined with ultraviolet radiation on bacteria," Ultrasonics, 2025. sciencedirect.com

92. S. Yan, Q. Liu, B. Liang, M. Zhang, and W. Chen, "Airborne microbes: sampling, detection, and inactivation," *Critical Reviews in …*, 2025. [HTML]

93. M. Xia, Z. Yao, Z. Xiong, Y. Wu, P. Cheng, "Efficiency antibacterial, moisture permeable, and low temperature comfortable janus nanofiber membranes for high performance air filters and respiration monitoring," *Advanced Materials*, vol. 2023. wiley.com

94. S. Yan, Q. Liu, Z. Wen, B. Liang, Z. Liu, J. Xing, and J. Li, "An AIE-active Janus filter membrane for highly efficient detection and elimination of bioaerosols," *Journal of Hazardous Materials*, vol. 2025, Elsevier. [HTML]

95. S. Zhu, H. Jiang, Z. Cui, Y. Zheng, and S. Wu, "Janus Hydrogel with Robust Bio- Adhesion and Multi- Mode Disinfection for Rapid Recovery of Multi- Drug- Resistant Staphylococcus aureus- Infected Open Wounds," *Advanced Functional Materials*, 2025. [HTML]

96. Z. Zhou, D. Wang, T. You, Z. Pan, G. Xu, "Functionalized Double- Gradient Janus Filters for Full- Scale Capture and Inactivation of Multiscale Aqueous Bioaerosols," *Advanced Functional Materials*, vol. 34, no. 1, 2024. [HTML]

97. A. Kishore, C. Singh, and G. Kaur, "Bio- nanomaterials: An Introduction," in Bio- Nanomaterials in …, 2025. [HTML]

98. D. Prajapati, D. Jabborova, B. S. Saharan, N. Singh, "Bionanotechnology: a paradigm for advancing environmental sustainability," Indian Journal of …, 2025. [HTML]

99. R. Asif, R. Yasmin, M. Mustafa, J. Nisar, "Antimicrobial Potential, Drug Delivery and Therapeutic Applications of Bio-nanoparticles in Medicine," in The Building Blocks of ..., 2023, Springer. [HTML]

100. A. P. Khedulkar, R. G. Bobade, R. Doong, B. Pandit, *et al.*, "Materials Today Chemistry," Materials Today, 2025. researchgate.net

101. A. K. Priya, L. Gnanasekaran, K. Dutta, and S. Rajendran, "Biosorption of heavy metals by microorganisms: Evaluation of different underlying mechanisms," Chemosphere, vol. 2022, Elsevier. [HTML]

102. N. D. Nnaji, H. Onyeaka, T. Miri, and C. Ugwa, "Bioaccumulation for heavy metal removal: a review," SN Applied Sciences, 2023. springer.com

103. R. Devi, B. Behera, M. B. Raza, V. Mangal, and M. A. Altaf, "An insight into microbes mediated heavy metal detoxification in plants: a review," *Soil Science and Plant Nutrition*, vol. 68, no. 2, pp. 123-135, 2022. [HTML]

104. A. Ayele and Y. G. Godeto, "Bioremediation of chromium by microorganisms and its mechanisms related to functional groups," Journal of Chemistry, 2021. wiley.com

105. T. Garvey, "Identifying the Potential Environmental Impacts of Engineered Nanomaterials," 2016. [PDF]

106. R. Watson, M. Oldfield, J. A. Bryant, L. Riordan *et al.*, "Efficacy of antimicrobial and anti-viral coated air filters to prevent the spread of airborne pathogens," 2022. ncbi.nlm.nih.gov

107. R. Li, L. Cui, M. Chen, and Y. Huang, "Nanomaterials for airborne virus inactivation: a short review," Aerosol Science and Engineering, 2021. nih.gov

108. M. Chen, Z. Shou, X. Jin, and Y. Chen, "Emerging strategies in nanotechnology to treat respiratory tract infections: Realizing current trends for future clinical perspectives," Drug Delivery, 2022. tandfonline.com

109. R. Huang, Q. Hu, C. N. Ko, F. K. Tang, S. Xuan, "Nano-based theranostic approaches for infection control: current status and perspectives," *Materials Chemistry*, 2024. rsc.org

110. X. Chen, J. Xu, B. Ji, X. Fang, K. Jin, and J. Qian, "The role of nanotechnology-based approaches for clinical infectious diseases and public health," *Frontiers in Bioengineering*, vol. XX, no. XX, pp. XX-XX, 2023. frontiersin.org

111. J. Richmond-Bryant, "Transport of exhaled particulate matter in airborne infection isolation rooms," 2008. ncbi.nlm.nih.gov

112. A. Farnoud, H. Tofighian, I. Baumann, K. Ahookhosh, *et al.*, "Numerical and machine learning analysis of the parameters affecting the regionally delivered nasal dose of nano-and micro-sized aerosolized drugs," *Pharmaceuticals*, vol. 16, no. 5, 2023. mdpi.com

113. I. J. Yu, "Dosimetry and dose metric considerations on in vitro inhalation toxicity testing of nano-aerosols," Journal of Toxicological Research, 2025. researchgate.net

114. D. H. Park, J. Choi, A. Piri, J. Hwang, "Nano-dry-salt deposition on electret nonwoven confers anticoronaviral effect while retaining aerosol filtration performance," *Environmental Science*, vol. 2021. [HTML]

115. W. Song, S. Guo, and H. Li, "Size-dependent acidity of aqueous nano-aerosols," Physical Chemistry Chemical Physics, 2024. [HTML]

116. S. Zhang, X. Chen, C. Dai, J. Wang, and H. Wang, "Associations between air pollutants and risk of respiratory infection: Patient-based bacterial culture in sputum," *Geochemistry and Health*, vol. 2022, Springer. [HTML]
117. Z. Zhang, J. Qi, Y. Liu, M. Ji, W. Wang, W. Wu, K. Liu, "Anthropogenic impact on airborne bacteria of the Tibetan Plateau," Environment, vol. 2024, Elsevier. sciencedirect.com
118. H. Lee, B. G. Lee, Y. J. Kim, J. E. Shim, and M. K. Yeo, "Assessment of airborne bacteria in the indoor of public-use facilities concentrated on influencing factors and opportunistic pathogenic bacteria," *Air Quality, Atmosphere & Health*, 2024. springer.com
119. Y. Wang, W. Wang, X. Yu, Z. Wang *et al.*, "Global diversity of airborne pathogenic bacteria and fungi from wastewater treatment plants," Water Research, 2024. [HTML]
120. B. Barsola, S. Saklani, D. Pathania, P. Kumari, "Exploring bio-nanomaterials as antibiotic allies to combat antimicrobial resistance," 2024. [HTML]
121. G. Boyno, M. R. Rişvanlı, S. E. El-Abeid, and M. A. Mosa, "6 Bio-Nanomaterials," ResearchGate. researchgate.net
122. V. Pandey, A. Sharma, D. Kumar, "Industrial Application of Bio- nanomaterials in Agriculture," Bio- Nanomaterials, 2025. [HTML]
123. V. Stone, M. R. Miller, M. J.D. Clift, A. Elder *et al.*, "Nanomaterials Versus Ambient Ultrafine Particles: An Opportunity to Exchange Toxicology Knowledge," 2017. ncbi.nlm.nih.gov
124. C. Fromen, B. Jarai, Z. Stillman, A. Zimmerman *et al.*, "Engineered nanotherapeutics for pulmonary aerosol delivery," 2018. [PDF]

125. P. Li, J. Li, X. Feng, J. Li *et al.*, "Metal-organic frameworks with photocatalytic bactericidal activity for integrated air cleaning," 2019. ncbi.nlm.nih.gov

126. J. Kamalakkannan and G. P. Sahoo, "A summary of current developments in the use of bio-based nanomaterials in agriculture and the environment," jnao-nu.com, . jnao-nu.com

127. N. Saini, A. Yadav, and N. K. Jangid, "Bio-Nanomaterials in Environmental Remediation," in *Nanomaterials in …*, 2025. [HTML]

128. M. A. Ammulu, K. D. D. Nelluri, P. K. Vemuri, *et al.*, "Bio-nanomaterials: a promising approach to producing polymeric composites," in *Plasticizers for Polymer Composites*, 2025, Elsevier. [HTML]

129. M. K. M. Z. Hyder, S. J. Nine, M. A. Uddin, "Effect of Biopolymer Based Nanoparticles on Plant Growth and Health," Biopolymer, 2025. [HTML]

130. X. Zhang, B. Lu, G. Chen, L. Wang, B. Lin, and Z. Peng, "Culturable and inhalable airborne bacteria in a semiunderground municipal wastewater treatment plant: Distribution, transmission, and health risk assessment," *Journal of Hazardous Materials*, vol. 2023, Elsevier. [HTML]