

Research Article

Microbial Air Contaminants: Diversity and Health Effects

Wisdom Ebiye Sawyer¹, Sylvester Chibueze Izah^{1,2*}, Glory Richard¹ and Matthew Chidozie Ogwu³

¹Department of Community Medicine, Faculty of Clinical Sciences, Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria

²Department of Microbiology, Faculty of Science, Bayelsa Medical University, Yenagoa, Bayelsa state, Nigeria

³Goodnight Family Department of Sustainable Development, Appalachian State University, 212 Living Learning Center, 305 Bodenheimer Drive, Boone, NC 28608, USA

***Corresponding author**

Sylvester Chibueze Izah, Department of Microbiology, Faculty of Science, Bayelsa Medical University, Yenagoa, Bayelsa state, Nigeria

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Abstract

Biological air contaminants like bacteria, fungi, viruses, and algae, and their by-products like endotoxins, mycotoxins, volatile organic compounds, etc. are present in both indoor and outdoor environments. These contaminants may have both known and unknown negative effects on human health and well-being. The activities of these biological contaminants may have direct detrimental effects on health or serve as vectors for new or existing diseases. The air of indoor environments like homes, hospitals, workplaces, schools, museums, etc. are especially most vulnerable to these microbial contaminants because of the sort of activities within them. In the case of atmospheric microbial contamination of outdoor environments, increasing anthropogenic modifications often exacerbate the air contamination threats from these actual and potential microbes. This review focuses on microbial air contaminants and seeks to document known ones like bacteria, fungi, and viruses and their by-products like endotoxins that could cause allergies. Some microbial genera commonly isolated in the air environment include *Aspergillus*, *Penicillium*, *Alternaria*, *Cladosporium* (fungi), *Bacillus*, *Staphylococcus*, *Micrococcus*, and *Acinetobacter* (bacteria). Some of these contaminants are known to cause allergic or inflammatory reactions or infectious diseases like *aspergillosis*, *coccidioidomycosis*, and *cryptococcosis*. The key factors that encourage the development of these microbial air pollutants are moisture, temperature, and nutrition. Maintaining an adequate level of hygiene will be essential to reducing the diversity and density of the air environment and preventing health catastrophes.

INTRODUCTION

Due to the rates of industrialization, urbanization, and population growth, environmental challenges are now on the rise [1]. Furthermore, the quantity of waste being generated as a result of human activities globally is also on the rise. Unsustainable human activities affect the environmental matrix negatively, which in turn affects the quality of life and well-being [2,3]. Studies have shown that human activities are the leading cause of pollution in the aquatic ecosystem, groundwater resources [4,5], sediment [6,7], soil [8-11], and air environment [12-16]. Human actions are also directly and indirectly leading to the contamination of food sources by microbes [17-23] and chemical agents such as trace metals [24-26]. Some of the notable sources of these environmental contaminants are the flaring of gases into the atmosphere [27], crude oil spills [28-32], and the unsustainable use and discharge of the remains of pesticides [33-40], among others.

Basically, in many developing countries, there are a lot of poorly managed open dumpsites [41-44]. The constituents of the dumpsites when combusted in the open space, release dangerous chemical pollutants into the environment. This suggests that long-term waste management plans built on public health principles

are inadequate or unavailable for utilization. Generally, poorly managed waste disposal sites endanger the groundwater supply because chemical leachates from these sites can leak into the soil and aquifers, endangering the environment and human health [45].

Globally, ecosystems and climate are directly impacted by air quality [46]. Any substance, whether chemical, physical, or biological, that modifies the air environment is considered to be air pollution. Both indoors (in a confined space, including inside a house, like classrooms, hospitals, hostels, hotels, etc.) and outdoors (outside of houses, but still within the general environment) can experience air pollution. Automobiles, industrial processes, home appliances that burn fuel, and forest fires are typical causes of air pollution. The burning of fossil fuels is one of the main causes of air pollution and greenhouse gas emissions.

Particulate matter, carbon monoxide, ozone, nitrogen dioxide, and sulfur dioxide are common examples of air pollutants that are extremely dangerous to human health. It is well recognized that air pollution, whether indoors or outdoors, has a significant impact on morbidity and mortality, as well as respiratory and other disorders [46]. Some of these pollutants can occur in

indoor environments, especially during cooking with fuel wood, which is a common practice among rural dwellers in developing countries. They can also occur in outdoor environments through the combustion of waste, industrial emissions, bush burning, and other human activities. Approximately 99% of people globally breathe air that is contaminated and exceeds WHO limits, and low- and middle-income nations have the largest level of exposure and associated consequences [46]. Furthermore, WHO [47] reported that about 6.7 million people die due to poor air quality on a global scale. The report further reported that about 3.2 million people worldwide die due to household air pollution. More than 99% of the world's population also resides in areas where air pollution levels are higher than WHO air quality limits, and 4.2 million people each year die from ambient air pollution [47]. Health issues may arise from both acute and chronic exposure to air pollutants. The ailments most frequently connected to exposure to chemical air pollutants include chronic obstructive pulmonary disease, asthma, bronchiolitis, lung cancer, cardiovascular events, central nervous system dysfunctions, and skin diseases [48].

Bioaerosols are incredibly small airborne particles produced biologically by plants, animals, and even microorganisms. Bioaerosols range from 0.001 to 100 μm in size and include living organisms [49]. As a result, bioaerosols may contain dangerous and/or non-pathogenic dead or alive microorganisms (such as viruses, bacteria, and fungi, particularly molds) Manisalidis, et al [48]. called bioaerosols biological contaminants and reported that they have varying sizes, including bacteria and bacterial spores (0.7-1.0 - 1.0 μm), viruses (0.01-1.00 - 1.00 μm), fungi and molds (2.00-12.00 - 12.00 μm), allergens such as pollens and household dust (0.1-100 - 100 μm). Due to their tiny size and lightweight, they are easily transported from one environment to another. Again, due to the potential health effects, there has been a lot of interest in indoor and outdoor bioaerosol exposure. The indoor environment is where most people spend the majority of their working hours. Since both indoor and outdoor pollution sources have an impact on population exposures, it appears that indoor air pollution is more important for public health.

The air can hold up to 1000 fungal spores per cubic meter despite being an unfavorable environment (indoor and outdoor) for the growth and survival of microorganisms. The characteristics of the air environment and the permanence of biological contaminants are regulated by abiotic parameters such as temperature, moisture, relative humidity, oxygen requirements, etc. [50]. In contrast to indoor environments, where UV light is harmful to airborne organisms, outdoor air may contain a lower density and a distinct diversity [50].

There are significant changes in the density of bioaerosols in different regions of similar microenvironments because microbes possess diverse adaptation strategies. The season could also affect the diversity and population of air microorganisms due to climatic factors such as temperature, relative humidity, etc. A diversity of microorganisms has been reported in diverse environmental conditions in different regions of the world [51]. Owing to the pathogenic nature of certain microbes within

indoor and outdoor atmospheres, inhalation of their spores could have adverse health effects. Therefore, this review focuses on the microbial air environment, components, and constituents of the air environment.

Bio Contaminants and Microbial Air Contaminants

Pollutants of biological origin are referred to as "bio-contaminants". Microbes, including bacteria cells and cellular fragments, viruses, fungal spores and hyphae, algae, and unicellular organisms, as well as the by-products of microbial activity, are examples of biological pollutants [52]. Mites, insect remnants, animal epithelia, and their by-products are additional biological contaminants in addition to pollen grains [50]. Pets (including dogs, cats, and birds), plants (pollen, smells, and allergies), and building materials are some of their origins [53,54]. Wind, rain, and wave splash, spray irrigation, wastewater treatment, cooling towers, air handling water spray systems, agricultural operations including harvest and tilling, and construction projects are a few examples of outdoor activities that produce bio-contaminants [52]. The sizes of these bio-contaminants vary; the ones with a large size and weight tend to deposit on surfaces, while the smaller bio-contaminants could stay in the air for a longer period.

Microbial air contaminants are produced by naturally occurring processes and human action in both indoor and outdoor settings [52]. The generation and spread of indoor microbial air contaminants often result from both mechanical and human activities. Operations in the industrial, manufacturing, and bio-fermentation sectors have the potential to produce substantial amounts of microbial aerosols. Microbial elements are carried through the air via wind action, heating, ventilation, and air conditioning systems, water sprayers (including humidifiers and showerheads), and cleaning techniques (such as sweeping, vacuuming, and mopping). Microbial air pollutants, some of which may be contagious, are also released while speaking and coughing. Facilities for animal care, dentistry, and medicine may release infectious microbial aerosols [52].

Microbes are ubiquitous. Therefore, indoor air is never completely free of microbes and their spores. In indoor structures, humidifiers, air conditioners, fans, coolers, and other similar equipment are significant sources of microbial reproduction and transmission. According to Dubey and Maheshwari [55], some of the fungi, bacteria, and yeasts that can be found in ventilation equipment, such as fans and air conditioners, include *Aspergillus*, *Penicillium*, *Phialophora*, and *Geotrichium*. Because the indoor and outdoor ecosystems are interrelated, microbes could spread at random. The indoor-to-outdoor microbial density or ratio of microbial air contaminants is essential in the identification of their sources [50]. Generally, the microbial air contaminants tend to be from the outdoor environment, in which case the ratio of indoor to outdoor air contaminants will be > 1 [50].

Indoor and Outdoor Air Pollutants: Diversity and Health Effects

Generally, microorganisms play both beneficial and

detrimental roles. The beneficial roles include its role in the production of certain foods, the leaching of precious metals from their ore, agriculture, the removal of pollutants from the environment, vaccine and antibiotic production, the generation of energy, etc. Similarly, the notable detrimental effects of microorganisms are their ability to cause diseases, spread harmful materials, etc. In humans, when the cells or spores of pathogenic microbes are inhaled into the system, it could lead to adverse health conditions. These pathogens could elicit immunologic reactions or immediate hypersensitivity reactions. The pathogens inhaled mostly affect the respiratory system. From there, other organs and systems can be affected. Because the microbes and their by-products of metabolism are very small and lightweight, they could persist in the environment for a prolonged period and deposit on surfaces, including human skin. The microbes found in the air environment could directly or indirectly cause dermatitis or irritating dermatitis, diarrhea, or flu-like symptoms from mycotoxin exposure.

The variety and number of microbial air pollutants are a serious problem since many of them can produce dangerous spores that could harm or kill sensitive hosts. Due to the ubiquitous nature of microorganisms, they can be found in many environments under diverse conditions. Some of the indoor environments where microbes may cause a major concern include hospital environments (wards, theaters, surfaces, etc.), schools (classrooms and offices), household settings (particularly those with poor housing conditions), etc. Some notable indoor environments where bio-contaminants could wreak havoc if not properly controlled include.

Hospitals are large indoor environments where pathogenic microorganisms (viruses, bacteria, and molds) can spread through the air. During conversing, sneezing, and engaging in other human activities, body fluids such as saliva, which act as reservoirs for certain disease-causative agents, could be disseminated to other people, such as patients, health care personnel, administrative staff, visitors, etc. This could lead to several types of diseases. Therefore, all kinds of personnel who work in hospital environments are at risk of infectious diseases. This is because of the dynamic of the hospital environment and the number of personnel (as well as their habits regarding hygiene and health) who visit the hospital [56]. Individuals with compromised immune systems are at high risk of contracting infectious diseases, especially nosocomial respiratory infections.

Like hospitals, schools, markets, warehouses, museums, and household settings, they harbor a diverse group of microbial air contaminants. Individuals can contact the microbes by touching surfaces and coming into contact with fluids from people who are infected by such microbes. Generally, environmental reservoirs like soil, water, dust, and decomposing organic waste are home to a wide range of microorganisms. The resident microbes can spread throughout numerous interior ecological niches whenever they are brought into a setting (an area where humans dwell or work) by prospective vehicles like humans, winds, or construction materials. Airborne diseases can be brought on by

these microorganisms, which can include bacteria, viruses, or fungi [57]. Notably, contact with fungus or bacterial spores may cause susceptible individuals to develop a range of fungal or bacterial illnesses. Although invasive fungal diseases continue to have a high morbidity and mortality rate, therapeutic antifungal medications are less common than antibacterial medications [57].

The quality of the air in office buildings (schools, museums, archives, libraries, public places, etc.) as well as residential buildings has a growing impact on the happiness and health of workers as well as the occupants. More than 30% of office workers report having health problems connected to indoor environmental contaminants, according to previous epidemiological research on office indoor environments [58], which is mostly associated with poor air quality [59]. This is because the occupants of these buildings are exposed to a variety of dangerous substances, including biological and chemical pollutants, mechanical vibration, noise, light, electromagnetic fields, static electricity, and different microclimates [59]. Furthermore, the buildings are vulnerable to microbial invasion, particularly molds and, to lesser extents, bacteria. Generally, when the density of microorganisms are low and no pathogens of public health importance are identified, they are often not considered to constitute a threat to human health. But when the density of the microbial contaminants exceeds a specific threshold, microbial contamination of buildings and their environs becomes a serious public health problem.

Generally, bacteria, viruses, fungi, and other organisms can cause infectious diseases, which spread quickly from one person to another. Numerous symptoms, such as headache, rhinitis, fever, chills, coughing, shortness of breath, vomiting, and diarrhea, can be used to diagnose an individual with an infectious condition [50]. Infectious diseases can be transmitted either directly by ingesting the harmful substances they create, such as neurotoxic and enterotoxin substances, or indirectly by pathogenic microbes, most frequently bacteria and viruses, in the form of microbial air contaminants [50].

In the indoor environment, the operation of heating, ventilation, and air conditioning systems, species distributions, and microbial sources should be thoroughly considered in developing guidelines for preventive activities against nosocomial microbial infections [57]. Also, in outdoor settings, many species of microorganisms have been reported, which to a large extent depend on the prevailing climatic and weather conditions of the area. Several species of microorganisms (particularly bacteria and fungi) have been reported in different outdoor and indoor environments (Table 1). Most of the bacteria that have been reported in the air belong to the following.

The prevalence of microbial diversity tends to vary according to the prevailing conditions as well as the type and level of human activities in the area. For instance, Cho, et al. [57], reported 25 fungal species both within and outside the Hematology Hospital in Seoul, South Korea, *Aspergillus* was the most prevalent species both outside (62.0%) and inside the hospital (47.0%). After

Penicillium and *Alternaria* (8.9%), *Talaromyces* (4.4%) is ranked as the fourth most common species by the authors. The authors conclude that 37.9% of the fungi species in the hospital and 8.9% of those outside were *Penicillium*. In both the indoor and outdoor environments of libraries, Hassan, et al. [60] found that the most common bacterial genera were in the order: *Bacillus* species > *Staphylococcus* species > *Micrococcus* species, and the most common fungal genera were in the order *Penicillium* species > *Cladosporium* species > *Aspergillus* species. The most prevalent bacterial species, according to Almatawah, et al. [59], are *Staphylococcus hemolyticus*, *Acinetobacter nosocomialis*, *Bacillus thuringiensis/cereus*, *Acinetobacter lwoffii*, and *Stenotrophomonas maltophilia*. The authors further reported that the fungi species were in the order: *Aspergillus* > *Penicillium* > *Rhodotorula* > *Cladosporium* > *Ulocladium* > *Fusarium*. The most prevalent microorganisms discovered in the work settings of museums, archives, and libraries, according to Skóra, et al. [61], were *Micrococcus*, *Staphylococcus*, *Bacillus* species (bacteria), *Aspergillus puulaensis*, *Cladosporium cladosporioides*, *Penicillium crustosum*, and *Rhizopus oryzae* (fungi).

Components of Air Environment

A diversity of living organisms is found in the air. The common ones include bacteria, fungi, viruses, endotoxins, and mycotoxins produced by living organisms. Others include allergens (which can be life forms or non-life forms) and volatile organic compounds (Figure 1) (Table 2).

Bacteria

The bulk of bacteria are widely distributed free-living creatures with rare, single biological cell. They make up a large component of the prokaryotic microbial population. Bacteria, which are among the first living forms that have existed on Earth and are typically a few micrometers in length, may be found in the majority of their habitats, including the skin, digestive, reproductive, respiratory, and oral systems of humans, among others. The majority of bacteria are not dangerous, but some of them can cause diseases in other living organisms. Bacteria can

swiftly multiply inside your body and release toxins, which cause diseases, especially in immunocompromised individuals [62-64].

The typical microflora in the nose, mouth, ears, and other body parts is primarily composed of saprophytic bacteria associated with human activities and derived from outdoor air [65]. The increasing cases and spread of various infections like *aspergillosis*, *coccidioidomycosis*, and *cryptococcosis* in the indoor and outdoor environments are connected to human activity. Sneezing, coughing, and talking all serve to regularly rid the upper respiratory tract of bacteria. The majority of the microbes (fungi and bacteria) that cause diseases in humans are typically found in indoor environments. Many of these bacteria have been widely reported by authors (Table 1).

Fungi

Fungi are eukaryotic microorganisms. Fungi include yeasts, molds, and mushrooms. Most pathogenic fungi can cause systemic, cutaneous, subcutaneous, allergic, or allergy-related disorders. Furthermore, spore fungi, particularly mold, can cause respiratory problems. Some of the fungi have found useful applications in the fields of biotechnology and microbiology. Fungi can exist as unicellular or multicellular organisms. The aerosolization of fungi is facilitated by the spore-bearing structures. Depending on the prevailing conditions, the spores of fungi can be up to a hundred thousand fungal spores per cubic meter. Because of this, they have been isolated in different environments, including building materials, literature, wood, paint, cooking oil, water, soil, and air. The distribution of fungi spores is influenced by the local environment, including water activity and season. Furthermore, the density of the fungi and ventilation quality could also affect their distribution. Typical examples of fungi that require high water activity include *Trichoderma*, *Fusarium*, *Yeast*, *Phialophora*, and *Stachybotrys*, while others such as *Aspergillus* and *Penicillium* require lower water activity to grow [50]. Under ideal water activity, other factors that enhance microbial growth, such as temperature, pH, nutrients, etc., also need to be optimal. Diverse species of fungi have been reported in both outdoor and indoor environments (Table 1).

Mycotoxins

Certain fungi naturally produce mycotoxins, which are deadly chemicals. These mycotoxins are secondary metabolites that can infect and kill both humans and animals. This is because they tend to harm DNA while impeding the synthesis of RNA as well as its cytotoxicity and cancer development. Molds can grow in certain food sources for humans, including cereal, dried fruit, nuts, and spices. Furthermore, these molds have been detected in human food sources [66-69], as well as in water, soil, and air in the environment. Depending on the season and environmental variables (such as moisture content, temperature, relative humidity, and oxygen requirement) [65]. Most mycotoxins are resistant to heat and have strong chemical properties. Although there are hundreds of distinct mycotoxins that are known, aflatoxins, ochratoxin A, patulin, fumonisins, zearalenone, and nivalenol/deoxynivalenol are the most often discovered and pose

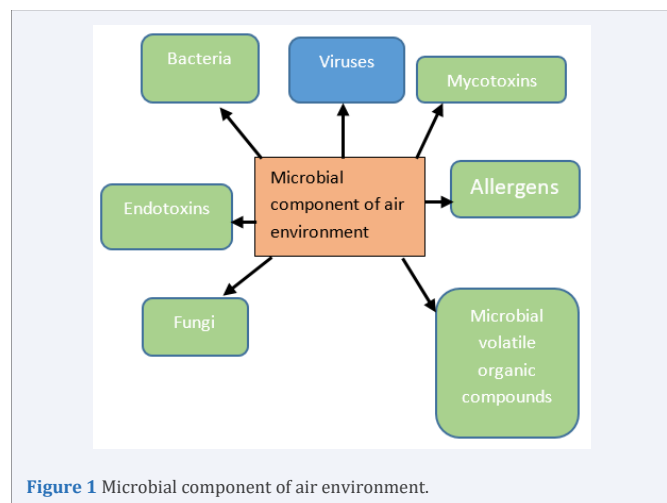


Table 1: Diversity of microbes found in air environment.

Bacteria group	Fungi Group	Location	References
<i>Alloiococcus otitis</i> , <i>Bacillus atrophaeus</i> , <i>B. licheniformis</i> , <i>B. pseudomycesoides</i> , <i>B. pumilus</i> , <i>B. subtilis</i> , <i>Macrocococcus caseolyticus</i> , <i>Microcococcus luteus</i> , <i>Paenibacillus amylolyticus</i> , <i>P. glucanolyticus</i> , <i>Rothia nasimurium</i> , <i>Staphylococcus aureus</i> and <i>Staphylococcus</i> species.	<i>Acremonium</i> , <i>Aspergillus flavus</i> , <i>Aspergillus fumigatus</i> , <i>Aspergillus niger</i> , <i>Aspergillus ochraceus</i> , <i>Aspergillus</i> sp., <i>Alternaria</i> , <i>Bipolaris</i> , <i>Cephalosporium</i> , <i>Cladosporium chaetomium</i> , <i>Curvularia</i> , <i>Diplococcum spicatum</i> , <i>Drechslera</i> , <i>Emmericella</i> , <i>Epicoccum</i> , <i>Eurotium</i> , <i>Fusarium</i> , <i>Monilia</i> , <i>Mucor</i> , <i>Nigrospora</i> , <i>Penicillium</i> , <i>Phoma</i> , <i>Rhizopus</i> , <i>Scopulariopsis</i> , <i>Stachybotrys chartarum</i> , <i>Trichoderma viride</i> , <i>Trichothecium</i> , and <i>Ulocladium</i>	Some public buildings in Giza and Cairo.	[62]
<i>Aneurinibacillus aneurinilyticus</i> , eight species of <i>Bacillus</i> , <i>Brevibacillus laterosporus</i> , 2 species of <i>Kocuria</i> , <i>Lactobacillus delbrueckii</i> , <i>Leuconostoc mesenteroides</i> , Two species of <i>Microcococcus</i> , <i>Micromonospora</i> sp., <i>Nocardia</i> sp., <i>Paenibacillus polymyxa</i> , 3 species of <i>Pseudomonas</i> , <i>Sphingomonas paucimobilis</i> , 5 species of <i>Staphylococcus</i>	Two species of <i>Acremonium</i> , 4 species of <i>Alternaria</i> , nine species of <i>Aspergillus</i> , <i>Aureobasidium pullulans</i> , <i>Beauveria</i> sp., two species of <i>Botrytis</i> , <i>Chaetomium globosum</i> , <i>Chrysionilia scatophilina</i> , three species of <i>Cladosporium</i> , <i>Epicoccum nigrum</i> , <i>Eurotium amstelodami</i> , <i>Gliocladium</i> sp., six species of <i>Mucor</i> , <i>Paecilomyces variotii</i> , fourteen species of <i>Penicillium</i> , <i>Rhizopus oryzae</i> , <i>Talaromyces wartmannii</i> , <i>Trichoderma koningii</i> , <i>Trichoderma viride</i> and <i>Ulocladium</i> sp. (molds), two species of <i>Candida</i> , three species of <i>Cryptococcus</i> and two species of <i>Rhodotorula</i> (yeast)	Museums, archives, and libraries	[61]
<i>Acinetobacter lwoffii</i> , <i>Acinetobacter nosocomialis</i> , <i>Bacillus thuringiensis/cereus</i> , <i>Bacillus murimartini/gibsonii</i> , <i>Bacillus pseudomycesoides/cereus</i> , <i>Macrocococcus brunensis</i> , <i>Microcococcus yunnanensis</i> , <i>Kytococcus aerolatus</i> , <i>Microcococcus equiperficum</i> , <i>Pseudomonas aeruginosa</i> , <i>Staphylococcus hemolyticus</i> , <i>Staphylococcus hominis</i> , <i>Stenotrophomonas maltophilia</i> , and <i>Streptococcus downei</i>	<i>Alternaria alternata</i> , <i>Aspergillus niger</i> , <i>Aspergillus foetidus</i> , <i>Aspergillus brasiliensis</i> , <i>Aspergillus chevalieri</i> , <i>Aspergillus parasiticus</i> , <i>Cladosporium macrocarpum</i> , <i>Cladosporium sphaerospermum</i> , <i>Cryptococcus albidus</i> , <i>Curvularia lunata</i> , <i>Emmericella veriochlor anam</i> , <i>Aspergillus stelfer</i> , <i>Fusarium chlamydosporum</i> , <i>Fusarium cocciciocola</i> , <i>Hortaea werneckii</i> , <i>Nigrospora oryzae</i> , <i>Paecilomyces variotii</i> , <i>Penicillium aurantiovirens</i> , <i>Penicillium expansum</i> , <i>Penicillium lanosum</i> , <i>Penicillium verrucosum</i> , <i>Pitomyces sacchari</i> , <i>Rhodotorula mucilaginosa</i> , <i>Rhodotorula mucilaginosa</i> , <i>Scopulariopsis brumptii</i> , <i>Ulocladium chartarum</i> , <i>Ulocladium botrytis</i>	Kuwait City on the Al-Shuwaikh coast	[59]
<i>Staphylococcus haemolyticus</i> , <i>Microcococcus luteus</i> , <i>Microcococcus aloeverae</i> , <i>Bacillus pumilus</i> , <i>Lysinibacillus macroides</i> , <i>Bacillus cereus</i> , <i>Bacillus para-licheniformis</i> .	<i>Cladosporium asperulatum</i> , <i>Penicillium oxalicum</i> , <i>Talaromyces macrosporus</i> , <i>Penicillium chrysogenum</i> , <i>Talaromyces funiculosus</i> , <i>Penicillium expansum</i> , <i>Penicillium mallochii</i> , <i>Aspergillus niger</i> , <i>Aspergillus fumigatus</i> .	Libraries of a public university in Islamabad	[60]
<i>Cinetobacter iwoffii</i> , <i>Enterobacter aerogenes</i> , <i>Enterococcus faecalis</i> , <i>Escherichia coli</i> , <i>Morganella morganii</i> , <i>Proteus mirabilis</i> , <i>Proteus vulgaris</i> , <i>Pseudomonas aeruginosa</i> , <i>Staphylococcus aureus</i> , <i>Staphylococcus epidermidis</i> , <i>Bacillus</i> , <i>Microcococcus</i> species	<i>Aspergillus niger</i> , <i>Aspergillus Brevipes</i> , <i>Aspergillus flavus</i> , <i>Aspergillus parasiticus</i> Speare, <i>Cladosporium</i> species, <i>Penicillium halicum</i> , <i>Phanerochaete chrysosporium</i> , <i>Rhizopus stolonifer</i> , <i>Ulocladium chartarum</i>	Landfill site in Greater Accra Region of Ghana	[63]
NR	<i>Aspergillus fumigatus</i> , <i>Aspergillus flavus</i> , <i>Aspergillus niger</i> , <i>Microsporium canis</i> , <i>Trichoderma</i> , <i>Cladosporium</i> , <i>Alternaria</i> , <i>Pullularia</i> , <i>Fusarium</i> , <i>Trichothecium</i> , <i>Mucor</i> , <i>Rhizopus</i> , <i>Trichophyton</i> , <i>Helminthosporium</i> , <i>Penicillium</i> , and <i>Candida</i> species	Waste dumpsite in Bayelsa State	[13]
<i>Escherichia coli</i> , <i>Lactococcus lactis</i> , <i>Staphylococcus haemolyticus</i> , <i>Enterobacter cloacae</i> , <i>Acinetobacter baumannii</i> , <i>Staphylococcus hominis</i> , <i>Bacillus pumilus</i> , <i>Exiguabacterium aurantiacum</i>	NR	OPD, ICU King Khalid Hospital, Hail, KSA, Saudi Arabi	[64]
NR	<i>Rhizomucor pusillus</i> , <i>Cephalotheca foveolate</i> , <i>Cochliobolus lunatus</i> , <i>Fusarium fujikuroi</i> , <i>Ganoderma carnosum</i> , <i>Gloeophyllum trabeum</i> , <i>Irpex lacteus</i> , <i>Thermoascus crustaceus</i> , <i>Thermoascus lanuginosus</i> , <i>Thielavia terricola</i> , <i>Phlebia tremelloso</i> , <i>Porostereum spadiceum</i> , <i>Purpureocillium lilacinum</i> , <i>Aspergillus</i> , <i>Penicillium</i> , <i>Alternaria</i> , <i>Talaromyces</i> , <i>Trichoderma</i> , <i>Paecilomyces</i> , <i>Byssoschlamys</i> , <i>Curvularia</i> , <i>Cercospora</i> , <i>Sordariomycetidae</i> , <i>Periconia</i> , and <i>Corticaceae</i> species	Hospital, Seoul, South Korea	[57]

NR – Not reported

Genera: *Alloiococcus*, *Bacillus*, *Macrocococcus*, *Microcococcus*, *Paenibacillus*, *Rothia nasimurium*, *Staphylococcus*, *Aneurinibacillus*, *Brevibacillus*, *Kocuria*, *Lactobacillus*, *Leuconostoc*, *Micromonospora*, *Nocardia*, *Paenibacillus*, *Pseudomonas*, *Sphingomonas*, *Acinetobacter*, *Kytococcus*, *Microcococcus equiperficum*, *Pseudomonas*, *Stenotrophomonas*, *Streptococcus*, *Escherichia*, *Lactococcus*, *Enterobacter*, *Exiguabacterium*, *Cinetobacter*, *Enterococcus*, *Morganella*, *Proteus*, *Lysinibacillus*, etc. Furthermore, the fungi genera that have been identified in the air environment include *Acremonium*, *Aspergillus*, *Alternaria*, *Bipolaris*, *Cephalosporium*, *Cladosporium*, *Curvularia*, *Diplococcum*, *Drechslera*, *Emmericella*, *Epicoccum*, *Eurotium*, *Fusarium*, *Monilia*, *Mucor*, *Nigrospora*, *Penicillium*, *Phoma*, *Rhizopus*, *Scopulariopsis*, *Stachybotrys*, *Trichoderma*, *Trichothecium*, *Ulocladium*, *Acremonium*, *Aureobasidium*, *Beauveria*, *Botrytis*, *Chaetomium*, *Chrysionilia*, *Epicoccum*, *Eurotium*, *Gliocladium*, *Paecilomyces*, *Talaromyces*, *Trichoderma*, *Candida*, *Cryptococcus*, *Rhodotorula*, *Cryptococcus*, *Emmericella*, *Hortaea*, *Nigrospora*, *Paecilomyces*, *Pitomyces*, *Scopulariopsis*, *Microsporium*, *Trichothecium*, *Trichophyton*, *Helminthosporium*, *Pullularia*, *Rhizomucor*, *Cephalotheca*, *Cochliobolus*, *Ganoderma*, *Gloeophyllum*, *Irpex*, *Thermoascus*, *Thielavia*, *Phlebia*, *Porostereum*, *Purpureocillium*, *Paecilomyces*, *Byssoschlamys*, *Curvularia*, *Cercospora*, *Sordariomycetidae*, *Periconia*, and *Corticaceae*.

a threat to both human and animal health. Mycotoxins enter the food chain when crops become contaminated with mold before and after harvest.

Some mycotoxins have quick effects, with symptoms of severe illness appearing shortly after exposure to the mycotoxins through ingestion and inhalation. The development of cancer and immunological deficits are just two long-term adverse

health effects associated with mycotoxins [67]. Some of the most hazardous mycotoxins are produced by certain molds (*Aspergillus flavus* and *Aspergillus parasiticus*), which are frequently found in soil, decaying plants, hay, and cereals. These species of *Aspergillus* that produce these mycotoxins have been isolated from the air environment (Table 1). Acute poisoning from high exposure to aflatoxins is known as aflatoxicosis. These could be lethal and are frequently brought on by organ damage (such as liver damage).

Table 2: Description of the key microbial components of the air environment.

Microbial Aspect	Description of the key microbial components
Bacteria	- Bacteria are abundant free-living single-celled organisms, some of which can cause diseases.
	- They are found in various human habitats, including the skin, digestive, reproductive, and respiratory systems.
	- Bacteria can rapidly multiply and release toxins, leading to diseases, especially in immunocompromised individuals.
Fungi	- Fungi are eukaryotic microorganisms, including yeasts, molds, and mushrooms.
	- Pathogenic fungi can cause various disorders, including respiratory issues.
	- Fungi can exist as unicellular or multicellular organisms and are widely distributed in different environments.
Mycotoxins	- Certain fungi produce mycotoxins, which are toxic chemicals that can harm humans and animals.
	- Mycotoxins are found in various food sources, including cereal, dried fruit, and nuts, and can lead to severe health effects.
Endotoxins	- Endotoxins, released by gram-negative bacteria, can cause various health issues, including septic responses.
	- They are commonly present in the environment and can be influenced by factors like ventilation and humidity.
Allergens	- Allergens can trigger allergic reactions, with typical sources including pollen, fungi, etc
	- Allergens can lead to a wide range of immunological reactions affecting various organ systems.
Volatile Organic Compounds	- Volatile organic compounds are low-molecular-weight molecules released into the environment through various human activities.
	- Some microbes can produce microbial volatile organic compounds (mVOCs) during their early growth phases.
Viruses	- Viruses are acellular entities that require a living host to reproduce.
	- Airborne viruses can be disseminated through human actions like coughing, sneezing, and talking, causing various diseases.

Also, aflatoxins possess genotoxic tendencies, which means they can harm DNA and result in cancer [67].

Numerous species of *Aspergillus* and *Penicillium* produce ochratoxin A, a typical mycotoxin that contaminates food. Varying species of molds that produce ochratoxin A have been reported in the air as well as in foods. The toxins could be detrimental to the immune system, kidney function, liver cancer (cirrhosis), and fetal development. Patulin is another mycotoxin produced by a few species of *Aspergillus*, *Penicillium*, and *Byssoschlamys* [70]. Also, the molds that produce the mycotoxins have been isolated from the air. Studies have shown that exposure could cause immune system toxicity and kidney, liver, and spleen damage [71].

Numerous trichothecenes, such as deoxynivalenol, nivalenol, zearalenone, and fumonisins, are produced by certain species of *Fusarium* [72]. Like other molds, *Fusarium* has been detected in several environments, including soil, water, air, and even food. Trichothecenes could irritate the human skin or mucous membranes, diarrhea, and dysfunction in the immune system [73].

Endotoxins

Endotoxins, also known as lipopolysaccharides, or LPS, which are a part of the outer membrane, are released into the bloodstream when intact gram-negative bacteria are injured (by cell lysis or death) [74,75]. Endotoxin, which is typically present in every area of our surroundings, is the most common pyrogen in parenteral medications and medical equipment. Endotoxins can alter the humoral and cellular host mediation processes in many human organs and systems [76]. They might also cause bloodstream septic responses, which can result in a range of symptoms like fever, hypotension, nausea, trembling, and shock. High doses may result in unfavorable side effects such as endotoxin shock, adult respiratory distress syndrome, and disseminated intravascular coagulation. According to Moldoveanu [65], higher levels of endotoxin, or gram-negative bacteria, are linked to having pets, storing food waste, using humidifiers, having

inadequate ventilation, and storing food waste. These conditions are suitable for the growth of microorganisms.

Allergens

A material that can trigger an allergic reaction is known as an allergen. Some individual's immune systems see allergens as foreign or threatening. The immune system responds by producing the kind of antibody known as Immunoglobulin E (IgE) to protect against the allergen. Allergy symptoms come from this reaction. Typical allergens include certain medications, foods (including eggs, fish, milk, almonds, peanuts, wheat, soy, and other legumes), spores of microorganisms, particularly mold and bacteria, insect and mite feces, venom produced by bug stings and bites, pollen from grass and trees, rubber latex, animal fur, particularly that of cats and dogs, bug stings, notably those from bees and wasps.

The terms "hypersensitivity" and "allergy" both cover a broad spectrum of immunological reactions, the majority of which have negative effects on one or more organ systems of the body [77,78]. Allergens are usually low-molecular-weight glycoproteins or chemically complex compounds. Pollen, fungi, household dust mites, animal dander, medications, foods, insect emanations, debris, and other things are some of the common causes of allergies [77]. Numerous respiratory disorders are caused by Type 1 hypersensitivity reactions, which are brought on by allergens from molds such as *Penicillium*, *Aspergillus*, *Alternaria*, *Cladosporium*, *Curvularia*, *Epicoccum*, *Pullularia*, *Ganoderma*, *Trichoderma*, and *Stemphylium* species [50].

Volatile Organic Compounds

The term "volatile organic compounds" refers to a vast class of chemical compounds that all have the property of having volatile carbon molecules at ambient temperature. They can be divided into a variety of families based on their chemical compositions, each of which has traits in common despite the possibility of significant variances in toxicity. They are released

into the environment through diverse human activities such as food processing such as oil palm [16,79,80], burning of wastes, use of solvents and adhesives, cosmetics, pesticides, cleansers and sanitizers, cosmetics and deodorants, gasoline and kerosene, office copiers and printers, etc.

Volatile organic compounds are low-molecular-weight molecules having a high vapor pressure and low solubility. As such, certain microbes can produce volatile organic compounds. According to Weisskopf, et al. (2021) and Korpi, et al. (2009), microbial Volatile Organic Compounds (m VOCs) are volatile organic compounds produced as a result of microbial metabolism. Kumar et al. [50], reported that *Aspergillus* and *Penicillium* species and *Alternaria alternata* can release the mVOCs during their early growth phases [82].

Viruses

Viruses are acellular entities made of either DNA or RNA. They cannot reproduce on their own because they lack self-directed biosynthesis. Hence, it requires a living, susceptible host to reproduce. Infectious viruses may get established in the respiratory tract's host cells after inhalation [52]. Others were moved to different tissues, such as the digestive system. Millions of airborne viruses can be disseminated indoors through droplets by human actions such as coughing, sneezing, talking, and laughing [50]. Numerous circumstances have led to viral isolation. But the common ones that are found in the air environment include Norwalk-like virus (an RNA virus), which can cause acute projectile vomiting and diarrhea; severe acute respiratory syndrome-associated coronavirus (an RNA virus) that can cause acute respiratory distress; Sin Nombre virus (with a single-stranded RNA) which causes respiratory problems; and Varicella-zoster virus (a double-stranded DNA) which causes chickenpox [52].

Factors that Enhance the Growth of Microbial Air Contaminants

Numerous environmental factors, such as temperature and relative humidity, as well as characteristics specific to the microbial strain (biochemical composition), have an impact on the growth and survival of microorganisms. Furthermore, for bacteria to grow and reproduce, certain conditions must be satisfied. Water activity, osmotic pressure, pH, oxygenation, moisture, and temperature are some of these variables (Figure 2). These factors are essential considerations in understanding the growth and persistence of microorganisms in indoor and outdoor environments (Table 3). It is essential for there to be water available for bacteria to survive in a temperature range that is suitable for them. A dry environment typically inhibits the growth or reproduction of bacteria.

One of the most crucial elements in the emergence and persistence of microbial air contaminants in indoor and outdoor environments is temperature. Even among members of the same genus, different organisms may have different preferred temperatures. Different microbes can survive in diverse

temperature conditions. The organisms that can survive in a low or very cold temperature, are known as psychrophiles (a typical example of an organism that can survive in such an environment is *Polaromonas vacuolata*). The microbes that can survive in a mid-range temperature range, are known as mesophiles (a typical example of an organism that can survive in such an environment is *Escherichia coli*). The microbes that can survive in a high temperature, are known as thermophiles (a typical example of an organism that can survive in such an environment is *Bacillus stearothermophilus*). Thermococcus celer and Pyrolobus fumarii are examples of hyperthermophiles and very hyperthermophiles, respectively, very high-temperature conditions that may include geysers and deep sea hydrothermal vents. Like higher organisms, microbes need nutrients to grow. Many of the nutrients required by a diversity of organisms are protein, carbon, vitamins, amino acids, fats, metals, vitamins, nitrogen sources, etc. When these nutrients are not available for the microbes to utilize for their growth and reproduction, it could lead to their death.

Moisture is essential for the growth of microbial air contaminants. Numerous microorganism species may thrive and survive better in environments with high moisture content. Buildings with water damage have a disproportionately higher number of microorganisms than ordinary structures. Therefore, in household settings, the amount of microbial air contaminants produced can be regulated by controlling the amount of indoor humidity, namely by controlling ventilation rates and using dehumidifiers, chillers, and humidifiers wisely as appropriate. A humidity level of over 60% may increase the risk of developing upper respiratory issues, which could be detrimental to individuals with other conditions such as asthma or allergies [83]. Skin dryness or discomfort may develop at moisture content levels below 20%. pH is another factor that enhances the growth of microbes. When the pH is ideal, most microbes will grow and proliferate. Generally, most organisms grow optimally in a pH range of 6.0-8.0. Many disease-causing microbes can grow in a pH range of 4.5-10.0. While the ones that are involved in the spoilage of food can grow with a pH of 1.4-10.0. Many fungi (molds and yeast) can survive in both alkaline and acidic pH conditions.

Oxygen requirements are another important factor that enhances microbial growth. Some organisms can enhance

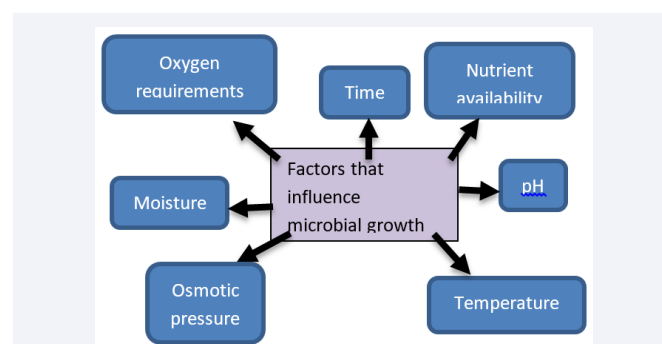


Figure 2 Factors affecting the growth of microbes.

Table 3: Factors affecting the growth and survival of microorganisms.

Factors	Description
Temperature	- Different organisms have varying preferred temperature ranges, from psychrophiles (cold-adapted) to thermophiles (heat-adapted).
Nutrients	- Microbes require nutrients like proteins, carbon, vitamins, amino acids, fats, metals, and nitrogen sources for growth. Lack of essential nutrients can lead to their death.
Moisture	- Moisture is essential for the growth of microbial air contaminants. High moisture levels can support the survival of many microorganisms. Controlling indoor humidity is essential in regulating microbial air contamination.
pH (Acidity/Alkalinity)	- Microbial growth is influenced by pH levels. Most microbes grow optimally in the pH range of 6.0–8.0, while some disease-causing microbes can thrive in a broader pH range.
Oxygen Requirements	- Oxygen requirements are categorized into obligate aerobes, obligate anaerobes, facultative anaerobes, aerotolerant anaerobes, and microaerophiles, which impact microbial growth.
Time	- Different microbes have varying replication times, and changes in environmental conditions can affect their optimal replication.
Osmotic Pressure	- Osmotic pressure influences microbial growth. Increased external osmotic pressure leads to dehydration, while a decrease causes swelling and lysis, affecting microbial survival.

microbial growth. The oxygen requirements are grouped into obligate aerobics, obligately anaerobic, facultatively anaerobic, aerotolerant anaerobic, and microaerophiles. Reduced oxygen levels in the atmosphere can affect bacterial metabolism, which can also impede their growth [84]. Furthermore, oxygen can promote the oxidation reaction, and too much of it may be detrimental to the growth of bacteria [84]. Time is another factor that enhances microbial growth [85]. Different microbes have varying replication times. Therefore, when the replication time interval of a particular microorganism under suitable conditions is adversely affected, optimal replication may not be achieved. Osmotic pressure could also influence the rate of microbial growth. An increase in external osmotic pressure causes dehydration and water loss, while a decrease causes swelling and even lysis [86]. Simultaneous, highly rapid water flows disturb multiple cellular properties [86].

Multifaceted Impact of the COVID-19 Pandemic on Microbial Diversity and Public Health

The COVID-19 pandemic has far-reaching implications for microbial diversity, particularly in the context of air quality, as summarized in (Table 4). However, it's essential to acknowledge that various factors, including regional differences, population dynamics, and other contextual aspects can influence the precise impact of the COVID-19 era on microbial diversity. Moreover, the pandemic and the public health measures implemented to combat its spread have introduced a series of effects on microbial diversity and infectious diseases, reducing certain diseases and altering antibiotic resistance patterns. As per the findings of Gul, et al. [87], public health measures such as social distancing, mask-wearing, and lockdowns, designed to curb the transmission of COVID-19, inadvertently led to a decrease in the transmission

of other infectious diseases. Notably, the incidence of Kawasaki disease saw a 30% decline in Taiwan in 2020 compared to 2018. This reduction is attributed to a combination of precautionary measures and a decrease in hospital admissions, by Gul, et al. [87] research.

Furthermore, the pandemic gave rise to changes in the pattern of microbial infections, particularly Urinary Tract Infections (UTIs) in children, as observed by Gul, et al. [87]. The male-to-female ratio in UTIs increased during the pandemic. One plausible explanation for this shift is that girls, who previously used public toilets in schools and playgrounds, transitioned to better hygiene practices at home when schools were closed [87]. Factors such as anatomical differences, hygiene, and reduced exposure to potential pathogens may underlie this transformation.

In addition, Gul, et al. [87] study highlighted shifts in antibiotic resistance patterns during the COVID-19 pandemic. Notably, resistance to antibiotics, particularly in the case of *E. coli*, significantly decreased, with ampicillin, fosfomycin, and nitrofurantoin showing the most substantial declines. Several contributing factors may explain this phenomenon, including reduced antibiotic usage, the effects of lockdown measures, and decreased interpersonal interactions. Notably, a decrease in antibiotic use was observed in both inpatient and outpatient settings in numerous countries, likely contributing to this decline in antibiotic resistance [87]. Additionally, travel restrictions during the pandemic could have limited the transmission of antibiotic resistance genes.

Therefore, the COVID-19 pandemic has far-reaching effects on microbial diversity, particularly on air quality. These effects extend to changes in the incidence of infectious diseases and

Table 4: Possible multifaceted impact of the covid-19 pandemic on microbial diversity and public health.

Aspect	Possible Multifaceted Impact
Human Microbiota	The pandemic may cause alterations in the human microbiota due to stress, dietary changes, and antibiotic usage.
Environmental Microbiota	Lockdowns and reduced human activity may have short-term effects on air quality, potentially impacting airborne microbial diversity, with some urban areas experiencing reduced air pollution.
Healthcare Facility Microbiota	Increased infections in hospitals during the pandemic might affect microbial communities in these environments. Widespread use of disinfectants and antimicrobial agents may promote antibiotic resistance.
Animal Microbiota	Various animal populations, including domesticated animals, livestock, and wildlife, may experience changes in their microbiota due to zoonotic diseases and the potential spread of viruses that may impact animals
Research Opportunities	The pandemic may accelerate research on the human microbiome, exploring links between microbiota and viral disease effects.

alterations in antibiotic resistance patterns, as demonstrated by Gul, et al. [87] study. However, it is essential to consider the interplay of various factors that can shape the specific outcomes of the pandemic on microbial diversity.

CONCLUSION

Due to the ubiquitous nature of microbes, indoor, and outdoor air environments contain a lot of microbial contaminants. Hence, during inhalation, microbes and their spores may be ingested into the system. Exposure to an air environment contaminated with pathogenic microbes could predispose the individual to health crises such as respiratory infections, allergies, infectious diseases, and skin diseases, among others. The major components of the air environment include bacteria, fungi, viruses, endospores, mycotoxins, allergens, and volatile organic compounds. The microorganisms found in the air environment can thrive, especially when there are nutrients, temperature, and moisture. Therefore, it will be important to maintain an adequate hygiene level to reduce the diversity and density of the air environment and forestall health crises.

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