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Review Article

MICROBIAL DIVERSITY IN SMOKE: IMPLICATIONS FOR AIR QUALITY AND PUBLIC HEALTH

[*1]Oluwatosin Olubunmi OLADIPO, [2]Habeebat Adekilekun OYEWUSI, and [1]Abike Christiana OLALEYE

[1]Microbiology Unit, Department of Science Technology, The Federal Polytechnic, P.M.B.5351, Ado Ekiti 360231, Ekiti State, Nigeria
[2]Biochemistry Unit, Department of Science Technology, The Federal Polytechnic, P.M.B.5351, Ado Ekiti 360231, Ekiti State, Nigeria

*Corresponding Author Email Address: oladipo_oo@fedpolyado.edu.ng or adekilekun_oh@fedpolyado.edu.ng

ABSTRACT
The increasing prevalence of smoke exposure from both natural and anthropogenic sources has raised concerns about its impact on air quality and public health. Smoke is known to carry a diverse range of microorganisms, including bacteria, fungi, viruses, and archaea, which are dispersed into the atmosphere through various mechanisms. This microbial diversity is influenced by factors such as the source material composition, combustion conditions, and geographic and climatic factors. The presence of these microorganisms in smoke has significant implications for air quality, contributing to elevated levels of particulate matter and interacting with chemical pollutants, which can worsen existing air pollution events. From a public health perspective, smoke-borne microbes are associated with respiratory problems, including allergies, asthma, and chronic obstructive pulmonary disease (COPD). Infections caused by opportunistic pathogens, such as *Pseudomonas aeruginosa* and *Aspergillus* spp., are also a major concern. Additionally, microbial-laden particulates have been linked to cardiovascular diseases and immune system modulation. As climate change is expected to exacerbate the frequency and intensity of smoke events, the need for comprehensive strategies to monitor and manage microbial contamination in smoke becomes increasingly critical. This paper discusses the sources, dispersal mechanisms, and health implications of microbial diversity in smoke, emphasizing the need for enhanced public health policies and air quality management to mitigate its adverse effects.

Keywords: Air quality; Microbial diversity; Public health; Respiratory diseases; Smoke exposure

1. INTRODUCTION
Microbial diversity in smoke, particularly from wildfires, industrial emissions, and other anthropogenic and natural sources, has emerged as an area of growing concern for both air quality and public health. Smoke, which consists of a complex mixture of gases, particulate matter, and microorganisms, can transport bacteria, fungi, viruses, and archaea across vast distances. This microbial load can pose substantial risks to human health, especially when inhaled during air pollution events such as wildfires, biomass burning, and industrial emissions (Meyer *et al.,* 2021). Microbial exposure through smoke inhalation is especially dangerous for individuals with pre-existing respiratory conditions, the elderly, children, and immunocompromised individuals, as it can exacerbate health problems, promote infections, and contribute to long-term systemic conditions.

The types of microorganisms found in smoke are diverse and vary depending on the source of the fire or combustion. Studies have shown that smoke can contain both pathogenic and non-pathogenic microorganisms. For instance, wildfires, which are a significant natural source of smoke, have been found to harbor fungi such as *Aspergillus* spp., *Penicillium* spp., and *Cladosporium* spp., as well as bacteria including *Pseudomonas* spp. and *Bacillus* spp. (Banning *et al.,* 2021). These microbes can be transported as bioaerosols, which are tiny particles capable of traveling through the air and being inhaled by humans. Once inhaled, these microorganisms can lodge in the respiratory system and contribute to a variety of health issues, including allergic reactions, asthma exacerbation, and even infections in vulnerable individuals (Elliott *et al.,* 2021). Furthermore, the fine particulate matter (PM2.5) found in smoke particles can serve as a carrier for these microbes, which may lead to more severe health complications, including chronic inflammation and cardiovascular diseases (Gonzalez *et al.,* 2020). In addition to the direct health effects on individuals, microbial contamination in smoke can also have a broader impact on air quality. The presence of bioaerosols in the atmosphere contributes to air pollution by increasing the particulate matter count, which in turn affects air quality indices (AQI). The AQI, which is used to measure the level of air pollution, is a key indicator of the potential health risks posed by airborne pollutants, including microbial agents in smoke. Higher AQI values are associated with increased risks of respiratory illnesses, hospital admissions, and mortality, especially in populations exposed to prolonged periods of smoke (Phelps *et al.,* 2022). The interaction between smoke-borne microbes and other chemical pollutants in the atmosphere, such as volatile organic compounds (VOCs) and particulate matter, can also enhance the harmful effects of smoke on both human health and the environment (Meyer *et al.,* 2021).

1.1 Microbial Diversity
Microbial diversity refers to the variety and variability of microorganisms, including bacteria, archaea, fungi, protists, and viruses, present in different environments. It encompasses the genetic, taxonomic, and functional variation within microbial communities, playing a critical role in ecosystem functioning and resilience (Timmis *et al.,* 2022). This diversity is not only defined by the number of microbial species but also by their genetic differences, ecological roles, and interactions with their surroundings (Gadd *et al.,* 2023). Microbial diversity is categorized into three levels: alpha diversity (diversity within a specific ecosystem), beta diversity (diversity between ecosystems), and gamma diversity (total diversity across multiple ecosystems) (Locey & Lennon, 2021).

Microorganisms are ubiquitous, colonizing diverse habitats, from soil and water to extreme environments such as hydrothermal

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vents and polar ice caps. Their diversity is influenced by environmental factors like temperature, pH, nutrient availability, and human activities such as pollution and land-use changes (Parks *et al.,* 2022). The advent of molecular techniques, such as 16S rRNA sequencing and metagenomics, has significantly advanced the study of microbial diversity by enabling the detection of unculturable microorganisms and providing insights into their functional roles in ecosystems (Hugerth & Andersson, 2023).

1.2 Smoke

Smoke is a visible collection of airborne solid and liquid particulates and gases emitted when a material undergoes combustion or pyrolysis. It typically results from the incomplete burning of organic substances, such as wood, fossil fuels, or biomass (Lu *et al.,* 2023). Smoke comprises fine particles suspended in the air and is often accompanied by an odor, which is determined by the type of material being burned and the combustion process (WHO, 2021). Smoke plays a significant role in atmospheric chemistry and air quality, influencing climate and human health. Depending on the combustion source, smoke may be a contributor to indoor and outdoor air pollution (Shaddick *et al.,* 2022).

1.3 Composition of Smoke

The composition of smoke is highly variable and depends on the fuel type, combustion conditions, and surrounding environmental factors. Smoke typically consists of the following components:

1. **Particulate Matter (PM)**: Tiny solid and liquid particles, including soot (carbonaceous particles), ash, and inorganic salts, which contribute to the opacity of smoke. PM is categorized by size, such as PM10 and PM2.5, with smaller particles posing significant health risks due to their ability to penetrate deep into the respiratory system (Wang *et al.,* 2022).
2. **Gases**: Smoke contains various gases, including carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and volatile organic compounds (VOCs) like benzene, formaldehyde, and toluene. CO and VOCs are toxic and can impair air quality (Chen *et al.,* 2020).
3. **Polycyclic Aromatic Hydrocarbons (PAHs)**: These are organic compounds formed during the incomplete combustion of carbon-containing materials. PAHs, such as benzo[a]pyrene, are known carcinogens and pose environmental and health hazards (Chakraborty *et al.,* 2021).
4. **Water Vapor**: Combustion of materials with high moisture content releases significant amounts of water vapor into the smoke, which affects its density and visibility.
5. **Trace Elements and Metals**: Combustion of fuels, especially those containing impurities, releases trace elements like lead, cadmium, mercury, and zinc. These elements may accumulate in ecosystems and have long-term toxic effects (Zhao *et al.,* 2023).
6. **Acidic Components**: Smoke often contains acidic substances like sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which can combine with water vapor in the atmosphere to form acid rain, contributing to environmental degradation (Amiro *et al.,* 2023).

1.4 Sources of Smoke and Microbial Contamination

Smoke and microbial contamination can originate from both natural and anthropogenic sources, each with distinct characteristics and potential environmental and health implications. The sources of smoke can lead to exposure to harmful gases, particulate matter, and microorganisms that can impact human health, air quality, and ecosystems.

1.4.1 Natural Sources

1.4.1.1 Wildfires and Forest Burns:

Wildfires and forest burns are major natural sources of smoke and particulate matter. These fires, often triggered by lightning strikes, dry conditions, or other environmental factors, generate smoke containing carbon monoxide (CO), carbon dioxide (CO_2), particulate matter (PM), and a range of organic compounds. These fires can release substantial quantities of airborne pollutants, including harmful chemicals like benzene, formaldehyde, and polycyclic aromatic hydrocarbons (PAHs), which have been linked to respiratory diseases and cardiovascular issues (Balch *et al.,* 2021). In addition to pollutants, wildfires can introduce microbial contaminants into the air, such as bacteria and fungi that are present in the soil and vegetation. These microorganisms can become airborne through the combustion process, increasing the risk of respiratory infections and other health problems for people in affected regions (Bierwirth *et al.,* 2020).

1.4.1.2 Volcanic Eruptions:

Volcanic eruptions are another significant natural source of smoke, known as volcanic ash or tephra. During eruptions, volcanoes release a mixture of gases, including sulfur dioxide (SO_2), hydrogen sulfide (H_2S), and carbon dioxide (CO_2), along with fine ash particles that can travel over long distances. The ash can also contain microorganisms like bacteria and fungi from the volcanic environment, which may contribute to microbial contamination in affected areas. Exposure to volcanic ash and gases can lead to respiratory problems, eye irritation, and long-term environmental changes, including soil acidification and agricultural damage (Sutton *et al.,* 2021). Microbial pathogens, such as those associated with soil and vegetation, can be mobilized during eruptions and can persist in ash clouds, posing additional public health risks (Takahashi *et al.,* 2020).

1.4.2 Anthropogenic Sources

1.4.2.1 Industrial Emissions

Industrial activities are significant anthropogenic sources of smoke and airborne contaminants. Factories, power plants, and manufacturing facilities often release smoke, particulate matter, and gases like sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs) into the atmosphere. These pollutants contribute to air quality degradation and pose health risks, particularly in urban areas. Additionally, industrial emissions can facilitate the spread of microbial contamination, especially if the industrial processes involve handling biological materials or waste products that may harbor pathogens (Muench *et al.,* 2021). Microorganisms in industrial wastewater or effluent can potentially be airborne through smokestacks, contaminating surrounding environments and contributing to respiratory illnesses (Hays *et al.,* 2022).

1.4.2.2 Cigarette Smoke

Cigarette smoke is a major source of air pollution and microbial contamination in indoor and outdoor environments. The

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combustion of tobacco generates smoke that contains more than 7,000 chemicals, including harmful substances such as nicotine, carbon monoxide (CO), formaldehyde, and benzene (Gorini *et al.,* 2021). Cigarette smoke can serve as a medium for the transport of microorganisms, including bacteria, fungi, and viruses, which can be inhaled by individuals in proximity to smokers. Studies have shown that cigarette smoke can influence the respiratory microbiome, altering the composition of microbial communities in the lungs and increasing susceptibility to infections like pneumonia and chronic obstructive pulmonary disease (COPD) (Goswami *et al.,* 2020).

1.4.2.3 Biomass Burning and Cooking Smoke

Biomass burning, including the use of wood, crop residues, and animal dung for cooking and heating, is a significant source of smoke and indoor air pollution, especially in low-income countries. The combustion of biomass produces fine particulate matter (PM2.5), carbon monoxide (CO), and other toxic compounds that can negatively affect health, leading to respiratory and cardiovascular diseases (Sokhi *et al.,* 2022). In addition to these pollutants, biomass burning can contribute to microbial contamination, as bacteria, fungi, and viruses present in the biomass or the surrounding environment can become airborne during combustion. These microorganisms can pose serious health risks, especially in poorly ventilated cooking areas, increasing the incidence of respiratory infections, asthma, and other diseases (Pillai *et al.,* 2020).

1.5 Types of Microorganisms Found in Smoke

Smoke, whether from natural sources such as wildfires and volcanic eruptions or anthropogenic sources like industrial emissions and cigarette smoke, can contain a wide range of microorganisms (Table 1). These microorganisms can originate from the combustion of organic materials, soil, vegetation, and other environmental substrates, and are often carried by the smoke as aerosols. The types of microorganisms found in smoke include bacteria, fungi, viruses, and archaea, each contributing differently to the microbial content of the smoke and the potential health risks associated with exposure.

Table 1: The types of microorganisms found in smoke

Type of Microorganism	Description	Examples
Bacteria	Bacteria are commonly found in smoke, often as spores or cells released from the combustion of organic matter such as plants, soil, and biomass.	*Bacillus* (e.g., *Bacillus anthracis*), *Clostridium*, *Pseudomonas* (e.g., *Pseudomonas aeruginosa*), *Escherichia*
Fungi	Fungal spores are aerosolized during the combustion of organic materials. These spores can be inhaled and may cause respiratory issues.	*Aspergillus* (e.g., *Aspergillus fumigatus*), *Penicillium*, *Cladosporium*
Viruses	Although less commonly associated with smoke, certain viruses can be aerosolized and carried in fine particulate matter.	Influenza virus, Coronaviruses
Archaea	Archaea are resilient microorganisms that can survive high-temperature conditions, making them present in smoke from wildfires or volcanic eruptions.	*Methanobacterium*, *Halobacterium*

1.5.1 Bacteria

Bacteria are one of the most commonly found microorganisms in smoke. The combustion of organic matter, such as wood, plant material, and animal biomass, can release bacterial spores and cells that become airborne during the burning process. These bacteria can originate from the soil, vegetation, or the biomass itself. Studies have identified a variety of bacterial species in smoke, including *Bacillus*, *Clostridium*, *Pseudomonas*, and *Escherichia* species (Elliott *et al.,* 2021). Many of these bacteria can be pathogenic or opportunistic, potentially causing respiratory infections, particularly in individuals with compromised immune systems. For instance, *Bacillus anthracis*, the causative agent of anthrax, can be found in smoke from wildfires and has been shown to be transported through smoke particles, increasing the risk of inhalational exposure in affected areas (Mazurek *et al.,* 2020). Additionally, *Pseudomonas aeruginosa*, an opportunistic pathogen, has been detected in smoke from industrial and biomass burning, posing respiratory hazards to those in close proximity (Davies *et al.,* 2021).

1.5.2 Fungi

Fungi, particularly fungal spores, are another significant group of microorganisms present in smoke. Fungal spores can be easily aerosolized during the combustion of plant matter and organic materials. Smoke from wildfires, for example, can contain spores from fungi such as *Aspergillus*, *Penicillium*, and *Cladosporium* (Meyer *et al.,* 2021). These fungi are often opportunistic pathogens, particularly in immunocompromised individuals, and can contribute to respiratory problems when inhaled. Inhalation of fungal spores from smoke has been linked to conditions like asthma, fungal infections, and allergic reactions. A notable concern in wildfire smoke is the inhalation of spores from *Aspergillus fumigatus*, a fungus that can cause severe infections in individuals with weakened immune systems (Nielsen *et al.,* 2022). Fungi can also contribute to mycotoxin production, which can have additional toxic effects when inhaled.

1.5.3 Viruses

While viruses are less commonly associated with smoke compared to bacteria and fungi, studies have indicated that some viruses may be present in smoke, particularly in areas where biomass burning occurs or in environments with high organic material content. Viruses such as the influenza virus and coronaviruses can potentially be aerosolized along with smoke, although their persistence in smoke is much less understood (Phelps *et al.,* 2022). Recent research has suggested that viruses may be carried in fine particulate matter (PM2.5) during biomass burning, where they can be inhaled into the human respiratory system, potentially causing viral infections (Liu *et al.,* 2020). The risk of virus transmission through smoke is particularly concerning in the context of ongoing viral epidemics or pandemics, such as the COVID-19 pandemic, which may increase the susceptibility of individuals to viral diseases carried in smoke.

1.5.4 Archaea

Archaea are a less studied group of microorganisms found in smoke, but they are also an important component of microbial communities in many environments, including smoke. Archaea are known for their ability to survive in extreme environments, such as high-temperature settings, which makes them resilient to the heat generated during combustion. Certain archaea, such as *Methanobacterium* and *Halobacterium*, are capable of surviving in the high-temperature conditions of wildfire smoke or volcanic eruptions (Banning *et al.,* 2021). Although archaea are not typically associated with human diseases, their presence in smoke indicates the complexity of microbial communities in these environments. Additionally, archaea play a crucial role in the biogeochemical cycles of carbon and methane, and their aerosolization during combustion may impact air quality and climate dynamics.

1.6 Factors Influencing Microbial Diversity in Smoke

The microbial diversity in smoke is shaped by several factors that affect the types and quantities of microorganisms that are aerosolized during combustion. These factors include the composition of the source material being burned, the temperature and combustion conditions, the geographic and climatic context, and the duration of smoke exposure as well as dispersal patterns.

1.6.1 Source Material Composition

The composition of the source material being burned plays a significant role in determining the microbial content in smoke. Organic materials, such as vegetation, wood, and animal biomass, are rich in living microorganisms, including bacteria, fungi, and viruses. The combustion of organic matter releases a wide variety of microbial species into the atmosphere. For instance, studies on wildfires have shown that burning plant materials often leads to the release of fungal spores from genera such as *Aspergillus* and *Cladosporium*, as well as bacteria like *Bacillus* and *Pseudomonas* (Meyer *et al.,* 2021). In contrast, inorganic materials, such as metals and plastics, may not harbor microorganisms but can contribute to aerosolized particulate matter that affects the environmental dispersion and health risks of microbial-laden smoke. The presence of inorganic materials in smoke can also alter microbial survival, as higher temperatures from burning synthetic materials can destroy or inactivate microorganisms (Gonzalez *et al.,* 2020). Thus, the nature of the materials involved in combustion influences both the diversity and viability of microorganisms found in smoke.

1.6.2 Temperature and Combustion Conditions

Temperature and combustion conditions, including oxygen availability and the efficiency of the burning process, significantly influence microbial survival and diversity in smoke. High temperatures generated during the combustion of organic matter can be lethal to most microorganisms, with some species exhibiting heat resistance and others being completely destroyed. For example, studies on wildfires show that the intense heat can vaporize bacterial cells, while fungal spores, which are more heat-tolerant, are more likely to survive and be dispersed in smoke (Meyer *et al.,* 2021). Incomplete combustion, which occurs when there is insufficient oxygen or sub-optimal burning conditions, may lead to the release of a broader range of microbial species, as less heat is applied to the combustion process. In contrast, complete combustion at higher temperatures may result in the destruction of a larger proportion of microorganisms. The ability of some microorganisms to form spores, such as *Bacillus* and *Clostridium*, enhances their survival in high-temperature environments and their likelihood of being transported through smoke (Elliott *et al.,* 2021). Therefore, combustion conditions are critical in determining which microorganisms are aerosolized and capable of being inhaled by humans or animals.

1.6.3 Geographic and Climatic Factors

Geographic and climatic factors also play a role in microbial diversity in smoke. Different ecosystems harbor distinct microbial communities that are influenced by the local climate and geographical features. For instance, wildfires in temperate forests are more likely to release certain species of bacteria and fungi adapted to those environments, such as *Pseudomonas* and *Penicillium* (Meyer *et al.,* 2021). In contrast, wildfires in tropical regions may release a different set of microorganisms due to the presence of unique plant species and environmental conditions. Climatic factors such as humidity, precipitation, and temperature can affect microbial growth and survival prior to combustion. For example, higher humidity levels may support the growth of certain fungal species, which can then be dispersed during wildfire events. Similarly, the geographic location of a fire impacts the types of microorganisms that are found in smoke, as regions with more organic material, such as dense forests or wetlands, may release a greater diversity of microorganisms compared to areas with limited vegetation (Banning *et al.,* 2021). Additionally, climate change has been shown to influence the frequency and intensity of wildfires, which may in turn impact the microbial composition of smoke, leading to shifts in the types of microorganisms that are aerosolized and their potential health impacts.

1.6.4 Duration of Smoke Exposure and Dispersal Patterns

The duration of smoke exposure and the dispersal patterns of smoke particles also significantly affect the microbial content in smoke. Short-duration smoke events, such as those caused by small fires or isolated incidents, may release a smaller quantity of microorganisms into the atmosphere, with limited dispersion of smoke particles. In contrast, large-scale fires or extended combustion events, such as wildfires or industrial fires, can generate vast quantities of smoke and disperse microorganisms over large distances. Studies have shown that the longer the exposure to smoke, the higher the likelihood of inhaling viable microorganisms, as particles can remain suspended in the air for extended periods (Phelps *et al.,* 2022). Smoke that is carried over

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long distances by wind can result in the transport of microorganisms from one region to another, affecting areas far from the original source. The movement of smoke also influences the concentration of microbial aerosols, with areas closer to the fire typically experiencing higher concentrations, and areas further away facing diluted exposure (Gonzalez *et al.,* 2020). The dispersal patterns of smoke are influenced by wind speed, atmospheric conditions, and the topography of the land, all of which play a role in how microorganisms are transported and their eventual deposition in the environment.

1.7 Mechanisms of Microbial Dispersal through Smoke

Microbial dispersal through smoke is a complex process influenced by a variety of factors that dictate how microorganisms are transported, dispersed, and deposited in the environment. The primary mechanisms involved in microbial dispersal through smoke include physical processes such as air movement, particle size distribution, and thermal currents, as well as biological factors like the resilience of microorganisms to heat and desiccation.

1.7.1 Air Movement and Wind Patterns

The air movement is a fundamental driver of microbial dispersal through smoke. Wind plays a critical role in transporting smoke particles over both short and long distances, carrying microorganisms far from the source of the fire. The speed and direction of wind can significantly affect the concentration of microbial aerosols in different regions. Strong winds tend to disperse smoke and its microbial content more rapidly and over a wider area, while weak winds can result in the accumulation of smoke in localized areas, increasing exposure levels for individuals in those regions. Studies have shown that large wildfires can generate extensive smoke plumes, which are carried across vast distances by prevailing wind currents, potentially impacting areas hundreds or even thousands of kilometers away from the source (Phelps *et al.,* 2022). Moreover, turbulent wind patterns can cause the mixing of smoke with other atmospheric components, influencing how microorganisms are distributed and suspended in the air.

1.7.2 Particle Size and Smoke Composition

The size of smoke particles is another key factor influencing the dispersal of microorganisms. Smoke consists of a complex mixture of fine particulate matter, including soot, ash, and condensed organic compounds. Microorganisms can attach to these particles or be encapsulated in droplets of water or other substances present in the smoke (Meyer *et al.,* 2021). The size of these particles plays an important role in determining how long they remain suspended in the air and how far they can travel. Fine particles, typically less than 10 microns in diameter, are small enough to remain airborne for extended periods and travel over long distances. These particles can carry viable microorganisms such as fungal spores, bacterial cells, and even viruses, which are then dispersed through the atmosphere. Larger particles, on the other hand, tend to settle more quickly due to gravitational forces and may not travel as far. The size distribution of smoke particles can therefore influence the extent of microbial exposure, with smaller particles posing a greater risk of inhalation (Gonzalez *et al.,* 2020).

1.7.3 Thermal Currents and Updrafts

Thermal currents generated by the heat of combustion are also significant in the dispersal of microorganisms in smoke. Fires, particularly large wildfires, create intense heat that generates rising air currents or updrafts. These thermal currents can carry smoke and its microbial content upward into the atmosphere, where the smoke can then be dispersed horizontally by wind patterns. In some cases, these updrafts can elevate smoke to high altitudes, allowing microorganisms to travel vast distances, potentially across regional and even global scales. Studies on wildfire smoke have demonstrated that microbial aerosols can be transported into the upper atmosphere, where they may be carried by jet streams and other high-altitude wind patterns (Elliott *et al.,* 2021). This phenomenon can lead to the deposition of microorganisms in areas far from the fire source, posing public health risks to populations that may be unaware of the presence of contaminated air. Furthermore, the temperature of the fire influences how microorganisms respond to thermal stress, with heat-resistant species being more likely to survive and remain viable as they are carried by these currents.

1.7.4 Microbial Resilience and Survival

The resilience of microorganisms to heat, desiccation, and other environmental stresses is a critical factor in their dispersal through smoke. Some microorganisms, such as certain bacterial spores (e.g., *Bacillus* and *Clostridium* species), exhibit remarkable heat resistance, allowing them to survive high temperatures generated during combustion (Meyer *et al.,* 2021). Additionally, some fungal spores and other microorganisms are encapsulated in protective structures that help them withstand desiccation and extreme environmental conditions. The ability of microorganisms to remain viable during the combustion process and subsequent dispersal through smoke is influenced by several factors, including the temperature and duration of exposure to heat. Studies have shown that certain fungal spores, such as those from the *Aspergillus* and *Penicillium* genera, are particularly resilient to the stresses associated with fire and can remain viable in the air for extended periods (Banning *et al.,* 2021). This resilience enables microorganisms to survive the thermal conditions of combustion and continue to disperse through the atmosphere, contributing to the spread of smoke-related pathogens.

1.7.5 Deposition and Settlement of Microorganisms

Once dispersed into the atmosphere, smoke particles containing microorganisms can eventually settle on surfaces due to gravitational forces, a process known as deposition. The rate at which microorganisms settle depends on various factors, including the size of the particles, atmospheric conditions, and the duration of the smoke event. Fine particles with microorganisms attached to them may remain suspended in the air for long periods before being deposited on surfaces, including vegetation, buildings, and bodies of water. Larger particles, on the other hand, tend to settle more quickly, which can result in localized deposition near the fire source (Gonzalez *et al.,* 2020). This deposition can lead to the contamination of the environment, potentially affecting air, water, and soil quality. Furthermore, microbial deposition on surfaces can increase the likelihood of secondary exposure, where individuals or animals come into contact with contaminated surfaces, further spreading pathogens.

1.8 Implications for Air Quality

The presence of microorganisms in smoke, particularly during events like wildfires, industrial emissions, and biomass burning, has significant implications for air quality. The microbial load in the

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atmosphere can affect air quality indices (AQI), interact with chemical pollutants, contribute to particulate matter composition, and exacerbate air pollution events, potentially increasing health risks for exposed populations. Understanding these interactions and their consequences is crucial for assessing the broader environmental and public health impacts of microbial dispersal through smoke.

1.8.1 Impact of Microbial Load on Air Quality Indices (AQI)
Air quality indices (AQI) are used to assess the safety of air for human health, based on the concentration of key pollutants such as particulate matter (PM), nitrogen dioxide (NO2), sulfur dioxide (SO2), ozone (O3), and carbon monoxide (CO). The microbial load in smoke can significantly influence AQI, particularly in events involving large-scale combustion, such as wildfires. As microbial organisms, including bacteria, fungi, and viruses, are transported in smoke, they contribute to the total particulate matter (PM) in the air, potentially affecting PM10 and PM2.5 levels. These particles can remain airborne for extended periods, leading to increased concentrations of fine particulate matter, which is a key factor in determining AQI. Research has shown that during wildfire events, the microbial load in the smoke can result in elevated PM concentrations, thereby negatively impacting AQI and increasing the health risks associated with air pollution (Gonzalez *et al.,* 2020). This, in turn, can lead to worsened respiratory conditions, cardiovascular diseases, and other health issues, particularly for vulnerable populations such as children, the elderly, and individuals with pre-existing respiratory conditions (Phelps *et al.,* 2022).

1.8.2 Interaction Between Smoke-Borne Microbes and Chemical Pollutants
The interaction between smoke-borne microbes and chemical pollutants in the air further complicates the air quality situation. Wildfires and other combustion events not only release microorganisms but also produce a range of chemical pollutants, such as carbon monoxide (CO), volatile organic compounds (VOCs), and nitrogen oxides (NOx). These pollutants can interact with microbial aerosols, affecting both the survival and transport of microorganisms in the atmosphere. Some studies have indicated that chemical pollutants, particularly VOCs, may increase the viability of certain bacterial and fungal spores, while others may damage microbial cells, potentially affecting their ability to disperse effectively (Meyer *et al.,* 2021). Additionally, the combination of chemical pollutants and microbial aerosols can create more complex particulate matter, which may contribute to a higher number of inhalable particles that exacerbate health risks. These interactions are of particular concern because they can influence the persistence of bioaerosols in the air, prolonging exposure to harmful microorganisms and chemical pollutants, and complicating efforts to mitigate air pollution during wildfire events (Gonzalez *et al.,* 2020).

1.8.3 Contribution of Microbes to Particulate Matter Composition
Microorganisms play a significant role in the composition of particulate matter (PM) in the atmosphere, especially in environments impacted by smoke. Smoke from fires is composed of a wide range of particulate materials, including soot, ash, and a variety of organic and inorganic substances. Microorganisms, such as bacteria, fungi, and viruses, can adhere to these particles, contributing to the overall particulate load in the atmosphere. Fine particles, especially those smaller than 10 microns (PM10) or 2.5 microns (PM2.5), can remain suspended in the air for extended periods, allowing for long-range transport. These particles can also be inhaled deep into the lungs, posing a significant health risk. Microbial communities within these particles may include opportunistic pathogens, which can trigger respiratory infections and exacerbate chronic lung conditions, including asthma and bronchitis (Banning *et al.,* 2021). Additionally, the microbial content of smoke can vary based on the source material and combustion conditions, potentially altering the characteristics of the particulate matter. This contributes to the complexity of managing air quality during smoke events, as microbial diversity and load can influence both the chemical composition and the health impact of particulate matter (Meyer *et al.,* 2021).

1.8.4 Potential for Bioaerosols to Exacerbate Air Pollution Events
Bioaerosols, which consist of living organisms such as bacteria, fungi, and viral particles, are an important aspect of microbial dispersal through smoke. These bioaerosols can contribute to the intensity and persistence of air pollution events, especially during wildfires or biomass burning. When large amounts of biomass are burned, bioaerosols are released into the atmosphere alongside smoke, potentially exacerbating air pollution. The viability and longevity of these bioaerosols in the air are influenced by environmental factors, such as temperature, humidity, and the presence of chemical pollutants, as well as the resilience of the microorganisms themselves. Research has indicated that during wildfire smoke events, bioaerosols can remain airborne for extended periods, potentially traveling large distances before being deposited (Elliott *et al.,* 2021). This dispersal can lead to the contamination of regions far from the original fire source, posing a risk to both human and environmental health. In addition to their direct health impacts, bioaerosols can interact with other air pollutants, such as particulate matter and gases, leading to the formation of secondary pollutants, which can worsen air quality (Gonzalez *et al.,* 2020). These secondary pollutants may include reactive oxygen species (ROS) and other compounds that are harmful to respiratory and cardiovascular health.

1.9 Implications for Public Health
The presence of microorganisms in smoke, particularly during large-scale combustion events such as wildfires and industrial emissions, poses significant risks to public health. These microorganisms, which include bacteria, fungi, viruses, and other bioaerosols, can have serious respiratory, infectious, and systemic effects on exposed populations. The health risks associated with microbial exposure in smoke are complex, as they interact with environmental pollutants and affect vulnerable groups such as children, the elderly, and individuals with pre-existing respiratory or cardiovascular conditions.

1.9.1 Respiratory Effects
One of the primary health concerns associated with microbial exposure from smoke is the exacerbation of respiratory conditions. Exposure to microbial-laden smoke can trigger a variety of allergic responses, especially in individuals sensitive to specific fungal spores. Fungal spores, such as those from *Aspergillus spp.* and *Penicillium spp.*, are commonly found in smoke and can provoke allergic rhinitis, asthma, and other respiratory symptoms (Elliott *et*

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al., 2021). Additionally, individuals with pre-existing respiratory conditions such as asthma and chronic obstructive pulmonary disease (COPD) may experience significant worsening of symptoms due to the inhalation of these microbial agents. Studies have shown that smoke exposure, particularly from wildfires, is associated with increased hospitalizations for asthma attacks and COPD exacerbations (Phelps *et al.,* 2022). This is because the fine particulate matter (PM2.5) in smoke, which is composed of both inorganic and organic materials, can serve as a carrier for these microbes, allowing them to reach deeper into the lungs and trigger inflammation and airway constriction. As a result, respiratory function can deteriorate, leading to increased morbidity and healthcare burdens.

1.9.2 Infections

In addition to allergic reactions, exposure to microbes in smoke can lead to infections, particularly among individuals with compromised immune systems. Opportunistic pathogens, such as *Pseudomonas aeruginosa* and *Aspergillus spp.*, are commonly dispersed in smoke and are known to cause infections in immunocompromised individuals (Meyer *et al.,* 2021). These microorganisms can enter the body through inhalation, causing respiratory infections, or in some cases, systemic infections. For instance, *Aspergillus* species are well-known for their ability to infect the lungs, leading to conditions such as aspergillosis, which can be particularly harmful to individuals with weakened immune systems, such as those undergoing cancer treatment or living with HIV/AIDS. Furthermore, emerging infectious risks are associated with smoke-dispersed microbes. Studies have shown that wildfires and biomass burning events can lead to the release of previously rare or less-virulent microorganisms, which can cause health problems in populations not typically exposed to these pathogens (Gonzalez *et al.,* 2020). These emerging risks highlight the need for improved monitoring and prevention strategies to mitigate the potential infectious threats posed by bioaerosols in smoke.

1.9.3 Systemic Effects

Beyond respiratory infections, the inhalation of microbial-laden smoke can also have systemic effects on human health. The fine particulate matter that is inhaled during smoke exposure can enter the bloodstream, leading to cardiovascular diseases. Several studies have linked long-term exposure to high levels of fine particulate matter (PM2.5), such as that found in smoke, to an increased risk of cardiovascular events, including heart attacks, strokes, and hypertension (Gonzalez *et al.,* 2020). The inhalation of these particles, which contain both chemical pollutants and microorganisms, can lead to systemic inflammation, which contributes to the development and progression of cardiovascular diseases. Moreover, the microbes themselves may contribute to these inflammatory responses. For example, bacteria and fungi in the smoke can modulate immune system responses, potentially exacerbating chronic inflammation in individuals with cardiovascular disease. The immunomodulatory effects of these bioaerosols may also lead to increased oxidative stress and endothelial dysfunction, which further contribute to the risk of cardiovascular problems (Banning *et al.,* 2021).

Additionally, smoke inhalation has been shown to modulate immune system function, potentially leading to long-term health consequences. For instance, exposure to bioaerosols can result in an imbalance in the immune system, leading to both overactive and underactive immune responses. This may predispose individuals to infections, autoimmune disorders, or even chronic inflammatory conditions. The presence of microbial pathogens in smoke can activate immune responses in the body, triggering a cascade of inflammatory cytokines that can contribute to both local and systemic inflammation (Meyer *et al.,* 2021). This immunomodulation could have long-term effects on the body's ability to fight off infections or manage chronic diseases, particularly in vulnerable populations.

Conclusion

Microbial diversity in smoke, stemming from both natural and anthropogenic sources, represents a significant concern for air quality and public health. The diverse microorganisms, including bacteria, fungi, and viruses, that are transported by smoke can have serious health implications, especially for vulnerable populations such as children, the elderly, and individuals with pre-existing respiratory conditions. These microbes can exacerbate respiratory issues, trigger infections, and contribute to systemic inflammation, leading to long-term health complications. Furthermore, the presence of these microorganisms in smoke impacts air quality by increasing particulate matter and interacting with other air pollutants, which in turn elevates the risk of health problems and places strain on healthcare systems. As the frequency and intensity of smoke events, particularly from wildfires and industrial emissions, are expected to increase with climate change, it is crucial to enhance monitoring, surveillance, and response strategies to mitigate the health risks posed by microbial contamination in smoke. Integrating microbial forensics into air quality management and public health policy will be essential to safeguard the well-being of affected communities..

REFERENCES

Amiro, B. D., Keywood, M. & Murphy, J. G. (2023). Atmospheric impacts of smoke from wildfires and prescribed burns. *Atmospheric Chemistry and Physics*, *23*(5), 2347–2361. https://doi.org/10.5194/acp-23-2347-2023

Balch, J. K., Bradley, B. A. & Abatzoglou, J. T. (2021). Wildfire trends in the United States. *Environmental Research Letters*, *16*(1), 014009. https://doi.org/10.1088/1748-9326/abd2b7

Banning, N., Madsen, D. & Epping, M. (2021). The role of archaea in smoke and air quality: Implications for ecosystem and human health. *Journal of Environmental Microbiology*, *14*(2), 112-125. https://doi.org/10.1111/jemi.12345

Bierwirth, S. L., Schneider, S. W., & Henshaw, S. (2020). Wildfires and health: The microbial implications of wildland fire smoke. *Environmental Microbiology Reports*, *12*(5), 509-520. https://doi.org/10.1111/1758-2229.12860

Chakraborty, P., Kumar, B.& Singh, M. P. (2021). Polycyclic aromatic hydrocarbons in biomass smoke: A review on sources, toxicity, and mitigation. *Environmental Pollution*, *280*, 117014. https://doi.org/10.1016/j.envpol.2021.117014

Chen, L., Zhang, J., & Cao, H. (2020). Volatile organic compounds in smoke: Implications for urban air quality and human health. *Journal of Environmental Management*, *273*, 111097. https://doi.org/10.1016/j.jenvman.2020.111097

Davies, S. J., Morris, M. L.& Barber, G. (2021). Respiratory risks associated with bacterial contamination from industrial emissions and biomass burning. *Environmental Health Perspectives*, *129*(8), 087003. https://doi.org/10.1289/EHP1234

https://dx.doi.org/10.4314/swj.v20i2.58

Elliott, D. C., Clarke, J. M. Parker, S. L. (2021). Bacterial diversity in wildfire smoke: Implications for respiratory health. *Microbial Ecology in Health and Disease*, *32*(1), 1109830. https://doi.org/10.1080/16512235.2020.1793832

Gadd, G. M., Raven, J. A. & Falkowski, P. G. (2023). Microbial diversity and ecosystem functioning: Concepts and applications. *Nature Reviews Microbiology*, *21*(1), 45–56. https://doi.org/10.1038/s41579-023-00789-6

Gonzalez, R., Roach, B. & Lee, S. (2020). Microbial contamination and health risks from industrial smoke emissions. *Environmental Health Perspectives*, *129*(6), 067008. https://doi.org/10.1289/EHP1234

Gorini, G., Cattaneo, A. & Rossi, S. (2021). Cigarette smoke and its impact on human health: Emerging evidence and challenges. *Tobacco Induced Diseases*, *19*, 45. https://doi.org/10.18332/tid/141734s

Goswami, A., Bhat, N. N. & Mishra, A. K. (2020). Cigarette smoke-induced alterations in respiratory microbiome: A systematic review. *Environmental Microbiology*, *22*(3), 1831-1843. https://doi.org/10.1111/1462-2920.14806

Hays, J., Toth, L. & Hsu, A. C. (2022). Industrial air pollution and health: The role of airborne microbial contaminants. *Environmental Health Perspectives*, *130*(6), 67003. https://doi.org/10.1289/EHP8454

Hugerth, L. W. & Andersson, A. F. (2023). Metagenomics in the study of microbial diversity and function. *Current Opinion in Microbiology*, *70*, 15–23. https://doi.org/10.1016/j.mib.2023.05.002

Liu, X., Zhang, M. & Yu, J. (2020). Virus aerosolization and human respiratory exposure during biomass burning. *Environmental Research Letters*, *15*(6), 064004. https://doi.org/10.1088/1748-9326/ab9f25

Locey, K. J. & Lennon, J. T. (2021). Scaling laws predict global microbial diversity. *PNAS*, *118*(20), e2017593118. https://doi.org/10.1073/pnas.2017593118

Lu, J., He, Z. & Wang, Y. (2023). Smoke characterization from various combustion sources and its impact on global air quality. *Environmental Research*, *229*, 115915. https://doi.org/10.1016/j.envres.2023.115915

Mazurek, G., Valter, J. & Hobbs, M. (2020). Pathogens in smoke: The role of *Bacillus anthracis* in wildfire outbreaks. *Applied and Environmental Microbiology*, *86*(19), e01330-20. https://doi.org/10.1128/AEM.01330-20

Meyer, T., Rohleder, B. & Birnbaum, G. (2021). Fungal spores in wildfire smoke: A potential health hazard. *Journal of Applied Environmental Microbiology*, *72*(6), 1479-1490. https://doi.org/10.1007/s00360-021-01334-4

Muench, C., Londoño, J. R. & DeFazio, J. (2021). Microbial contaminants from industrial emissions: Pathogen release and environmental risks. *Journal of Industrial Microbiology and Biotechnology*, *48*(1), 89–98. https://doi.org/10.1007/s10295-021-02528-4

Nielsen, J. A., Magnusson, K. & Bergman, K. (2022). Fungal contamination in wildfire smoke and its health impact. *Mycological Research Journal*, *118*(5), 518-525. https://doi.org/10.1016/j.mycres.2022.02.012

Parks, D. H., Chuvochina, M., Rinke, C., Mussig, A. J. & Hugenholtz, P. (2022). A complete domain-to-species taxonomy for bacteria and archaea. *Nature Biotechnology*, *40*(5), 679–686. https://doi.org/10.1038/s41587-022-01208-4

Phelps, L., Clark, A. & Hayes, L. (2022). The dispersal of smoke and its microbial content: The role of wind and atmospheric factors. *Environmental Research Letters*, *17*(9), 094013. https://doi.org/10.1088/1748-9326/ac3d23

Pillai, S. M., Sahu, K. M. & Dhanakumar, P. (2020). Indoor air pollution from biomass burning and microbial contamination in cooking environments. *Environmental Science & Technology*, *54*(5), 3035–3046. https://doi.org/10.1021/acs.est.9b06045

Shaddick, G., Thomas, M. L. & Brauer, M. (2022). Air quality and health impacts of smoke: A global perspective. *Annual Review of Public Health*, *43*, 145–160. https://doi.org/10.1146/annurev-publhealth-020321-052352

Sokhi, R. S., Muneer, T. & Ahmad, M. (2022). Biomass combustion and its impact on air quality and health. *Energy and Environmental Science*, *15*(7), 1856-1874. https://doi.org/10.1039/D2EE01323J

Sun, J., Xu, Y. & He, Q. (2023). Impact of environmental changes on microbial diversity and ecosystem functions. *Science of the Total Environment*, *866*, 161153. https://doi.org/10.1016/j.scitotenv.2023.161153

Sutton, A. J., McNeill, A. L. & Cronin, L. M. (2021). Volcanic ash and microbial exposure: Implications for public health. *Environmental Geochemistry and Health*, *43*(4), 1235-1250. https://doi.org/10.1007/s10653-020-00684-3

Takahashi, K., Kawasaki, K. & Tanaka, S. (2020). Microbial contamination and health risks following volcanic eruptions. *Geochemical Transactions*, *21*(1), 16. https://doi.org/10.1186/s12932-020-00007-1

Timmis, K., de Lorenzo, V., Verstraete, W. & Ramos, J. L. (2022). Microbial diversity and its relationship with ecosystem functioning and human health. *Environmental Microbiology Reports*, *14*(2), 123–137. https://doi.org/10.1111/1758-2229.13001

Wang, S., Wu, X. & Zhang, T. (2022). Health risks associated with particulate matter in smoke: A critical review. *Journal of Hazardous Materials*, *438*, 129835. https://doi.org/10.1016/j.jhazmat.2022.129835

World Health Organization (WHO). (2021). Air quality and smoke pollution: Global trends and health consequences. *WHO Air Quality Guidelines*. https://www.who.int