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Review

Bioaerosols in Agriculture: A Comprehensive Approach for Sustainable Crop Health and Environmental Balance

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Abstract: Bioaerosols have risen as pivotal constituents of airborne particles. Closely intertwined with the agricultural domain, these particles exert a significant influence on crops through the dissemination of various microorganisms that modulate crop growth dynamics, adaptive responses to environmental stimuli, and the nutritional profile of agricultural products. As the main vector, airborne particles are at the forefront in the transmission of plant pathogens. Therefore, this review explains the main factors influencing their composition in agricultural settings and their spreading. Furthermore, it elucidates the complex bioaerosol-based communication networks, including bacteria–bacteria, bacteria–plant, and plant–plant interactions, mediated by specialized volatile organic compounds (VOCs) released by plants and bacterial volatile compounds (BVCs) produced by bacteria. These compounds play a crucial role in synchronizing stress responses and facilitating adaptive processes. They serve as a pathway for influencing and regulating the behavior of both plants and microorganisms. Delving into their origin and dispersion, we assess the key methods for their collection and analysis while also comparing the strengths and weaknesses of various sampling techniques. The discussion also extends to delineating the roles of such particles in the formation of biodiversity. Central to this discourse is an in-depth exploration of their role in the agricultural context, particularly focusing on their potential utility in forecasting pathogen transmission and subsequent plant diseases. This review also highlights the importance of applying bioaerosol-based strategies in the promotion of sustainable agricultural practices, thus contributing to the advancement of ecological balance and food security, which remains a neglected area in scientific research.

Keywords: bioaerosols; crop health; agriculture; patch fragments; biodiversity; air mingling; monitoring system; one health

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1. Introduction

Bioaerosols are particles containing microorganisms, ranging in size from nanometric to millimetric, and are found in indoor environments, nature, and fields [1]. They are ubiquitous in the air due to various sources such as agricultural practices, material decomposition, and human activities [2]. Key contributors include animals, feces, food waste, and other organic materials, which release bioaerosols into the air and introduce them into agricultural settings [3]. In the Amazon rainforest, bioaerosols constitute approximately 24% of the total airborne particle count but represent 47% of the total particle mass due to their relatively heavier weight [4]. These aerosols show substantial spatial and temporal fluctuations [5] and cannot source nutrients for growth in the air [6]. Therefore, the atmosphere acts as a temporary habitat, reflecting the biological activity of terrestrial, aquatic, and phytological ecosystems [7,8].

Bioaerosols play a significant role in climate change by influencing key atmospheric processes. These particles, which include microorganisms, bacteria, and fungi, can impact cloud formation and precipitation patterns [9]. Bioaerosols serve as ice nuclei, facilitating the formation of ice crystals in clouds at warmer temperatures than would typically be needed. This ability to alter cloud properties can lead to changes in rainfall distribution and intensity, which in turn disrupt weather systems and the global water cycle. As a result, bioaerosols can influence regional and global climate patterns, potentially contributing to more unpredictable weather, altered precipitation trends, and shifts in ecosystems. In addition to their effects on weather, bioaerosols can impact the migration of microorganisms, the spread of infectious diseases, and the contamination of water and soil, all of which can further stress ecosystems already affected by climate change. These interconnected effects highlight the need for further research into the complex role of bioaerosols in shaping both regional climates and global climate systems [10]. Moreover, bioaerosols can influence the oxidative capacity of particulate matter (PM), altering broader atmospheric chemistry [11]. In agriculture, factors like cultivation practices, soil characteristics, and microclimatic conditions govern the movement of microorganisms between soil and air, which can influence crop productivity [6].

The relevance of bioaerosols was especially raised in its importance levels during the COVID-19 pandemic in 2019, which underscored the critical importance of understanding and monitoring bioaerosol exposure, as airborne transmission plays a key role in the spread of infectious agents [12]. Extensive research has demonstrated this pathway's significance, further addressing challenges related to other infectious diseases, such as Severe Acute Respiratory Syndrome (SARS), avian influenza virus A (H5N1), seasonal and swine flu (H1N1), and Middle East Respiratory Syndrome (MERS) [13,14].

The One Health framework emphasizes the interconnectedness of human, plant, and environmental health, highlighting the global importance of food security. With the growing global population, ensuring food security is crucial. Bioaerosol-mediated pathogens pose significant risks to agricultural productivity, affecting both food accessibility and economic viability. Proactive bioaerosol management is essential for maintaining consistent agricultural production and safeguarding food security. By monitoring bioaerosols, plant pathogens can be better controlled, while beneficial microbes can enhance crop growth and resilience, leading to higher yields. Moreover, effective bioaerosol management contributes to safer food processing environments and a more stable food supply chain. While previous studies have largely focused on bioaerosols in indoor or clinical settings, their role in plant disease transmission and their contribution to antimicrobial resistance (AMR) in agriculture remain underexplored. Although AMR has been extensively studied in clinical and environmental contexts, its link to airborne transmission in agricultural environments is often overlooked, despite growing evidence that resistant bacteria and antibiotic resistance genes (ARGs) in bioaerosols can shape soil microbiomes, compromise crop health, and impact food safety [15]. This review addresses this critical gap by synthesizing recent findings on bioaerosols across agricultural, clinical, and environmental domains, highlighting their dual role as both beneficial and pathogenic agents. By integrating bioaerosols into broader discussions on food security and One Health, this work provides a comprehensive overview of their implications for plant resilience, human health, and AMR management. Since bioaerosols can travel over large-scale distances [16], it is important to understand the spatial boundaries where we can accurately predict their movement. A single aerosol particle can contain thousands of bacteria, and among bioaerosols, fungi—particularly from the *Aspergillus* and *Fusarium* genera—stand out as significant plant pathogens [17]. Their damaging potential is attributed to versatile life cycles and potent metabolic activity. *Aspergillus flavus* and *Aspergillus parasiticus* are prominent aflatoxin-producing species, posing serious health risks to humans and animals through contamination of crops like maize, peanuts, and tree nuts [18]. Similarly, *Fusarium sambucinum* and *Fusarium incarnatum-equiseti* produce trichothecene mycotoxins (TRIs), known for their teratogenic, nephrotoxic, and genotoxic effects, commonly found in wheat and maize [19].

Despite their relevance, the composition of the air microbiome remains poorly studied. Figure 1 presents publication trends on bioaerosols and agriculture from 2010 to 2024 in PubMed (a), Scopus (b), and Web of Science (c). A spike in publications was observed in 2020, likely driven by heightened interest during the COVID-19 pandemic. However, the trend has since declined, suggesting ongoing challenges in research engagement. While studies have explored the application of bioaerosols in agriculture, integrating them within a One Health framework remains rare.

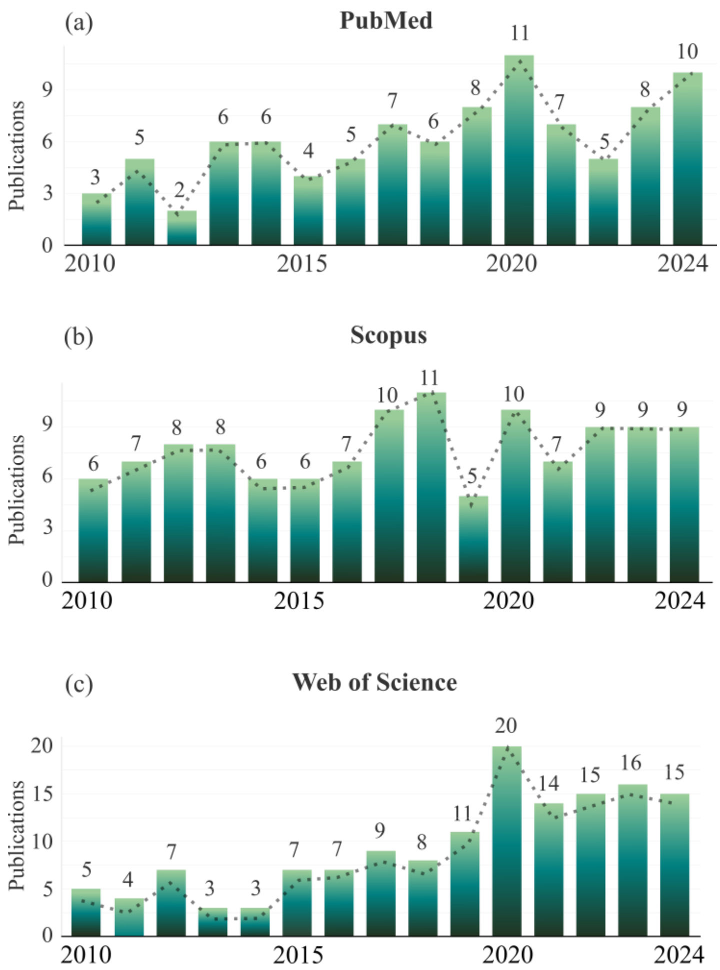

Figure 1. Publication trends in bioaerosols (2010–2024). Data were collected from (**a**) PubMed, (**b**) Scopus, and (**c**) Web of Science using the search terms "bioaerosols" AND "agriculture". All publication types were included with no restrictions. Bar plots were created with the ggplot2 R package (v3.5.0).

This review aims to address existing knowledge gaps by providing a comprehensive analysis of the role of bioaerosols in crop health within the One Health framework. Our objective is to deepen the understanding of how bioaerosols can be effectively managed to protect crops, support ecosystem balance, and promote public health. We emphasize the often-overlooked influence of airborne microorganisms, metaphorically described as a "biological mortar", that integrate and sustain vital environmental processes. These microbes play pivotal roles in the emergence and transmission of plant diseases, and understanding their behavior is essential for anticipating and mitigating future agricultural and health challenges. In addition, this review seeks to offer practical guidance on the selection of appropriate bioaerosol sampling methods based on specific research objectives. It evaluates the operational efficiency of various techniques in capturing a broad spectrum of particle sizes, sampling volumes, and spatial ranges. Special attention is given to the challenges of achieving representative sampling in heterogeneous agricultural landscapes, emphasizing the need to account for surrounding environmental conditions to ensure robust data interpretation. Lastly, the review advocates for the development of aerobiome-based indicators as tools for monitoring the success of environmental regeneration strategies and their effects on bioaerosol dynamics, crop productivity, and ecological sustainability. The primary objective of this review is to highlight the largely untapped potential within bioaerosol research, particularly its critical role in understanding the genesis and propagation dynamics of infectious diseases. This review aims to illuminate the profound influence of airborne microbes, metaphorically described as an 'invisible biological mortar', which are intricately woven into the fabric of life and play a pivotal role in the transmission of pathogens. Proper aerobiome-based monitoring methods for assessing the effectiveness of environmental regeneration strategies are crucial for understanding the impact of environmental changes on bioaerosol composition and dynamics, which in turn affects crop production efficiency and ecological health. Another key aim is to provide comprehensive methodological guidance on selecting appropriate sampling methods tailored to specific research objectives. This includes evaluating the operational efficiency of various investigative techniques across different particle sizes, volumes, and effective ranges. The review will address the challenge of representativeness in sampling, particularly in large and diverse agricultural areas, and the importance of considering environmental conditions in adjacent regions to ensure accurate and comprehensive data collection.

2. Factors Influencing Bioaerosols' Composition

Bioaerosols consist of numerous living and non-living organisms, such as fungi, bacteria, algae, protozoa, and viruses [20]. They also encompass different microscopic materials like spores and pollen grains [21] and metabolism products such as VOCs and BVCs [22]. Their size varies significantly, ranging from 0.001 to 100 µm, depending on their composition [20]. Lichens and different plant fragments are also some of the most prevalent types of bioaerosols [23].

Numerous factors influence air, plants, and soil microbial composition, which can be classified into abiotic (salinity, aridity, pH levels, presence of heavy metals, and agrochemicals) and biotic factors (various microorganisms, including harmless and potential pathogens). Air is not the most suitable environment for the development of microorganisms; therefore, the access to certain genera is limited [24]. Although air is not a primary habitat for microorganisms, it serves as a highly informative medium that reflects the microbial composition of surrounding ecosystems. This is because it contains nucleic acid fragments shed from diverse habitats, offering a representative snapshot of the associated microbiomes. These airborne genetic traces can be used to decode the structure and dynamics of microbial communities linked to soils, plants, animals, and other environmental sources.

Seasonal distribution and air saturation patterns can also be determined. Several studies have described higher levels of microbial agents in air in summer and lower in winter due to the changes in temperature and humidity [25–27]. Due to elevated temperatures in early summer and high humidity in early autumn, bioaerosol concentrations tend to peak from late spring through late autumn [28]. Relative humidity affects bioaerosols behavior in the atmosphere, with Gram-positive bacteria exhibiting greater stability in high relative humidity environments compared to Gram-negative bacteria [29,30]. This is primarily due to differences in their membrane compositions, carotenoid content, and biofilm formation ability. The membrane structure of Gram-positive bacteria is characterized by thicker peptidoglycan layers, which help preserve cell integrity and prevent desiccation under environmental stresses [31]. Additionally, carotenoid pigments produced by species such as *Microbacterium* sp. and *Paracoccus carotinifaciens* act as antioxidants, protecting the bacteria from oxidative stress and UV damage, thus enhancing their survival in stressful environments [32]. The formation of biofilms is another critical factor, as the extracellular matrix provides a protective shield, helping to retain moisture and protect bacteria from environmental stressors such as high humidity and temperature changes [33]. Recent research has also highlighted the role of exopolysaccharides in biofilms, which help bacteria adhere to surfaces and retain moisture, crucial for their survival in various environments [34,35]. Additionally, many bacteria produce endospores, which are among the most resilient microbial structures in nature. Endospores can survive extreme conditions such as high temperatures, radiation, desiccation, and chemical exposure. Their exceptional durability allows them to persist in diverse environments—including soil, water, and air—for extended periods, even thousands of years.

Similarly, viruses' stability at varying humidity levels is influenced by the presence or absence of nucleocapsids. Those with a nucleocapsid have shown enhanced survival in environments of lower relative humidity [24]. Along with other factors, wind direction and its speed impact the composition of bioaerosols. Especially, there is a lower concentration of microorganisms in the air when strong winds with high speeds are present [32].

Further, solar ultraviolet radiation (UV) has an undeniable influence on these temperature limitations. When there are higher levels of UV radiation, it corresponds with lower concentrations of bacterial bioaerosols, and conversely, reduced UV exposure leads to increased bacterial presence [36]. UV radiation affects bioaerosols differently depending on their composition. For living components, such as microorganisms, UV radiation degrades DNA and proteins, leading to genetic mutations and potential cell death [37]. In contrast, UV radiation impacts non-living components by degrading organic matter and inducing chemical reactions, which alters their structure and chemical composition [38].

As these climatic changes continue to affect agricultural systems, we are witnessing an increase in disease outbreaks that threaten crop yields globally. Recently, the outbreak of wheat stripe rust (*Puccinia striiformis f.* sp. *tritici*) has been reported to be driven by the migration of new pathogen races from over-summering regions in China. These strains spread through two main routes, originating from Eastern Qinghai and Middle Gansu, eventually reaching the key wheat-growing Huang-Huai-Hai region. Also, in the United States, warmer temperatures have contributed to more frequent and severe wheat stripe rust (*Puccinia striiformis f.* sp. *tritici*) epidemics [39]. Environmental factors, such as wind and air currents, along with climate and cropping system changes, contribute to the disease's spread [40]. Between 2011 and 2015, Bangladesh experienced a significant rise in temperatures, with increases ranging from 1.8 to 6.5 °C. This temperature spike created favorable conditions for the emergence of a wheat blast epidemic in 2016, highlighting the vulnerability of crops to rapid climate shifts [41]. Similarly, fusarium head blight and crown rot caused by *Fusarium* species have thrived in areas like southern Australia, where prolonged drought conditions and stubble retention practices have increased the survival of fungal inoculum [42]. These diseases have already led to significant crop losses, and projections suggest they will persist, with warming and changing rainfall patterns continuing to favor their spread. Meanwhile, *Yellow Dwarf Viruses*, affecting cereals worldwide, are expected to become more widespread as increased rainfall and milder winters enhance aphid populations, the primary vectors for the virus [43].

Among the various microbial groups consistently detected in the air throughout multiple seasons are Gram-positive bacteria that can form endospores, such as the *Bacillus* and *Clostridium* genera [44]. These organisms' resilience, due in part to their endospore-forming ability, enables them to withstand diverse environmental conditions, including variations in temperature and UV radiation levels [45]. This way they maintain their presence in the atmosphere throughout different seasons due to the multiplex interaction between air microbial communities and factors from the surrounding environment.

Agricultural land is another factor influencing the bioaerosols' composition, with clay soils exerting a higher impact compared to sandy soils [9]. This effect can be primarily attributed to the superior moisture retention properties of clay soils [46]. Also, agricultural practices such as plowing, irrigation, and the application of fertilizers and various agricultural preparations promote the release of different microorganisms from the soil and plant rhizospheres that can be found in the surrounding air [47]. Conservation tillage, which reduces soil disturbance and keeps plant residues on the surface, has been found to encourage microbial species that feed on these residues. For example, dust from conservation tillage fields is often rich in fungi like *Cadophora* and *Phaeococcomyces*, which are typically found as wheat endophytes and have the potential to trigger allergic reactions in humans [48]. In contrast, conventional tillage, which incorporates plant residue into the soil, supports decomposers that thrive below the surface, such as *Fusarium* and *Trichoderma*. These fungi are often present in dust from conventionally tilled fields, with Fusarium, in particular, producing mycotoxins harmful to both humans and animals. The type of fertilizer applied can also influence the microbial makeup of windblown dust [49]. Specifically, biosolids enrich the dust with copiotrophic fungi and bacteria like *Mortierella* and *Clostridium*, which can become allergens or pathogens when aerosolized [48]. These microbes thrive on the organic material from biosolids and are carried by the wind, potentially posing a risk to public health. The harvesting process also disturbs the soil and plant materials, releasing spores and fragments of fungi into the air [20]. In addition, animals in the vicinity can also affect this composition through excrement and respiration, and these bioaerosols are spread by insects and birds [3]. Plant growth and its phenological changes further influence bioaerosol dynamics [50,51]. A plant's microbiome relies on the plant's leaf number, length, structure, shape, and biomass. Only in plant leaves are there over 107 microbes per cm^2 [52], but this number of microbes and their composition varies depending on the plant, mainly due to their structure. Therefore, even the smallest changes in the plant's genome affect its microbiome and the behavior of the plant, and consequently the microbiome of surrounding plants [53].

3. Spatial Distribution

Airborne microbes, spread through the atmosphere, serve as critical indicators of environmental conditions. The radius of spread of bioaerosols decreases from the initial source, and even their concentration can be up to 10 times lower at a distance of 50 m than at the initial point of the source [54]. In general, organisms and smaller particles tend to travel greater distances than other particles [55,56]. Depending on the area of their source, bioaerosols have different distribution diameters. Studies have shown that bioaerosols can spread at least 60 m downwind from an agricultural non-point source during the wheat harvesting season, with suspended particulates ranging from 10,000 μg/m^3 to 2420 μg/m^3 at 20–60 m. Dominant microorganisms, such as *Cladosporium, Fusarium, Streptomyces, Pseudomonas, Acinetobacter*, and *Enterobacteriaceae*, possess an aerodynamic diameter of less than 5 μm, enabling them to remain airborne for extended periods and travel greater distances [57].

According to Pepper and Gerba's [55] study, aerosol distribution can be divided into four groups. Very low distribution below 100 m is more present in urban environments that have rough buildings; low distribution from 100 m to 1 km is the most common distribution; medium distribution is up to 100 km; and high distribution is over 100 km [55]. Dispersal exceeding 100 km has been documented, including dust-associated microbes traveling over 5000 km from Africa to the Caribbean [58,59]. Also, a recent study conducted in 2024 suggests that both bacteria and fungi can travel long distances in the atmosphere [60]. Based on data collected from ten aircraft-based surveys over Japan's troposphere, researchers documented a high microbial diversity, identifying more than 266 fungal and 305 bacterial genera at altitudes reaching 3000 m above sea level. The findings indicate that powerful wind currents, originating from intensive agricultural zones in Northeast Asia, areas heavily treated with fertilizers and pesticides, can lift microorganisms beyond the planetary boundary layer and disperse them over distances greater than 2000 km [60]. Similarly, Abrego et al. [61] found that although the composition of the microbiome was not identical across different locations, fungi could still be found at distances of up to 100 km apart, suggesting that fungal species are capable of dispersing over significant distances.

While research on airborne pathogen dispersal in agricultural settings is limited, there are notable cases where it has been studied. For instance, the airborne spread of *Mycosphaerella fijiensis* occurs through long-distance dispersal of ascospores, which can travel at least 1 km as bioaerosols, while conidia facilitate rapid local expansion, allowing the pathogen to establish and proliferate in newly affected areas [62]. Furthermore, Bernal and Berger [63] studied the spread of *Xanthomonas campestris pv. vesicatoria* in pepper fields and found it can spread through airborne dispersal, with bacteria traveling up to 32 m from diseased plants during rainstorms and strong winds. This demonstrates how bacterial populations can spread as bioaerosols in agricultural environments, facilitating disease transmission across significant distances. Despite their importance, the study of bioaerosols is limited. Their wide distribution and long-range transport make it challenging to pinpoint their sources and determine their role in local microbiota. Variations in size complicate sampling, and the diversity of airborne organisms makes data analysis difficult. However, studying bioaerosols is crucial for understanding environmental microbiomes, especially in agriculture. Unlike soil microbiota, which varies with terrain and altitude, airborne microbiota provides a more consistent reflection of environmental conditions.

To address concerns regarding the empirical validation of bioaerosol transport over long distances, which remains limited in many studies, recent efforts have increasingly integrated meteorological modeling with real-time field observations to bridge this gap. The HYSPLIT model has been frequently used to trace the movement of bioaerosols, as shown in a study in China [64]. In that case, backward trajectory simulations linked fluorescent bioaerosols to distant sources, and the results were validated using real-time lidar measurements and sensor-based monitoring [64]. Likewise, aerial sampling above the planetary boundary layer has confirmed microbial transport over distances of up to 2000 km, with genomic analyses identifying agricultural sources of microbes collected at altitudes around 3000 m, corroborated by wind trajectory modeling [65]. These observations are consistent with atmospheric dispersion modeling (ADM) studies, which underscore the influence of factors like wind speed, atmospheric stability, and deposition patterns on pathogen movement, while also highlighting the limited availability of empirical validation for transport over longer distances. Recent technological advances, such as DNA-optimized membrane filters for sampling and lidar systems for vertical atmospheric profiling, enhance the ability to monitor bioaerosol dynamics with greater detail [66]. Still, difficulties remain in differentiating between locally emitted and long-range transported microbes and in accurately assessing their viability during atmospheric transit due to inconsistent findings on microbial survival [67]. Future research that integrates high-resolution ADM tools with genomic tracking across multiple sites could help resolve these issues and provide stronger empirical evidence for large-scale bioaerosol movement [65].

4. The One Health Approach

Bioaerosols play a critical role in the health of plants, animals, and humans, serving as a key element in the integrated One Health framework. A person inhales approximately 12,000 L of air daily while at rest, highlighting the importance of air quality in human health [68]. Bioaerosols, which are easily inhaled, act as a major pathway for the spread of infectious diseases and can lead to various health concerns. For instance, a study in Nigeria found pathogenic organisms like *Staphylococcus aureus, Escherichia coli*, and *Aspergillus* sp. in public spaces, with microbial diversity varying according to environmental factors such as waste management practices [69]. Similarly, Verde et al. [70] assessed bioaerosol quality in hospital environments, revealing the highest microbial contamination in emergency services. These findings underscore the need for regular bioaerosol monitoring to prevent hospital-acquired infections and ensure compliance with air control measures. In another study, the implementation of air disinfection technology and COVID-19 mitigation strategies led to a 45% reduction in healthcare-associated infections, demonstrating the effectiveness of bioaerosol treatment in controlling airborne pathogens [71].

In animal facilities, bioaerosols also pose health risks to both animals and humans. A study at the Kraków Zoo found significant bacterial bioaerosol concentrations across different animal enclosures, particularly *Staphylococcus* spp., which could harm exposed individuals [72]. Similarly, poultry and swine barns have been shown to harbor high concentrations of airborne bacteria such as *Acinetobacter*, *Clostridium*, *Pseudomonas*, and *Streptococcus* [73]. Bioaerosols also impact plant health, facilitating the dispersal of both beneficial and pathogenic bacteria and fungi. For example, *Alternaria* spores, which are harmful to crops, can travel long distances, as demonstrated by their movement from the Pannonian Plain to Poland, increasing disease risks in agricultural regions [74]. This can be potentially aided by the movements and activities of birds, which may potentially aid in the environmental spread of zoonotic agents, such as antimicrobial-resistant bacteria, even though they do not directly transport bioaerosols [75]. Conversely, beneficial species like *Pseudomonas* and *Bacillus* are also transported through the air, promoting plant growth by producing phytohormones and solubilizing nutrients [76,77]. Plant canopies themselves are a source of bacterial aerosols, with emissions peaking on warm, sunny days when leaves are dry and wind speeds are high [78]. Despite their critical role, bioaerosols remain largely overlooked in discussions about how pathogens and antimicrobial resistance (AMR) spread in agricultural systems. In farming environments, bioaerosols act as invisible carriers of plant pathogens (e.g., *Fusarium, Pseudomonas*), zoonotic agents (e.g., *Salmonella*, avian influenza), and AMR genes from treated animals or manure. Their airborne nature allows them to bypass traditional biosecurity barriers, making outbreak control more difficult. They also pose health risks to farmworkers and contribute to declining crop yields, increased chemical use, and environmental contamination. Nevertheless, air remains one of the least monitored and regulated transmission routes in agriculture.

Given the diverse impact of bioaerosols on human, animal, and plant health, it is essential to develop and implement strategies to integrate bioaerosol management into broader health initiatives. This will help mitigate the risks associated with airborne pathogens and promote overall public health. Air, as the pathway connecting all these sectors, forms a crucial link under the One Health framework. Several real-world case studies illustrate the effective integration of bioaerosol monitoring into disease prevention and environmental management within the One Health framework. For example, a pilot study in North Carolina employed non-invasive bioaerosol sampling over 23 weeks on a swine farm, successfully detecting pathogens such as influenza A and porcine circoviruses, providing early warnings for stakeholders in animal production systems [79]. In Bolivia, bioaerosol monitoring in areas with poor sanitation identified airborne human adenovirus and influenza A virus, offering valuable insights into environmental exposure risks and informing public health interventions [80]. However, practical applications of bioaerosol monitoring in plant health remain limited, highlighting a significant gap and an opportunity for future research and implementation within the One Health framework.

Beyond merely transporting pathogenic agents, bioaerosols are responsible for the transportation of antibiotic resistance genes (ARGs), further linking them to the broader issue of antimicrobial resistance (AMR) [81]. Recent data show that bacterial AMRs directly caused 1.27 million deaths in 2019 and contributed to 4.95 million deaths annually [82]. This alarming trend has led the WHO to advocate for national strategies to ensure responsible antibiotic use across healthcare, food production, and environmental sectors, all under the One Health approach. The WHO also emphasizes the need to raise awareness among stakeholders and support local food producers in reducing antimicrobial use, as AMR poses a significant threat to public health and economic stability [83]. WHO warns that without immediate action, drug-resistant diseases could cause 10 million deaths each year by 2050 [84], surpassing the number of deaths caused by cancer [85].

The spread of AMR is closely tied to bioaerosols, which facilitate the movement of resistant bacteria and ARGs into the air, allowing them to be inhaled by humans. In agricultural settings, the use of antibiotics in livestock not only promotes the spread of these resistance genes but also leads to their accumulation in plant tissues, entering the food chain [86]. This occurs through the application of manure and slurry in soil, as animal feces and manure are significant reservoirs of antibiotics and antibiotic-resistant bacteria [87]. Research has shown that using manure and slurry from animals treated with antibiotics increases the levels of antibiotic-resistant genes (ARGs) in the soil [88–90]. As a result, humans are exposed indirectly through contaminated food or direct contact with animals carrying these resistant bacteria [91]. Antimicrobial resistance not only threatens human health but also jeopardizes crop health, as it contributes to the development of a soil resistome. This resistome facilitates pathogen colonization of plant roots, hindering growth and nutrient uptake. Resistance genes are transmitted to plant microbiomes via horizontal gene transfer, posing significant risks to crop health [92].

Given that bioaerosols uniquely facilitate the transmission of antimicrobial resistance across food security, environmental health, and human health, research in this area must be intensified to effectively address these interconnected challenges. Effective measures include raising awareness among stakeholders, adopting strict regulations on antibiotic use in agriculture, and implementing robust monitoring systems. By addressing these issues through a One Health approach, which integrates healthcare, environmental protection, and food safety, we can better manage and reduce the global burden of antimicrobial resistance.

5. Behavioral and Communication Pathways

5.1. Bacterial Volatile Compounds (BVCs)

Airborne bioaerosols serve as a valuable mirror for the microbial composition of soils and plants, capturing the subtleties of their microbiota. They are involved in a complex network of communication, including interactions between bacteria, between bacteria and plants, and between plants themselves. As a result, research has increasingly focused on volatile compounds (VCs) produced by bacteria, which are an integral component of bioaerosols. These small molecules (<300 Dalton) are observed to have an impact as antimicrobial products and modulators of behavior [93]. Due to their low boiling points and high vapor pressure, they can easily disperse in air and water. BVCs span various organic classes, such as acids, sulfur compounds, terpenes, hydrocarbons, ketones, alcohols, and nitrogen-containing compounds, along with inorganic compounds like ammonia, nitric oxide, and hydrogen sulfide [94]. BVCs possess the ability to regulate crucial bacterial processes that include biofilm formation and resistance to antibiotics, influencing the behavior of airborne microbial communities [95]. They function as chemical signals that enable communication among microbial species impacting essential behaviors such as growth, movement, and gene expression [96]. Consequently, they shape the overall dynamics of microorganisms in the air, playing a role in their adaptation to the new conditions of their environment or even new habitats. In response to environmental signals, bacteria release specific VCs that allow them to adapt and thrive under different atmospheric conditions [94]. Bacteria, like *Escherichia coli*, can detect VOCs released by other bacteria, such as *Bacillus subtilis*. For instance, compounds like 2,3-butanedione and glyoxylic acid, which are emitted by *Bacillus subtilis*, cause significant changes in *Escherichia coli* gene expression, influencing its motility and antibiotic resistance [97]. Additionally, *Pseudomonas aeruginosa* was found to produce hydrogen cyanide (HCN), a VC that inhibits the growth of *Staphylococcus aureus*. This competition was observed both in vitro, in mixed biofilms and sputum medium, and in vivo in a mouse model of airway coinfection [98].

It is already well-known that plants communicate with each other through their rhizospheric microbiome [99,100]. They have different types of root systems and communicating with each other via BVCs makes it easier for them to raise their defense systems against pathogens and also makes it easier to obtain the nutrients necessary for their growth from soil. This system, known as 'root mingling', is presumed to have a potential counterpart in the aerial environment, which may function in a similar manner. This aerial analog, tentatively referred to as 'air mingling', could represent a communication network through which plants exchange various signals, allowing them to coordinate specific physiological or ecological functions within their surrounding ecosystem. Similar to how plants communicate through their rhizosphere, airborne signals allow plants to synchronize responses to both biotic and abiotic stresses. Building on the concept of "air mingling", studies have demonstrated that VOCs emitted by plants and bacteria play a crucial role in plant communication (Figure 2). For instance, plant growth-promoting rhizobacteria release BVCs that are transmitted through the air, influencing neighboring plants by triggering systemic resistance to pathogens, thereby enhancing plant health [101]. Additionally, plants exposed to VOCs from herbivore-damaged neighbors often activate defensive responses, such as producing secondary metabolites like methyl jasmonate, which serve to deter herbivores, showcasing a form of chemical communication [102]. Similarly, another study by Shulaev et al. [103] showed that methyl salicylate, produced in response to pathogen infection, acts as an airborne signal. Synthesized from salicylic acid, it travels through the air to activate disease resistance and trigger the expression of defense-related genes in neighboring plants and healthy tissues of the infected plant. Moreover, BVCs significantly influence plant physiology, supporting both growth and defense responses. For example, *Bacillus subtilis* SYST2 releases VOCs like albuterol and 1,3-propanediol, which have been shown to increase biomass and photosynthetic rates in tomato seedlings [104]. Similarly, endophytic bacteria like *Microbacterium* strain EC8 release sulfur-containing VOCs such as dimethyl disulfide and dimethyl trisulfide [105]. These compounds promote plant growth by enhancing shoot and root biomass, as well as lateral root density in lettuce and tomato. The ability of plants to communicate through airborne signals underscores the importance of aerial communication, where airborne signals facilitate coordinated responses to both biotic and abiotic stresses. Understanding BVCs and their role in the dynamics of airborne microbes has practical implications beyond microbial ecology. Manipulating BVC-mediated interactions, many possibilities arise for applications in environmental science, agriculture, and health. These interactions can have an impact on plant health and disease resistance. Plants sense the VCs that bacteria release, utilizing them as carbon sources and protective metabolites for them [96,106]. BVCs have been shown to enhance plant growth and tolerance to abiotic stresses [107]. This has been seen in treatments with volatiles from *Bacillus subtilis* GB03, which increased plant growth in Arabidopsis by regulating the expression of specific genes [108–110]. Furthermore, BVCs attract beneficial bacteria while deterring pathogenic ones, making them a potential tool for pest and disease control in agriculture [93].

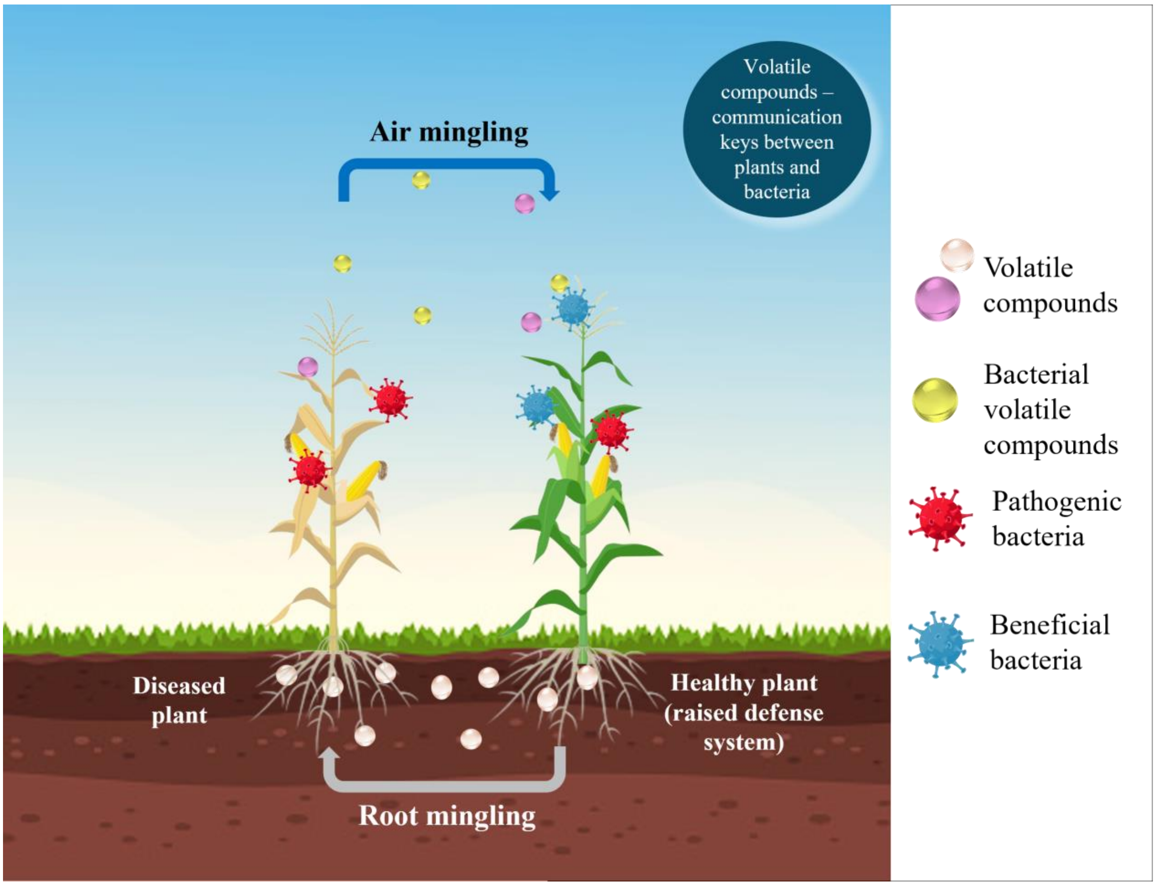

Figure 2. Bacterial communication pathways in bioaerosols, illustrating VOCs and BVCs in mediating interactions between plants and bacteria through air mingling and root mingling.

5.2. Volatile Organic Compounds (VOCs)

Plants sense the signals they receive from bacteria (BVCs), and they try to communicate with their neighboring plants. Since they are immobile, they have developed other forms of communication. Plants communicate with each other through aerial signals. The most well-known form of communication between plants is through the production of chemical compounds [111]. These compounds belong to different classes, such as phenols, terpenoids, alkaloids, and quinones, which are harmful to the attacker or are informative for other plants [112]. Neighboring plants absorb these signals and transmit them to others, influencing an even wider distribution of these compounds. The production of such compounds is used for communication even in situations where there is no danger. Plants use these VOCs to recognize their neighbors and create their own defense system [113] (Figure 2). VOCs commonly involved in plant-to-plant signaling include the oxylipin metabolites methyl jasmonate, methyl salicylate, and cis-jasmone, as well as asterpenoids and VCs of green leaves [114]. The main group of compounds through which plants communicate are terpenoids, which are carried by VOCs released through the leaves [115]. Such compounds include aldehydes, alcohols, and their esters [116]. Plants damaged by herbivores possess a mechanism to emit volatiles like (z)-3-hexenal and (E)-2-hexenal [117]. Through this mechanism, they deter further herbivore attacks on injured leaves and signal neighboring plants about the attack. Substances like these trigger alterations in the membrane of plasma, initiating the activation of diverse regulatory proteins, among them the WRKY transcription factor [118]. Such VOCs can be found in other, even more energetic forms, indicating the expression of specific regulatory genes and prompting the influx of calcium [119]. These energetic active forms include compounds like cis-3-hexenyl acetate (green leaf volatile) and cis-3-hexen-1-ol (leaf alcohol) [108]. According to Heil [120], salicylic acid and methylsalicylate are signals released by the tobacco plant and transmitted through the air to other plants, promoting the resistance mechanism in the surrounding plants. Similarly, jasmonic acid is released as a signal of herbivore danger [121]. For instance, lima beans (*Phaseolus lunatus*) release (E)-β-ocimene when attacked by spider mites, which alerts surrounding plants and induces their defensive responses [122]. Likewise, wild tobacco (*Nicotiana attenuata*) emits (E)-α-bergamotene, which functions both as a direct defense against herbivores and as a signal to neighboring plants to activate protective pathways [123]. Maize (*Zea mays*) produces indole upon herbivore attack, which not only attracts natural predators of the herbivores but also primes nearby plants for a faster defense response [124]. These findings highlight the diversity of plant-produced VOCs and their role in orchestrating a collective defense system across plant populations.

Another key communication mechanism involves ethylene, which has shown great potential in initiating plant-to-plant signaling. In particular, corn plants that have experienced mechanical damage release ethylene, which influences neighboring plants by strengthening their protective responses. When plants undergo mechanical damage, they release ethylene, which serves as a signaling molecule detected by nearby plants. This ethylene release triggers a cascade of defensive responses, enhancing the plants' ability to cope with potential threats. Specifically, ethylene can activate the expression of genes involved in fortifying plant defenses, such as the synthesis of protective compounds like cis-3-hexen-1-ol, a green leaf volatile known to contribute to plant defense mechanisms [125]. Together with other VOCs, ethylene helps initiate a systemic response that boosts the resistance of neighboring plants, even in the absence of direct contact. Ethylene is also involved in regulating plant responses to environmental stressors, especially during drought conditions. When a plant experiences water stress, it releases ethylene, signaling nearby plants to prepare for similar challenges. In this context, ethylene acts as an aerial signal, enabling neighboring plants to activate protective mechanisms like stomatal closure, which reduces water loss [126]. This communication system is widespread, but the distance over which signaling molecules can travel depends on factors such as tree height, biodiversity, and planting density. Research has shown that VOCs can effectively communicate over distances of up to 7 m [127].

6. Practical Importance of Bioaerosols in Agriculture

6.1. Combating Biodiversity Loss

The fragmentation of habitat is one of the main threats to biodiversity, primarily driven by anthropogenic activities such as agricultural expansion and urbanization. It significantly alters land use patterns, accelerates urbanization, affects agricultural productivity, and impacts food security [128]. Fragmentation reduces the size of natural habitats and isolates them into smaller patches, leading to decreased genetic diversity and increased vulnerability of species to environmental changes and human activities. Additionally, fragmentation creates "edge effects", where the environmental conditions at the periphery of habitat fragments differ from those in the core areas. These edge effects often result in altered microclimates that can be detrimental to certain species and disrupt the original habitat conditions [129]. There are two main problems related to fragmentation, which are biodiversity loss and decreased resilience. These two components are related to lower yield rates and higher prevalence of plant infections. Furthermore, loss of biodiversity from fragmentation can make plants more vulnerable and have an obvious effect on size decrease and isolation [130]. Bioaerosols offer a promising solution to these challenges. According to Corinaldesi et al. [131], microbiota associated with habitat-forming species, such as corals, seagrasses, and macroalgae, plays a crucial role in their health and resilience. Restoration efforts that incorporate native microbiota improve survival rates and growth of transplanted organisms, contributing to the recovery of degraded marine habitats. Similarly, Warren et al. [132] demonstrated that bioaerosols play a crucial role in the restoration of biological soil crusts, with airborne propagules aiding the re-establishment of these vital ecological communities on disturbed soils, thereby contributing to soil restoration and biodiversity conservation.

These particles are vital for soil regeneration and nutrient cycling, and they can potentially modify microclimatic conditions to favor native species [133]. Bioaerosols facilitate the dispersal of microorganisms such as fungi and bacteria, contributing to essential ecological functions, including decomposing organic matter and supporting nutrient cycling [134]. This is particularly important in fragmented landscapes where conventional ecological processes may be disrupted. One way to address this issue is by creating small patches within agricultural lands, which can help mitigate the negative effects of intensive farming. These patch-like fragments—small, isolated areas with distinct vegetation, microclimates, and ecological conditions—are valuable for studying local biodiversity and ecosystem health. Integrating such patches within agricultural landscapes has proven to enhance biodiversity and ecosystem resilience. A study by Takkis et al. [135] highlighted that small forest patches in agricultural areas are essential for supporting diverse plant communities and maintaining forest integrity, thus playing a crucial role in conserving biodiversity. Similarly, Wintle et al. [136] found that small, isolated habitat patches hold higher conservation value, as they support unique species assemblages and contribute significantly to landscape heterogeneity. These small patches not only provide important spaces for species but also improve ecological connectivity of fragmented landscapes. Small patch-like fragments are often overlooked in traditional conservation efforts, yet they are key to sustaining biodiversity in agricultural environments. Tiang et al. [137] highlighted that small patches in agricultural settings function as stepping stones, allowing species to move between larger habitat areas, which promotes genetic diversity and ecosystem resilience. Similarly, Duff et al. [138] reported that small habitat patches within agricultural landscapes significantly influence biodiversity, suggesting that integrating such patches with broader landscape strategies can improve ecosystem resilience and services.

Despite the promising potential of this approach, research remains limited. Benton et al. [139] highlighted that agricultural pollutants such as nitrogen oxides and ammonium significantly impact air quality and biodiversity, emphasizing the importance of preserving small vegetative patches to reduce airborne pollutants and protect ecosystems. Artificially created patches, or buffer zones, serve as transitional habitats between agricultural fields and natural ecosystems, enhancing connectivity and microorganism dispersal (Figure 3). This connectivity is crucial for maintaining biodiversity and ecological functions, particularly in large, fragmented areas impacted by tillage systems and agrochemicals [134]. These patches not only support crop production by providing beneficial microorganisms through bioaerosols [129], but also play a key role in species movement and ecosystem resilience [137].

Figure 3. Visual representation of patch-like fragments within an agricultural field.

Moreover, bioaerosols can promote ecosystem resilience by aiding in seed germination and increasing resistance to plant pathogens. The introduction of a variety of microorganisms through bioaerosols boosts microbial diversity, which is crucial for maintaining ecosystem stability and climate change adaptation [140]. Climate change significantly affects the composition, concentration, and dispersion of bioaerosols due to changes in environmental variables like temperature, humidity, wind patterns, and extreme weather events [141]. Rising global temperatures stimulate microbial activity in soils, vegetation, and aquatic systems, increasing bioaerosol emissions [142]. Warmer conditions also extend the growth and reproduction periods of bioaerosol-producing organisms, such as fungi and plants, resulting in prolonged exposure windows. Changes in precipitation and humidity influence bioaerosol release and resuspension. Wet–dry cycles promote fungal sporulation, while high humidity enhances microbial aerosol survival and persistence. Conversely, drought conditions increase dust-borne microbial transport from desiccated soils. Increased wind speeds further elevate bioaerosol burdens, and storms act as powerful dispersal mechanisms [141]. Climate-induced changes in vegetation and agricultural practices modify microbial compositions of surface environments, affecting bioaerosol emissions [142]. More frequent wildfires, driven by climate change, release large amounts of biological particles—such as fungal spores, plant debris, and thermotolerant microbes—into the air, impacting public health and environmental processes [143]. Climate change's influence on bioaerosols has significant implications for public health, agricultural productivity, and ecosystem resilience. Long-term meteorological data are particularly useful for studying the impacts of climate change on bioaerosols. For example, van Leuken et al. [144] analyzed 30 years of meteorological data and found that bioaerosol concentrations generally decrease due to higher temperatures, increased global radiation, and stronger winds. Elevated temperatures also contribute to rising CO2 levels, which are linked to changes in bioaerosol composition and exposure. Climate change is reshaping microbial communities, with notable impacts on fungal spores and airborne allergens [145]. Biological aerosols are recognized for their significant role in climate change, participating in the carbon cycle and influencing cloud condensation and ice nucleation processes [146]. Therefore, the diversity of microorganisms carried by bioaerosols is crucial for enhancing microbial diversity, which is vital for ecosystem resilience and mitigating the impacts of climate change. Additionally, bioaerosols facilitate natural pest control by transporting microorganisms that inhibit plant pathogens and pests, offering further protection to plants in fragmented habitats [147,148]. They present an environmentally friendly alternative to chemical pesticides, mitigating the harmful impacts of pesticides on both the environment and human health. This natural pest control is especially valuable in habitat fragments where plants may be more vulnerable to diseases and pests due to stressors such as edge effects and reduced genetic diversity. In this context, Chattopadhyay et al. [149] reported that bacterial insecticides are increasingly being adopted in integrated pest management systems due to their ability to target insect pests without contributing to pesticide resistance or environmental contamination. Similarly, *Bacillus thuringiensis* bacteria, which produce insecticidal Cry and Cyt toxins, play a significant role in pest control, both as soil-dwelling organisms and through bioaerosols in the environment [150]. When dispersed through the air, these bacteria can act as natural biocontrol agents, reducing the need for chemical pesticides [151]. The widespread distribution of Bt in soil, water, and plants further emphasizes its role in integrated pest management, including its potential as a bioaerosol in pest control [152].

Experimental evidence also demonstrates the potential of bioaerosols in contributing to ecosystem resilience. A recent study evaluated the glyphosate-degrading ability of airborne plant growth-promoting bacteria, including *Exiguobacterium indicum* AS03, *Kocuria sediminis* AS04, and *Rhodococcus rhodochrous* AS33. These isolates were tested both individually and in consortium, successfully removing up to 86.3% of glyphosate within 14 days [153]. This underscores the role of airborne beneficial bacteria not only in mitigating agrochemical pollution but also in supporting plant health through natural biodegradation processes.

6.2. Direct Role of Bioaerosols in Crops' Health

Bioaerosols not only enhance soil biodiversity and contribute to ecosystem resilience by supporting microbial diversity and enabling natural pest control, but they also have a direct impact on plant health. These airborne microorganisms, including bacteria and fungi, are crucial for plant growth, nutrient absorption, and disease resistance. As carriers of beneficial microbes, bioaerosols provide continuous support to plants, promoting their health and productivity across ecosystems. In turn, plants are significant contributors to the air microbiome, playing a key role in shaping the community of airborne microbes, which includes fungi and bacteria. Studies have shown that surrounding plants contribute more than 50% of the air microbiome [154,155]. Bioaerosols positively influence agricultural crop yields through several mechanisms. According to Greenwald et al. [156], these airborne particles contribute to mitigating water stress in plants by decreasing soil evaporation and plant transpiration rates. This process helps to maintain the balance of moisture within the soil, which is crucial for the healthy growth of plants. Additionally, well-maintained soil supports a diverse range of microorganisms that contribute to plant health and productivity.

The interactions of plants with microorganisms vary depending on their endophytic (inside the plant) and epiphytic (on the plant surface) nature. These interactions can directly influence plant growth by providing essential nutrients and managing their availability, such as through nitrogen fixation. They can also indirectly affect plant health by enhancing resistance to pathogens and pollutants [157,158]. For instance, beneficial microorganisms, including rhizobacteria, mycorrhizal fungi, and nitrogen-fixing bacteria, form symbiotic relationships with plants. These interactions improve nutrient uptake, promote root growth, and help plants resist diseases. *Rhizobacteria*, often referred to as plant growth-promoting rhizobacteria, supports root development and provides vital nutrients; mycorrhizal fungi extend a network of hyphae around plant roots, aiding in the absorption of water and minerals; and nitrogen-fixing bacteria, such as *Rhizobia*, convert atmospheric nitrogen into a usable form for plants, particularly in legumes, which form nodules to host these bacteria [159,160].

In contrast, dysbiotic conditions in soils and plant microbiota can adversely impact plant health. Pathogenic microorganisms, including certain fungi and bacteria, can lead to significant crop damage and yield losses [161]. Common pathogens, such as those causing root rot and various types of nematodes, can hinder plant growth [162]. Soil–plant microbiome dysbiosis can result in issues like leaf necrosis, stunted growth, and disease outbreaks (refer to Table 1), exemplified by *Fusarium oxysporum*, which causes tomato wilt disease and severe crop losses [163].

Even though there is not enough evidence, the same relationship is with the air microbiome, which is crucial for the health of crops. Fungal spores, such as *Phytophthora infestans*, responsible for potato late blight [164], and *Puccinia graminis*, which causes wheat stem rust [165], are often dispersed by air currents, allowing them to travel long distances and infect crops. Essential food supply in a secure manner is one of the main goals of agriculture for a stabilized economic and social environment. Interferences in this system include the introduction of different crops and livestock pathogens. Such disruptions are responsible for the crisis of crop disease transmission, contamination of food, and epidemics, which consequently pose risks for human health. Specific cereal pathogens such as *Fusarium* spp. and *Claviceps purpurea* produce mycotoxins, which are lethal for living organisms, including animals and humans [166]. These compounds have also been shown to be present as airborne particles, posing a higher risk not only to crops but also to workers in the area [167].

While plants significantly shape the air microbiome, utilizing this interaction for disease prevention remains underexplored. One major challenge is distinguishing between beneficial and harmful airborne microbes in real-time, as current methods primarily focus on detecting pathogens after infection has occurred. Advanced biosensors and rapid sequencing technologies could bridge this gap by enabling early detection of airborne pathogens before they establish in crops [168]. Additionally, applying beneficial airborne microbes, such as plant growth-promoting bacteria or naturally occurring antifungal species, could offer a proactive approach to disease control [169]. Research on bioaerosol-based biocontrol strategies is still in its early stages, but targeted microbial inoculations could help stabilize plant–microbe interactions and suppress harmful fungi and bacteria in the air [170]. Exploring these strategies could enhance crop resilience while reducing dependency on chemical pesticides, ultimately promoting a more sustainable agricultural system.

Table 1. Different crop diseases caused by microorganisms in the surrounding air.

Crop	Disease	Symptoms	Responsible microorganism	References
Cucumber, pumpkin, zucchini, and watermelon	Powdery Mildew of Cucurbits (*Podosphaera xanthii*)	Brittle yellow leaves, malformed fruit (not directly attacked), and white colonies on the surface of leaves and stems	Powdery Mildew of Cucurbits (*Podosphaera xanthii*)	[171]
Tomatoe	Bacterial speck of tomatoe	Leaves with brown–black spots, dark spots on fruit, low yield	*Pseudomonas syringae*	[172]
Potato	*Alternaria* disease of potato	Yield decrease, damage of all green parts of the plant	*Alternaria solani*	[173]
Wheat	*Pyricularia* disease	Partial or total loss of the heads, many infection cycles per season	*Pyricularia grisea*	[174]
Winter wheat	Eyespot	Loss in yield, weakened stems, elliptical lesions on stems	*Oculimacula acuformis* and *Oculimacula yallundae*	[174]
Corn	Tar Spot Complex (TSC) of maize	Dark, oval-to-round lesions on leaves (0.5–2.0 mm diameter), slightly raised black points randomly distributed on the leaf	*Phyllachora maydis*, *Monographella maydis*, and the hypeparasite *Coniothyrium phyllachorae*	[175,176]
Grape	Pierce's disease	Leaf marginal necrosis, decline of plant vigor, wilting, and fruit drying	*Xylella fastidiosa*	[177–179]

6.3. Bioaerosol-Based Disease Control

In ecosystems, plants, soil, air, and water are interlinked, each supporting the development of the others, and bioaerosols play a significant role in this dynamic [17]. Understanding the role of bioaerosols in crop production and disease spread is critical for controlling and monitoring infections. These airborne particles suspended in the air can carry pathogens, posing a potential threat to crop health, agricultural yields, and food security (Figure 4). Early detection of these bioaerosols is essential to prevent widespread infections and maintain crop health. In terms of this, microbial-based predictions can serve to make better environmental management [180] by looking for solutions to current global problems such as resistance to antibiotics, agrochemical residues in edible agricultural crops, low nutritional values of products, and yield decreases.

Farmers can leverage knowledge of the airborne microbiome to assess and monitor the health of agricultural land and crops. Even if pre-planting assessments are not conducted, air microbiota forecasts can help prevent diseases in later plant growth stages. Traditional farming often relies on excessive chemical use, which impacts both the environment and crop health. Sustainable agriculture aims to minimize chemical use by emphasizing effective disease surveillance and timely detection. By implementing reliable disease monitoring methods, farmers can reduce unnecessary agrochemical applications, promote healthier crops, and support environmental sustainability. Precision agriculture seeks to enhance food production quality and quantity while minimizing chemical use [181]. In terms of this, disease monitoring through bioaerosols can emerge as an innovative form to achieve this goal.

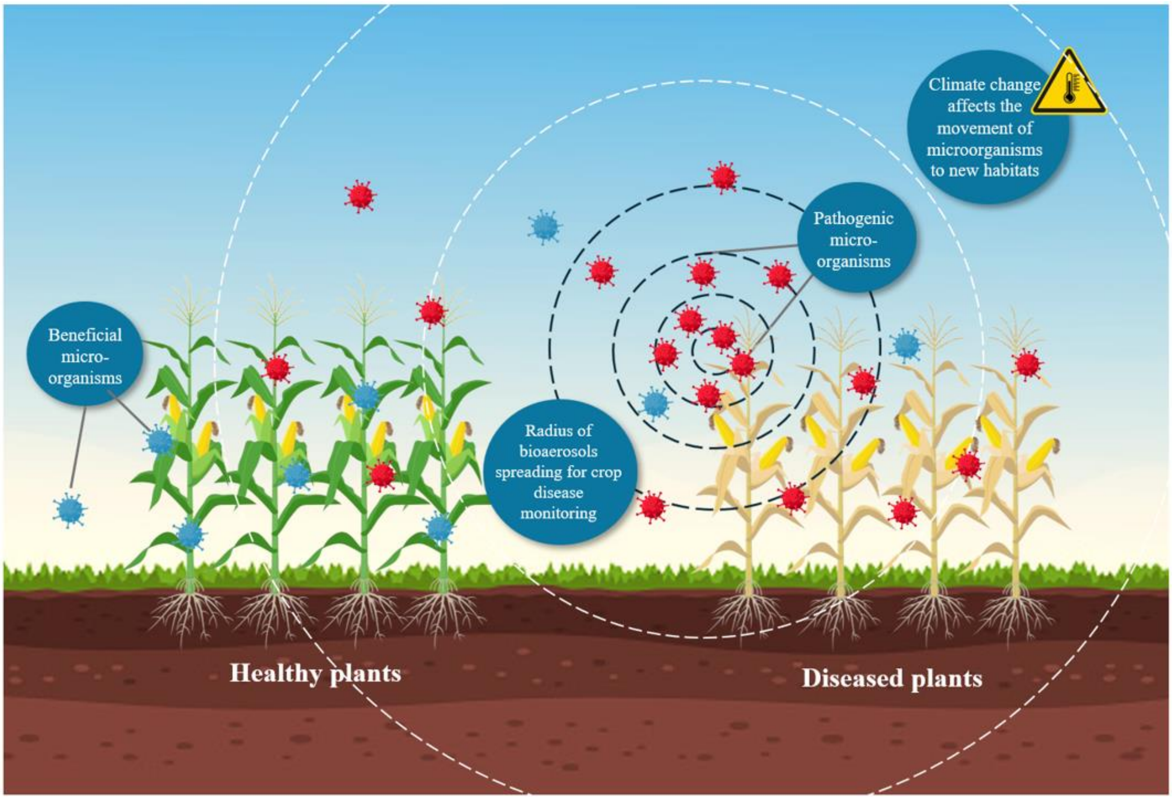

Figure 4. Radius of bioaerosols' spread for monitoring crop disease, with healthy plants on the left being influenced by beneficial microorganisms and diseased plants on the right affected by pathogenic microorganisms.

Innovative air monitoring systems, such as the one patented by Maggio [182], offer new methods for detecting biological particles and pathogens through a specialized microorganism-additive bio-oxidation process. Unlike conventional monitoring techniques, this system not only captures airborne contaminants, including viruses such as SARS-CoV-2, but also utilizes a bio-oxidation mechanism to degrade them. The system has been successfully deployed in healthcare settings, including COVID-19 hospital departments in Milan, where it demonstrated efficacy in both air purification and biomonitoring. Its ability to provide near-real-time surveillance of biological particles makes it a valuable tool for early outbreak detection, enabling proactive public health interventions before widespread transmission occurs. Furthermore, the integration of antigen test cassettes and biosensors allows for rapid, on-site detection, enhancing its utility in high-risk environments. Such systems can be applied in agriculture for early disease detection, potentially reducing economic losses and improving crop management. Developing bioaerosol-based surveillance systems is essential for effective disease control and maintaining economic stability in agriculture. It is crucial to understand the behavior, longevity, and transmission dynamics of bioaerosols to design targeted infection control strategies. Accurate risk information about bioaerosols can significantly enhance preventive measures and reduce the spread of airborne diseases.

7. Bioaerosol Collection Principles and Analysis Methods

Bioaerosol sampling is crucial for their investigation [183–186]. Patents for bioaerosol collection have been increasing since 1982, with a significant surge in 2022, reaching 203 methods (Figure 5), mainly due to the COVID-19 pandemic in 2019, which increased the urgency to study these particles. The designs of these sampling devices vary widely; for example, one system uses a box on a vehicle seat for automatic monitoring [184], while another employs atomizing nozzles, sterilization, and drying for accurate fluorescence analysis [183]. Generally, the primary objective is to extract a representative sample from the air for further analysis using specific techniques [185,186]. The aerodynamic diameter of particles, which indicates their size based on a density of 1 g/cm^3, is crucial for determining how particles move and are collected [187].

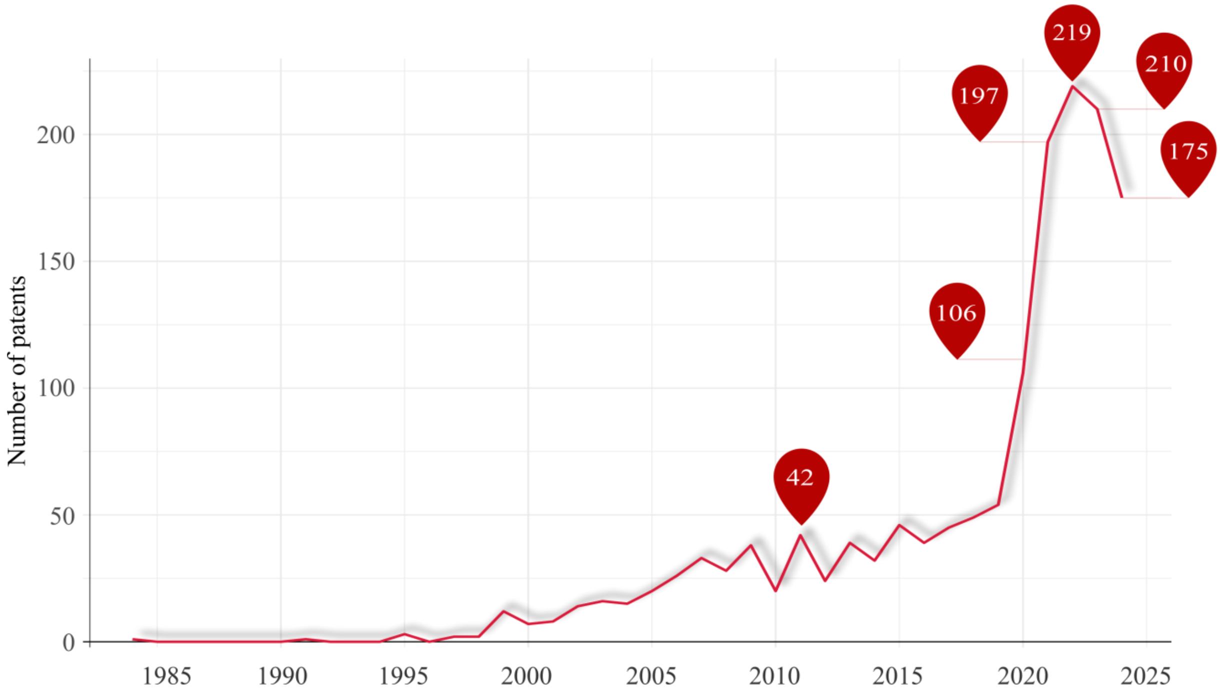

Figure 5. Patenting trend in methods and instruments for the collection and monitoring of bioaerosols in the air. Data were collected from the Espacenet (European Patent Office) database, covering patents related to bioaerosol collection and monitoring technologies. The dataset covers patents related to bioaerosol collection and monitoring technologies filed between 1984 and 2024. Patents were identified using the keyword "bioaerosol", with no exclusions applied. The trend over time was visualized using a line plot created with the ggplot2 R package (v3.5.0).

The collection of bioaerosols is performed using either passive or active methods [188]. Passive sampling, including gravity sedimentation and electrostatic collection, is typically used for larger particles (>5 µm) [185,189]. On the other hand, active sampling includes methods of collecting bioaerosols using devices that have specific pumps for the regulation of air amount [190]. This sampling method allows collection independently of the inertia and size of the particles; however, it is expensive and requires regular calibration [191].

There is a high number of sampling instruments for bioaerosols, but the main ones include filters, cyclones, impingers, impactors, and electrostatic precipitators [188]. Each of these sampling methods possesses distinct advantages and limitations, which are presented in Tables 2 and 3.

Choosing the appropriate sampling instrument and method should be should take into consideration the efficiency of the method, size of particles of interest, and the type of analysis to be conducted [66] (refer to Table 4). Filters are the most cost-effective and commonly used method for long-term bioaerosol monitoring [193], particularly in large outdoor areas. They are especially useful for continuous sampling over extended periods, but they can cause desiccation of collected particles, sample loss during elution, damage to microorganism structure, and contamination from non-biological particles. They are ideal for large-scale and long-term bioaerosol monitoring but are less effective for capturing smaller particles [185]. Impinger samplers are well-suited for environments with high pathogen concentrations, particularly in agricultural settings [202]. They allow for microbial analysis, especially when dilution of the sample is necessary, though their efficiency can decrease with prolonged sampling due to evaporation of the liquid medium, and they can be costly and require sterilization [203]. Impactors are beneficial for collecting bioaerosols in environments with a wide range of particle sizes, offering precise sampling for both culture-based and culture-independent methods. However, they may cause damage to sensitive microorganisms due to the high airflow speed, and their efficiency can decrease with particle size variations [204]. Cyclonic samplers provide high-efficiency collection for a broad range of particle sizes. They are suitable for both culture-based and culture-independent analysis, but their efficiency can be impacted by high concentrations of bioaerosols and water evaporation and require frequent maintenance [192]. Electrostatic precipitators are a cost-effective choice for rapid, large-scale bioaerosol monitoring in both indoor and outdoor environments. They are especially useful for detecting airborne pathogens over large areas and extended periods, but the production of ozone can interfere with sample collection and analysis, limiting their field applicability [205].

Table 2. Advantages and disadvantages of instruments used in bioaerosol sampling.

Method	Sampling Instrument	Advantages	Disadvantages	References
Passive	Agar settle plates	- Low-cost.	- Short sampling time.	[189]
	Petri dish	- Sterile collection; - Direct culturing.	- Identifies only viable, culturable microbes; - Growth is limited by culture conditions.	[30,191]
	Durham-type passive spore trap	- Protective cover during long sampling times.	- Microscopy-only design constraints.	[191,192]
	Filter	- Simple structure; - Cost-effective.	- Difficulties in recovering microorganisms on the filter; - Long sampling times can cause the microorganisms to dry out.	[193,194]
	Electrostatic precipitators	- Minimized microorganism damage; - Lower impaction stress; - Lower pressure drops.	- Problems with viability because of ozone generation.	[185,192]
Active	Impingers	- Reduce physical stress on microorganisms; - Prevent loss.	- Require sterilization; - Evaporation issue.	[195]
	Impactors	- Inexpensive; - Easy to use.	- Low microbial adherence, meaning less viability and efficiency.	[196,197]
	Cyclones	- Effective for long sampling periods; - Reduced particle bounce.	- Samples with lower quality samples; - Sample loss.	[20,196]

Table 3. Key specifications of bioaerosol sampling instruments.

Sampling Method	Filter Samplers	Impingers	Impaction Samplers	Cyclones	Electrostatic Precipitators	References
Multi-environmental	✓	✓	✓	✓	✓	[195,198]
Ease of use	✓	✓	✓	✓	✘	[192,195,199]
Cost effectiveness	✓	✘	✓	✘	✓	[192,200]
Maintenance	✓	✘	✘	✘	✓	[192,195]
Real-time monitoring	✘	✓	✘	✘	✓	[192,201]

Promising instruments in this field are also drones with sensors connected to a sampling instrument. They can be useful for providing meteorological data while simultaneously detecting zones with higher particle concentrations. Such an experiment was applied by Bieber et al. [206], who developed a drone-based aerosol particle sampling system to collect biological ice nucleation particles at low altitudes. This approach shows promising results for studying bioaerosol transport and emissions from natural sources.

Analysis methods for bioaerosols are categorized into conventional methods and advanced methods [20]. Among these, the most used methods remain culture methods, i.e., PCR and NGS [196]. Culture-based methods enable the analysis of living organisms, have low costs, but are time-consuming. In contrast to this, PCR offers rapid results with a simple technique. One of its advantages is its high specificity and sensitivity, detecting species even in very low concentrations. Currently, advanced methods are being used mostly, particularly NGS, which offers high sensitivity and specificity. Details about each analysis method are given in Table 5.

Table 4. Summary of different bioaerosol sampling methods.

Sampling Method	Filter Samplers	Liquid-Based Samplers (Impingers)	Impaction Samplers	Cyclones	Electrostatic Precipitators
Filtration Technique	Inertial forces, resistance forces, diffusion forces, and electrostatic attraction forces are responsible for collecting particles on a filter surface [194].	Use inertia for separating air particles into a liquid collection medium [185].	Inertial forces pull air through the perforated sampling head, and as air changes direction, microbes are collected on a Petri dish due to their inertia [207].	Bioaerosol capturing into a liquid system using centrifugal force [196].	Particles are collected through an electrostatic charge and deposited in a collection medium [185].
Air Volume Processed *	From 1 to 50 L/min [194]	12.5 L/min [208]	20–80 L/min [209]	100–1250 L/min [210]	75 L/min [211]
Particle Size	From 0.01 to 10 mm [194]	0.30–8 µm [212]	<2.5 µm [213]	From 1.7 to 9.8 µm [210]	From 30 nm to 10 mm [214]
Collection efficiency **	>93% [215]	80–90% [216]	<70% [217]	50–90% [218]	>80% [211]
Availability	Europe and USA [219]	USA [220]	USA and Europe [221]	USA [222]	Asia [223]

* Air volume processed refers to the volume of air that is sampled and processed by the bio sampler device.
** Collection efficiency refers to the ability of a sampler to capture and efficiently collect particulate matter or substances from the air.

Table 5. Comparison of conventional and advanced methods for bioaerosol analysis.

Category	Method		Advantages	Disadvantages	References
Conventional	Culture-Based Methods		- Low cost; - Enables analysis of living organisms; - Simple to operate.	- Time-consuming; - Cannot detect non-culturable organisms.	[20,224]
	PCR *		- Rapid; High sensitivity; Detects low concentrations.	- May require expensive equipment; - Cannot differentiate between live/dead organisms.	[20,224]
Advanced	Fluorescence Detection (Epifluorescence microscopy and Flow cytometry)		- Fast; Real-time detection; Non-destructive analysis; - Uses different fluorochromes for cell viability and activity.	- Limited to specific fluorescent markers.	[20,225]
	Mass Spectrometry (MALDI-TOF **)		- Highly sensitive; Identifies molecular composition.	- Expensive equipment; - Requires technical expertise; - Limited to larger molecules (>600 Da).	[20,225]
	ATP Bioluminescence		- Rapid; - Measures metabolic activity.	- Cannot differentiate between microbial species.	[20]
	NGS *** (high-throughput sequencing)	rRNA sequencing	- High sensitivity and specificity; - Bacterial and fungal sequencing.	- High cost; - Complex data interpretation.	[20,224]
		Shotgun sequencing	- High sensitivity and specificity; - Effective method for assessing microbial diversity and metabolic functions.		

* PCR—polymerase chain reaction. ** MALDI-TOF—matrix-assisted laser desorption/ionization time of flight. *** NGS—next-generation sequencing

8. Current Challenges in Bioaerosol Studies

Bioaerosols are an important topic when discussing preventing the transmission of airborne diseases, although their detection is quite difficult. Their challenging nature is due to their composition, which can include nonliving material and living organisms that current methods struggle to differentiate accurately. Current methods struggle with these distinctions, and inconsistent collection techniques often fail to account for size and mass criteria, leading to inaccurate counts of live pathogens [226]. Therefore, selecting the appropriate sampling technique is crucial, especially given the wide range of available samplers, each with its own mechanism, medium, and performance [185]. To overcome these challenges, recent advancements in artificial intelligence (AI) and remote sensing technologies offer significant promise in enhancing bioaerosol monitoring and detection. AI-driven models can analyze complex environmental data to predict bioaerosol concentrations, thereby improving early detection of airborne pathogens. For example, machine learning models have been developed to predict indoor airborne fungal concentrations using environmental variables, demonstrating the potential of AI to improve air quality management [227]. Additionally, innovations in real-time bioaerosol monitoring techniques, such as light-induced fluorescence-based instruments, allow for continuous detection and characterization of bioaerosol emissions, providing high-resolution data critical for proactive disease management [228]. These technological advancements not only enhance the accuracy and efficiency of bioaerosol detection but also support predictive modeling and targeted interventions, contributing to improved environmental health and agricultural productivity.

The low concentration of bioaerosols presents a significant challenge for sampling, requiring extended sampling times and high rates to capture sufficient material. Exploring microbial dynamics across land, water, and air ecosystems demands specialized sampling and analytical methods due to the substantial variations in biomass densities. There is no standardized method or instrument for their collection in different environments; therefore, it is challenging to choose the appropriate method. Ultralow biomass bioaerosol analyses are particularly important, as they allow for rapid sampling—from months to just hours or minutes—and enable early detection of disease-causing agents, supporting proactive disease management and higher crop yields. In terms of this, real-time PCR is commonly employed to detect specific pathogens in air samples, even at low concentrations, by amplifying their DNA [229]. High-efficiency aerosol samplers, such as the Andersen Cascade Impactor, are also used to collect bioaerosols from air, enabling the identification of microorganisms at very low biomass levels [230]. Additionally, optical particle counters and light-scattering devices allow for rapid, continuous monitoring of airborne particles, which can be coupled with molecular techniques for more precise analysis [226,227,231]. Such methods facilitate the early detection of disease-causing agents in agricultural settings, supporting proactive management strategies that can mitigate crop diseases and promote higher yields. Moreover, these analyses provide precise data on the air microbiome surrounding crops, informing precision agriculture techniques like targeted pesticide application and irrigation. Additionally, they help maintain ecosystem balance by preserving beneficial microorganisms, contributing to biodiversity preservation in agricultural landscapes. Recent advancements have also improved metagenomics, reduced gene amplification biases, and enhanced taxonomy accuracy through the combination of high-flow air samplers and next-generation sequencing technologies [232].

Given the significance of bioaerosols in environmental health and human well-being, developing specialized samplers for distinct environmental factors is crucial. Collaboration with the analytical community will further progress in bioaerosol research and the development of accurate analytical tools [185].

9. Conclusions

The presence of bioaerosols is evident in different environments; therefore, expanding the knowledge about their sources and transport mechanisms is crucial. Their influence is extremely significant in animal health, human health, and agriculture, especially in relation to food security. By forecasting air biomes, we can enhance the surveillance of agricultural areas for pathogens affecting crops. This proactive approach could help reduce reliance on agrochemicals, which pose risks due to their residues in final products. Predictive models are essential for farmers to prevent or manage disease outbreaks, thereby supporting sustainable agriculture and global food security. Research into the volatile substances involved in triangular communication—microbes–microbes, microbes–plants, and plants–plants—can be highly beneficial. While significant progress has been made in bioaerosol research, many gaps remain, particularly regarding their distribution, transport, and movement between crops. Future studies should focus on VOCs and BVCs to gain insights into the microbial atmosphere surrounding crops. Additionally, adopting a One Health approach, which integrates human, animal, and environmental health, is vital for addressing these issues comprehensively. Bioaerosols also play a critical role in spreading antimicrobial-resistant genes, highlighting their importance in public health. The lack of standardized methods for bioaerosol sampling further complicates research and calls for the development of universal protocols to advance this field.

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