PUBLIC HEALTH SIGNIFICANCE OF AIRBORNE BACTERIAL ISOLATES FROM STUDENT'S RESIDENCIAL RESIDENCE.

BY

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DEPARTMENT OF MICROBIOLOGY

FACULTY OF LIFE SCIENCES

UNIVERSITY OF BENIN

BENIN CITY

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A RESEARCH PROJECT SUBMITTED TO THE DEPARTMENT OF MICROBIOLOGY, FACULTY OF LIFE SCIENCES, UNIVERSITY OF BENIN, BENIN CITY, IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF DEGREE OF B. sc (HONS) IN MICROBIOLOGY, UNIVERSITY OF BENIN, BENIN CITY.

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CERTIFICATION

This is to certify that this project work was carried out by Joy Chinazaekpere MBA, in the department of microbiology, faculty of life sciences, university of benin, benin city under my supervision.

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Head of department	

DEDICATION

This project work is dedicated to God almighty, for bringing me this far. And also, to my parents, Mr Ephraim and Mrs Siena Mba, for their love, guidance and support. I am truly grateful.

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ABSTRACT

Airborne bacterial contamination in student residential areas poses significant public health risks, particularly in densely populated university settings. This study evaluated the microbial quality of air in two student hostels, Ekosodin and Osasogie, at the University of Benin, Edo State, Nigeria, over a three-week period. Air samples were collected and analyzed for total bacterial counts, cultural and biochemical characteristics, distribution patterns, frequency of occurrence, and antibiotic susceptibility profiles. The results revealed that Ekosodin generally exhibited higher bacterial loads, peaking at $5.4 \pm 0.35 \times 10^3$ CFU/m³ during Week 2, whereas Osasogie recorded the lowest load of $2.1 \pm 0.20 \times 10^3$ CFU/m³ in Week 3. Six bacterial species were isolated: *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella* sp., *Proteus* sp., *Pseudomonas aeruginosa* and *Bacillus* sp. *E. coli* (25%) and *S. aureus* (20%) were the most frequently occurring isolates. Antibiotic susceptibility testing revealed that fluoroquinolones (ciprofloxacin and pefloxacin) and aminoglycosides (gentamicin and streptomycin) were the most effective against the isolates, while beta-lactams (ampicillin and amoxicillin) and cotrimoxazole showed widespread resistance. The Multiple Antibiotic Resistance (MAR) indices ranged from 0.00 (*Bacillus* sp.) to 0.40 (*Pseudomonas aeruginosa*), highlighting the presence of multidrug-resistant bacteria in the residential air. These findings underscore the need for improved ventilation, hygiene, and routine microbial monitoring in student residential facilities to mitigate the risks of airborne bacterial infections.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Air is one of the most vital components of the environment, sustaining life by providing oxygen for respiration (Aversa *et al*., 2016). However, beyond its essential role in human survival, air also serves as a medium for the transmission of biological and chemical contaminants, including microorganisms (Kumar *et al*., 2021). The study of airborne microorganisms, commonly referred to as aeromicrobiology, has gained considerable attention due to its relevance in environmental health, epidemiology, and infection control (Douwes *et al*., 2003). Airborne bacteria, in particular, pose significant risks to human health, especially in indoor environments where individuals spend a substantial portion of their time (Prussin and Marr, 2015; Chawla *et al*., 2023).

Historically, airborne transmission of disease has been implicated in several devastating outbreaks. For instance, tuberculosis, a disease caused by *Mycobacterium tuberculosis*, continues to spread primarily through airborne droplets and remains a leading cause of morbidity and mortality globally (WHO, 2021). Similarly, outbreaks of meningococcal meningitis in Africa's "meningitis belt," which includes northern Nigeria, highlight the significance of airborne pathogens such as *Neisseria meningitidis* in epidemic-prone regions (Greenwood, 2006). The COVID-19 pandemic further reinforced global awareness of airborne transmission pathways, demonstrating how confined and crowded indoor environments amplify disease spread (Morawska and Cao, 2020). These historical and contemporary examples underscore the importance of investigating airborne bacteria, particularly in environments where people live in close proximity.

Indoor air quality has emerged as a pressing public health concern, as modern lifestyles dictate that individuals spend over 80% of their time indoors (Hospodsky *et al*., 2012). Unlike outdoor air, which is subject to constant dilution by atmospheric currents, indoor air often accumulates microorganisms due to restricted ventilation, human activity, and the resuspension of settled dust particles (Gandolfi *et al*., 2013). Factors such as poor sanitation, overcrowding, and inadequate architectural design further exacerbate the microbial load of indoor environments (Rai e*et al*., 2021; Chawla *et al*., 2023). In student residences, these conditions are common, creating an environment conducive for the survival and dissemination of airborne microorganisms, including bacteria of medical importance.

Airborne bacteria in student hostels can originate from several sources: human occupants (skin, respiratory droplets, hair, and clothing), building materials, water-damaged structures, and surrounding environmental inputs (Fang *et al*., 2007). Students frequently interact in shared spaces such as bedrooms, bathrooms, kitchens, and common rooms, which enhances microbial exchange. Pathogenic bacteria like *Staphylococcus aureus*, *Streptococcus pneumoniae*, *Klebsiella pneumoniae*, and *Pseudomonas aeruginosa* are known to be present in indoor air and can cause diseases ranging from respiratory tract infections to systemic illnesses (Mandell *et al*., 2020; Hussain *et al*., 2022). Opportunistic bacteria may not immediately cause disease in healthy individuals but can pose significant risks to immunocompromised students, such as those with underlying medical conditions or malnutrition.

In Nigeria, the problem of poor indoor air quality is aggravated by infrastructural and socioeconomic challenges. Many student residences in Nigerian universities are characterized by overcrowding, poor ventilation, inadequate waste disposal systems, and insufficient maintenance. These conditions create reservoirs for airborne bacterial contamination, contributing to frequent

outbreaks of communicable diseases such as respiratory infections, diarrheal illnesses, and skin infections among students (Nwankwo *et al*., 2012). Studies conducted in Nigerian institutions have reported high bacterial loads in indoor air samples, with isolates including *Bacillus spp.*, *Staphylococcus spp.*, and coliform bacteria, reflecting both human and environmental contamination (Udu-Ibiam *et al*., 2016; Ozoaduche and Idemudia, 2021; Adebayo-Olajide and Olorunfunmi, 2022; Osaghae *et al*., 2025). Despite these findings, comprehensive investigations on airborne bacteria in student residences remain scarce, particularly in relation to their public health significance.

The public health relevance of airborne bacteria extends beyond immediate infection risks. A growing concern is the emergence and dissemination of antimicrobial resistance (AMR) among airborne bacterial populations. Air can act as a vehicle for the spread of resistant bacteria, facilitating the transfer of genetic resistance elements across microbial communities (Zhu *et al*., 2021; George *et al*., 2022). The implications of this are profound, especially in densely populated environments such as hostels, where resistant pathogens can spread rapidly among students, complicating treatment outcomes and increasing healthcare burdens.

Globally, institutions of higher learning are recognized as micro-ecosystems where environmental health factors directly influence the wellbeing of young adults. Poor air quality in student residences has been linked to absenteeism, reduced academic performance, and higher susceptibility to infectious diseases (Mendell *et al*., 2011). In developing countries such as Nigeria, where health infrastructure is already under strain, understanding the contribution of airborne bacteria to student morbidity is critical for designing cost-effective public health interventions.

1.2 Statement of the Problem

The risk of airborne transmission of infectious diseases has gained renewed global attention, especially following outbreaks of respiratory illnesses such as COVID-19, tuberculosis, and influenza, all of which highlight the role of bioaerosols in disease spread. In student residential residences, poor ventilation systems, overcrowding, and unhygienic conditions create a favorable environment for the persistence and transmission of airborne bacteria. Despite the health risks, limited studies have been conducted in Nigeria and other parts of Africa to comprehensively characterize airborne bacteria in student living environments. The absence of such data hampers effective risk assessment and control measures, leaving students vulnerable to preventable infections.

1.3 Aim and Objectives

The primary aim of this study was to investigate the public health significance of airborne bacterial isolates from student residential residences.

The specific objectives of this study were to:

1. Enumerate, isolate and identify bacterial isolates present in indoor air of student residential residences.
2. Determine the antimicrobial susceptibility patterns of the bacteria isolates.
3. Evaluate the public health implications of the identified airborne bacteria isolates in relation to student health.

CHAPTER TWO

LITERATURE REVIEW

2.1 Concept of Aeromicrobiology

Aeromicrobiology is a branch of microbiology that deals with the study of microorganisms suspended in the atmosphere and their interactions with the environment and living organisms. It specifically focuses on bioaerosols, which are airborne particles of biological origin that may consist of bacteria, viruses, fungi, spores, microbial fragments, or toxins (Cox and Wathes, 1995). These bioaerosols can be generated through natural processes such as wind erosion, rainfall impact on soil, ocean spray, and plant emissions, or through anthropogenic activities including human respiration, coughing, sneezing, industrial processes, and poor sanitation (Eduard, 2009).

The scope of aeromicrobiology is broad and multidisciplinary, covering areas such as microbial ecology**,** environmental monitoring**,** epidemiology**,** occupational health and public health microbiology. It extends to understanding the survival, transport, and dispersion of airborne microorganisms, as well as their role in infectious disease transmission, allergenicity, and antimicrobial resistance (Franzetti *et al*., 2011). Aeromicrobiology also intersects with applied sciences, playing a key role in fields like hospital infection control, food safety, indoor air quality assessment, and biodefense. Importantly, the discipline is particularly relevant to environments where humans spend significant amounts of time indoors, such as student residential hostels, libraries, classrooms, and healthcare facilities.

By investigating the microbial composition of air, aeromicrobiology provides insights into potential health risks and supports the development of strategies to mitigate the spread of airborne pathogens. In essence, the discipline is not only concerned with identifying

microorganisms in the air but also with understanding their impact on human health, ecosystems, and global health security.

2.1.2. Historical Perspectives on Airborne Microorganisms

The recognition of air as a medium of disease transmission has a long and evolving history. In antiquity, the miasma theory dominated medical thought, suggesting that foul-smelling "bad air" or vapors from decaying matter were responsible for spreading diseases such as plague and cholera. Although the theory was later disproven, it provided early clues linking air quality with health outcomes (Baldwin, 1999).

A turning point came in the 19th century with the work of Louis Pasteur**,** who demonstrated that microorganisms were present in the air and played a role in fermentation and spoilage. His famous swan-neck flask experiment showed that air carried microscopic life capable of contaminating sterile broth, thereby refuting spontaneous generation and advancing the germ theory of disease (Pasteur, 1861). Building on Pasteur's findings, Robert Koch isolated disease-causing bacteria such as *Mycobacterium tuberculosis*, establishing a direct link between airborne microorganisms and human disease (Koch, 1884).

Further contributions came from early aerobiologists such as Miquel (1883)**,** who measured airborne microbes in Paris, and Duguid (1946)**,** who studied droplet transmission of bacteria, thereby advancing our understanding of how diseases spread through coughing and sneezing. By the mid-20th century, research on airborne transmission expanded to include viruses and fungal spores, especially in the context of influenza pandemics and occupational diseases.

In contemporary times, the emergence and re-emergence of infectious diseases have renewed focus on airborne transmission. Epidemics such as uberculosis **t**in sub-Saharan Africa, SARS in

2003, influenza A (H1N1) in 2009, and the COVID-19 pandemic in 2019 have highlighted the role of aerosols in spreading pathogens (Morawska and Cao, 2020). These events emphasized that air is not just a passive medium but an active vehicle for transmitting microbes across populations and geographies. As a result, aeromicrobiology is now central to global health security, with implications for pandemic preparedness, antimicrobial resistance monitoring, and environmental microbiology.

2.1.2. Importance of Studying Airborne Bacteria

The study of airborne bacteria is of profound significance due to their diverse implications for human health, environmental safety, and the development of effective public health policies. Airborne bacteria have long been recognized as critical agents in the transmission of infectious diseases. Pathogens such as *Mycobacterium tuberculosis*, *Streptococcus pneumoniae*, *Staphylococcus aureus*, and *Neisseria meningitidis* are capable of spreading through aerosols and droplets, leading to illnesses including tuberculosis, pneumonia, meningitis, and skin infections (Mandell *et al*., 2020; WHO, 2021). In communal living environments such as student residences, where overcrowding, close interpersonal contact, and inadequate ventilation are common, the risk of airborne bacterial transmission is significantly heightened, creating conditions that facilitate outbreaks of communicable diseases.

In addition to their role in disease transmission, airborne bacteria exert a considerable influence on indoor air quality. This issue has become increasingly relevant in contemporary times, as individuals spend the majority of their daily lives in enclosed spaces. Poor indoor air quality has been associated with a range of adverse health outcomes, including respiratory tract infections, exacerbation of asthma, allergic reactions, and conditions often described collectively as sick building syndrome (Hospodsky *et al*., 2012). Unlike outdoor air, which benefits from natural

dilution and circulation, indoor environments tend to accumulate bacterial loads due to limited ventilation and high human occupancy. As a result, the monitoring of indoor air quality is a crucial public health priority for protecting the well-being of occupants.

Airborne bacteria are also of importance in the context of antimicrobial resistance (AMR), which represents one of the most pressing global health challenges of the 21st century. Recent investigations have revealed that both antibiotic-resistant bacteria and resistance genes can be present in bioaerosols, particularly in settings such as hospitals, animal farms, and densely populated communities (Li *et al*., 2018). The circulation of resistant bacteria in the atmosphere complicates infection control measures and undermines the efficacy of conventional antibiotics, thereby posing a substantial threat to treatment outcomes. This highlights the need for aeromicrobiological studies as part of global surveillance strategies for AMR.

Beyond clinical implications, airborne bacteria also play a role in environmental and occupational health. Workers in occupations involving waste management, agriculture, food production, and healthcare are frequently exposed to high concentrations of bioaerosols, predisposing them to both respiratory and systemic infections (Douwes *et al*., 2003). Such occupational exposures underscore the necessity of establishing safety standards, protective measures, and monitoring frameworks that address airborne microbial risks.

Furthermore, the study of airborne bacteria provides the scientific foundation upon which public health interventions and policy frameworks are built. Research in aeromicrobiology informs the development of strategies such as improved ventilation designs, routine environmental monitoring, effective disinfection protocols, and awareness campaigns. In student residences,

where communal living is unavoidable, such interventions can be critical for safeguarding student health and reducing the burden of airborne infectious diseases.

2.2 Sources and Characteristics of Airborne Bacteria

Airborne bacteria are ubiquitous microorganisms that can be released into the atmosphere from a wide range of sources and can persist in the air for variable periods depending on environmental conditions. Their origin, survival mechanisms, and dispersal capacities are strongly influenced by both natural and anthropogenic activities, as well as by meteorological and physicochemical factors in the atmosphere. Understanding the sources and characteristics of airborne bacteria is critical in the context of public health, environmental monitoring, and epidemiological control.

2.2.1 Natural Sources of Airborne Bacteria

Natural environments represent major reservoirs of airborne bacteria. Soil is one of the most significant contributors, as disturbance of soil particles by wind, agricultural activities, or animal movement releases bacteria into the air. Soil is known to harbor diverse microbial communities, including species of *Bacillus*, *Streptomyces*, and *Clostridium*, many of which can form spores that are resistant to desiccation and can remain airborne for extended periods (Burrows *et al*., 2009).

Water bodies also contribute to airborne bacteria through processes such as bubble bursting, splashing, and wave action. Aerosolization of water droplets from oceans, lakes, and rivers introduces bacteria like *Pseudomonas*, *Vibrio*, and cyanobacteria into the air, which can be transported over long distances (Mayol *et al*., 2014). In addition, plants serve as natural reservoirs, releasing bacteria associated with leaves, flowers, and pollen. Leaf surfaces (phyllosphere) support diverse microbial populations, including *Pseudomonas syringae* and

Erwinia species, which may be aerosolized through wind or mechanical disturbances (Morris *et al*., 2014).

Animals also contribute significantly to airborne bacteria. Both wild and domesticated animals shed microorganisms through feces, skin, fur, and respiratory secretions, which can subsequently become aerosolized. Livestock farms, for example, are hotspots for airborne bacteria such as *Escherichia coli* and *Staphylococcus aureus*, which can pose zoonotic risks (Gibbs *et al*., 2006).

2.2.2 Anthropogenic Sources of Airborne Bacteria

Human activities significantly amplify the abundance and diversity of airborne bacteria. One of the most important anthropogenic sources is direct human emission. Humans continuously shed bacteria through breathing, talking, sneezing, coughing, and skin desquamation. Studies have shown that indoor environments with high human occupancy, such as classrooms, hospitals, and public transport, are strongly influenced by human-associated bacteria including *Staphylococcus epidermidis*, *Streptococcus mitis*, and *Corynebacterium* spp. (Qian *et al*., 2012).

Waste management practices, such as open dumpsites and wastewater treatment facilities, also release large amounts of bacteria into the air. Pathogens such as *Salmonella*, *Enterococcus*, and *Clostridium difficile* have been detected in bioaerosols near such sites (Niazi *et al*., 2015). Construction activities and industrial processes are additional anthropogenic contributors, as they disturb contaminated soil, dust, and building materials, thereby liberating bacteria into the air.

Crowding in enclosed spaces, such as schools, offices, or markets, significantly increases airborne bacterial load due to enhanced human-to-human transmission and poor ventilation. Similarly, transportation systems like buses, trains, and airplanes often act as confined environments where bacterial concentrations can be elevated (Hospodsky *et al*., 2012).

2.2.3 Survival and Dispersal Mechanisms of Airborne Bacteria

Once released into the atmosphere, bacteria employ various survival and dispersal mechanisms. Many species form spores or enter a viable but non-culturable (VBNC) state, which allows them to persist in adverse atmospheric conditions (Setlow, 2014). Gram-positive bacteria, such as *Bacillus* and *Clostridium*, are particularly resilient due to their thick cell walls and spore-forming abilities, while some Gram-negative bacteria may produce extracellular polymeric substances that confer protection against desiccation and UV radiation. Dispersal occurs through wind currents, turbulence, and convection, enabling bacteria to travel locally and globally. Long-distance transport of bacteria has been documented, with viable cells detected thousands of kilometers from their point of origin (Smith *et al*., 2013). Bioaerosols may attach to dust particles, water droplets, or organic matter, which act as carriers enhancing their stability and dispersal in the atmosphere.

2.2.4 Factors Influencing the Survival of Airborne Bacteria

The survival of airborne bacteria is not static but rather dependent on a dynamic interplay of environmental and physicochemical factors. Once liberated into the air, bacterial cells are immediately exposed to a range of stresses, including desiccation, radiation, and oxidative stress, which can compromise their viability. However, certain environmental conditions may either mitigate or exacerbate these stresses, thereby determining whether bacterial cells persist, lose viability, or adapt through protective mechanisms. Among the most important factors are humidity, temperature, ultraviolet radiation, ventilation, and particulate matter.

2.2.4.1 Humidity

Relative humidity (RH) exerts a profound influence on bacterial viability in aerosols. High humidity levels (>70%) generally favor the survival of Gram-negative bacteria such as

Escherichia coli and *Pseudomonas aeruginosa*, because the outer membrane of Gram-negative organisms provides some protection against osmotic stress in moist conditions (Tang, 2009). Conversely, low humidity environments (<30%) are often more favorable for Gram-positive bacteria, particularly spore-formers like *Bacillus* and *Clostridium*, which are adapted to resist desiccation due to their thick peptidoglycan walls and spore structures (Cox, 2010).

The relationship between humidity and bacterial survival is also influenced by droplet size. Small droplets evaporate quickly in low-humidity conditions, leaving behind desiccated residues that may preserve bacteria in a dormant or viable-but-non-culturable (VBNC) state. In contrast, at higher humidity, larger droplets persist longer, allowing active metabolic processes but also increasing susceptibility to predation by other microbes and chemical stress (Yang and Marr, 2012). Thus, humidity acts as both a stressor and a stabilizer, depending on the bacterial species and aerosol microenvironment.

2.2.4.2 Temperature

Temperature fluctuations in the atmosphere are another critical determinant of bacterial persistence. Moderate temperatures (15–25 °C) often support optimal survival, while extremes in heat or cold tend to reduce viability (Griffin, 2007). At high temperatures, proteins denature, membrane integrity is disrupted, and enzymatic activity ceases, leading to rapid inactivation of sensitive organisms. Conversely, cold temperatures may induce freezing or cause ice crystal formation, which mechanically damages bacterial cell membranes.

Nonetheless, some microorganisms exhibit adaptations to extreme conditions. Thermotolerant bacteria such as *Bacillus stearothermophilus* can withstand higher temperatures, while psychrotolerant bacteria like *Psychrobacter* species may survive in cold, high-altitude air masses

(Amato *et al*., 2007). Temperature also interacts with humidity, as warmer air holds more moisture, indirectly influencing bacterial survival. Importantly, seasonal variations in temperature contribute to the observed seasonality of certain airborne diseases, with bacterial infections tending to peak in cooler, drier conditions (Morawska, 2006).

2.2.4.3 Ultraviolet (UV) Light

Solar ultraviolet radiation is one of the most potent natural disinfectants in the atmosphere. UV radiation, particularly UV-B and UV-C wavelengths, induces DNA strand breaks, thymine dimer formation, and oxidative stress, ultimately leading to cell death (Häder *et al*., 2015). Studies have demonstrated that bacteria exposed to direct sunlight may lose culturability within minutes to hours, depending on the intensity of radiation (Krumins *et al*., 2014).

Nevertheless, some bacteria have evolved protective mechanisms. Pigment production, such as carotenoids in *Micrococcus luteus*, can shield cells by absorbing harmful radiation. Others produce antioxidants like superoxide dismutase and catalase to counteract oxidative stress. Spore-forming bacteria like *Bacillus subtilis* are exceptionally resistant to UV due to the presence of small acid-soluble proteins (SASPs) that bind and protect DNA (Setlow, 2014). Additionally, bacteria embedded in particulate matter or organic material may be physically shielded from direct UV exposure, prolonging their atmospheric persistence.

2.2.4.4 Ventilation

In enclosed environments, ventilation plays a decisive role in shaping bacterial concentrations. Adequate ventilation reduces the risk of bacterial accumulation by diluting contaminated indoor air with outdoor air, thereby lowering exposure risks (Qian *et al*., 2012). Conversely, poorly ventilated spaces create microenvironments where airborne bacteria can build up to levels

sufficient to increase the risk of transmission, particularly in high-occupancy areas such as classrooms, hospitals, or public transport (Hospodsky *et al*., 2012).

Ventilation systems, however, may act as both mitigators and amplifiers of bacterial spread. While mechanical ventilation can filter and remove contaminants, poorly maintained systems may become reservoirs themselves, harboring biofilms that release bacteria into recirculated air. Airflow dynamics, such as turbulence and directionality, further influence the spatial distribution of airborne bacteria, with stagnant zones in poorly designed systems allowing bacterial concentrations to rise (Zhao *et al*., 2020).

2.2.4.5 Particulate Matter (PM)

Particulate matter in the atmosphere serves as both a vehicle and a shield for airborne bacteria. Bacteria often attach to dust particles, organic debris, or droplets, which can protect them from desiccation and UV exposure (Després *et al*., 2012). This attachment not only prolongs bacterial survival but also facilitates long-range transport by enabling microorganisms to travel with suspended particles over hundreds or thousands of kilometers.

Particle size is particularly important in determining the health risks associated with bioaerosols. Fine particles (PM2.5; <2.5 μm) can penetrate deep into the alveoli of the lungs, delivering viable bacteria directly into the lower respiratory tract (Wang *et al*., 2020). Coarser particles (PM10; <10 μm) generally deposit in the upper airways but can still act as carriers for pathogenic organisms. Moreover, particulate matter often contains nutrients and organic compounds that may serve as substrates for bacterial metabolism, thereby enhancing survival during atmospheric transport. The interaction between particulate matter and bacteria also has climate implications. Bioaerosols can influence cloud formation by acting as cloud condensation

nuclei (CCN) or ice-nucleating particles, thereby linking microbial survival to atmospheric processes on a global scale (Morris *et al*., 2014).

2.3 Indoor Air Quality and Public Health

Indoor air quality (IAQ) has emerged as an important determinant of human health, particularly in urbanized and developing environments where individuals spend a significant proportion of their time indoors. Unlike outdoor air, which is influenced by large-scale environmental processes such as wind currents, ultraviolet radiation, and natural dilution, indoor air is often more confined, less ventilated, and enriched with human activities that facilitate microbial accumulation and survival (Douwes *et al*., 2003; Ghosh *et al*., 2015). Microorganisms suspended in indoor air, especially bacteria and fungi, can have significant implications for public health, contributing to both acute and chronic infections, allergic reactions, and in some cases, the spread of antimicrobial resistance within communities (Mandal and Brandl, 2011).

2.3.1 Indoor versus Outdoor Air Microbial Composition

The microbial composition of indoor air differs significantly from that of outdoor air. Outdoor air contains microorganisms originating from soil, plants, animals, and water bodies, and is generally more diverse due to continuous mixing with the external environment (Adams *et al*., 2013). Conversely, indoor air is shaped by human occupancy, ventilation systems, building materials, and indoor activities such as cooking, cleaning, and use of appliances (Kembel *et al*., 2012).

Studies have demonstrated that indoor air harbors higher concentrations of bacteria closely associated with the human microbiome, including species of *Staphylococcus*, *Streptococcus*, and *Corynebacterium* (Meadow *et al*., 2014). These organisms often originate from human skin,

respiratory secretions, and clothing. In contrast, outdoor air is dominated by environmental bacteria such as *Pseudomonas*, *Bacillus*, and *Actinobacteria*, which are less pathogenic to humans (Hospodsky *et al*., 2012). The balance between outdoor and indoor microbial composition depends largely on ventilation patterns. Naturally ventilated spaces may more closely resemble the outdoor microbial community, while poorly ventilated or mechanically controlled indoor environments tend to exhibit reduced microbial diversity but increased concentrations of human-associated microbes (Amann *et al*., 2014). This reduced microbial diversity in indoor spaces has been linked with higher risks of respiratory illnesses and allergic sensitization (Dannemiller *et al*., 2016).

2.3.2 Hostels, Dormitories, and Residential Environments as Hotspots for Airborne Bacterial Contamination

Hostels, dormitories, and similar residential environments represent important hotspots for microbial contamination due to their unique characteristics: high occupancy density, shared facilities, and prolonged human presence. Students and young adults who commonly reside in these facilities are frequently exposed to airborne microorganisms that originate from roommates, shared sanitation areas, and communal activities (Fisk, 2013).

Several studies have shown that bacterial concentrations in dormitories exceed those in other residential environments, primarily due to overcrowding, limited ventilation, and inconsistent cleaning practices (Qian *et al*., 2012). Common airborne bacterial genera identified in such environments include *Staphylococcus*, *Streptococcus*, and *Micrococcus*, many of which are opportunistic pathogens capable of causing skin infections, respiratory illnesses, and systemic infections in immunocompromised individuals (Kim *et al*., 2018). The risk is further compounded by behaviors common in these environments, such as drying laundry indoors, poor

waste management, and inadequate hand hygiene, which all increase microbial loads in the air (Cai *et al*., 2015). In tropical and humid regions, such as Nigeria, dormitories often lack adequate ventilation systems, leading to excessive heat and humidity that enhance microbial survival and persistence (Awosika *et al*., 2014).

From a public health perspective, these environments are potential hubs for the transmission of infectious diseases, particularly tuberculosis, influenza, and meningococcal meningitis, which spread efficiently in crowded, poorly ventilated settings (World Health Organization, 2010). Additionally, the presence of antibiotic-resistant bacteria in such environments raises further concern, as resistant organisms can spread rapidly within close-living communities (Otter *et al*., 2013). Thus, hostels and dormitories represent critical points of intervention in strategies to improve indoor air quality and safeguard public health. Regular monitoring, better ventilation, adoption of cleaning protocols, and public health education are necessary to mitigate microbial contamination and reduce health risks associated with indoor air exposure.

2.4. Public Health Significance of Airborne Bacteria

Airborne bacteria, dispersed through aerosols or droplets, pose significant public health challenges due to their role in disease transmission, impact on vulnerable populations, and contribution to antimicrobial resistance.

2.4.1 Role in Transmission of Respiratory Infections

Airborne bacteria are critical vectors in the transmission of respiratory infections such as tuberculosis (TB), pneumonia, and bacterial meningitis. These pathogens, including *Mycobacterium tuberculosis*, *Streptococcus pneumoniae*, and *Neisseria meningitidis*, are transmitted via respiratory droplets or aerosols generated through coughing, sneezing, or talking.

2.4.1.1. Tuberculosis

Tuberculosis, caused by *Mycobacterium tuberculosis*, is a leading airborne infectious disease. The bacteria are transmitted through droplet nuclei, which are small enough (<5 μm) to remain suspended in the air for extended periods and can be inhaled deep into the alveoli of the lungs. According to the World Health Organization (WHO), TB affected approximately 10 million people globally in 2020, with 1.5 million deaths (WHO, 2021). Crowded and poorly ventilated settings, such as prisons and homeless shelters, exacerbate transmission, making TB a significant public health concern in both developed and developing nations.

2.4.1.2. Pneumonia

Streptococcus pneumoniae is a major cause of community-acquired pneumonia, particularly in children and the elderly. The bacterium spreads through respiratory droplets, and its airborne transmission is facilitated in settings with close contact, such as schools and daycare centers. Studies estimate that pneumococcal pneumonia causes over 1.6 million deaths annually, predominantly in low-income countries (O'Brien *et al*., 2009). The ability of *S. pneumoniae* to colonize the nasopharynx and spread via aerosols underscores its public health significance.

2.4.1.3. Meningitis

Neisseria meningitidis, responsible for bacterial meningitis, is another airborne pathogen transmitted through respiratory secretions. Outbreaks are often reported in crowded environments, such as college dormitories and military barracks. The rapid onset and high mortality rate of meningococcal disease, with case fatality rates ranging from 10-15% even with treatment, highlight its public health importance (Cohn *et al*., 2013). Vaccination campaigns targeting meningococcal serogroups have reduced incidence, but airborne transmission remains a challenge in unvaccinated populations.

2.4.2 Association with Skin and Soft Tissue Infections

While airborne bacteria are primarily associated with respiratory infections, certain species can contribute to skin and soft tissue infections (SSTIs) through deposition on skin or wounds. *Staphylococcus aureus*, including methicillin-resistant *S. aureus* (MRSA), is a notable airborne pathogen linked to SSTIs.

Airborne transmission of *S. aureus* occurs in healthcare settings, where bacteria can settle on skin or open wounds, leading to infections such as cellulitis, abscesses, or surgical site infections. A study by Dancer (2008) found that *S. aureus* can be aerosolized during activities like bed-making in hospitals, contributing to nosocomial infections. Additionally, *Streptococcus pyogenes*, responsible for streptococcal skin infections like impetigo, can be transmitted via aerosols in crowded settings, further linking airborne bacteria to SSTIs. The public health implications are significant in healthcare facilities, where airborne *S. aureus* contributes to hospital-acquired infections. Infection control measures, such as improved ventilation and personal protective equipment, are critical to reducing transmission. Community settings, including schools and athletic facilities, also face challenges due to the potential for airborne bacteria to deposit on skin and cause outbreaks of SSTIs.

2.4.3 Impact on Immunocompromised Individuals

Immunocompromised individuals, including those with HIV/AIDS, cancer, or organ transplants, are particularly vulnerable to infections caused by airborne bacteria. Their weakened immune systems reduce their ability to combat pathogens, making even opportunistic bacteria like *Pseudomonas aeruginosa* or *Legionella pneumophila* life-threatening.

Legionella pneumophila, the causative agent of Legionnaires' disease, is transmitted through aerosols from contaminated water sources, such as cooling towers and air conditioning systems. Immunocompromised patients are at higher risk of severe outcomes, with mortality rates approaching 30% in hospitalized cases (Fraser *et al*., 1977). Similarly, *Pseudomonas aeruginosa* can be aerosolized in healthcare settings, posing a risk to patients with cystic fibrosis or those on ventilators. The susceptibility of immunocompromised individuals underscores the need for stringent environmental controls, such as air filtration and water system maintenance, to reduce exposure to airborne bacteria. Hospitals must implement high-efficiency particulate air (HEPA) filtration and regular Legionella testing to protect vulnerable populations. Public health campaigns targeting immunocompromised individuals also emphasize vaccination against preventable airborne pathogens like *S. pneumoniae*.

2.4.4 Allergic and Toxic Reactions Associated with Bacterial Bioaerosols

Bacterial bioaerosols, composed of whole bacteria, bacterial fragments, or endotoxins, can trigger allergic and toxic reactions in exposed individuals. Endotoxins, lipopolysaccharides found in the outer membrane of Gram-negative bacteria, are particularly potent in inducing inflammatory responses.

Exposure to bacterial bioaerosols is associated with allergic conditions such as asthma and allergic rhinitis. For example, *Actinomyces* and other environmental bacteria can trigger hypersensitivity pneumonitis in agricultural workers exposed to bioaerosols in barns or silos (Thorn, 2001). These allergic reactions result from the immune system's response to bacterial antigens, leading to symptoms like wheezing, coughing, and respiratory distress. Endotoxins from bacteria like *Escherichia coli* or *Pseudomonas* can cause toxic reactions, including fever, fatigue, and acute respiratory distress, particularly in occupational settings like wastewater

treatment plants. A study by Douwes *et al*. (2003) found that endotoxin exposure is linked to systemic inflammation and reduced lung function, posing risks to both healthy and sensitive populations. Public health strategies to mitigate these risks include workplace exposure limits for bioaerosols and the use of personal protective equipment in high-risk environments. Indoor air quality management, including proper ventilation and humidity control, is also critical to reducing bioaerosol-related health effects.

2.4.5 Contribution to Antimicrobial Resistance Spread

Airborne bacteria play a significant role in the dissemination of antimicrobial resistance (AMR), a growing global health crisis. Resistant bacteria, such as MRSA and multidrug-resistant *Mycobacterium tuberculosis* (MDR-TB), can be transmitted through aerosols, spreading resistance genes in both community and healthcare settings. Airborne transmission of resistant bacteria occurs in hospitals, where patients with resistant infections can aerosolize pathogens during coughing or medical procedures like intubation. A study by Roberts *et al*. (2012) demonstrated that MRSA can remain viable in aerosols for extended periods, facilitating its spread in healthcare environments. Similarly, MDR-TB poses a significant threat, with WHO estimating 480,000 new cases annually, driven partly by airborne transmission in high-burden regions (WHO, 2021). The spread of AMR via airborne bacteria complicates treatment and increases healthcare costs. Infection control measures, such as isolation rooms and negative-pressure ventilation, are essential to limit transmission. Additionally, public health efforts focus on antibiotic stewardship to reduce the selective pressure driving resistance and surveillance systems to track resistant strains in the environment.

Airborne bacteria pose multifaceted public health challenges, from their role in transmitting respiratory infections like TB, pneumonia, and meningitis to their contribution to SSTIs, severe

infections in immunocompromised individuals, allergic and toxic reactions, and the spread of antimicrobial resistance. Effective public health interventions, including improved ventilation, vaccination, infection control measures, and antibiotic stewardship, are essential to mitigate these risks. Continued research and surveillance are critical to understanding and addressing the evolving threat of airborne bacterial pathogens.

2.5. Epidemiology of Airborne Bacteria:

Airborne bacterial diseases, transmitted through aerosols, respiratory droplets, or dust particles, pose a significant global public health challenge. Pathogens such as *Mycobacterium tuberculosis*, *Legionella pneumophila*, and *Staphylococcus aureus* contribute to substantial morbidity and mortality, particularly in densely populated and resource-limited settings. The epidemiology of these diseases is shaped by environmental factors, human behavior, and socioeconomic conditions, with antimicrobial resistance (AMR) emerging as a critical threat.

2.5.1. Global Trends and Evidence of Airborne Bacterial Diseases

Airborne bacterial pathogens are a major contributor to the global burden of infectious diseases. According to the World Health Organization (WHO), tuberculosis (TB) affected approximately 10 million people and caused 1.5 million deaths in 2020, making it one of the leading airborne bacterial diseases worldwide (WHO, 2020). TB is particularly prevalent in low- and middle-income countries, where overcrowding, poor ventilation, and limited access to diagnostics exacerbate transmission. The emergence of multidrug-resistant TB (MDR-TB) has further complicated control efforts, with 206,030 cases reported globally in 2020, predominantly in Southeast Asia and sub-Saharan Africa (WHO, 2020).

Legionella pneumophila, the causative agent of Legionnaires' disease, is another significant airborne pathogen. It thrives in water systems and is aerosolized through showers, air conditioning units, and cooling towers, leading to severe pneumonia, especially in immunocompromised individuals. A study by Parr *et al*. (2015) highlighted the bacterium's resilience across a wide temperature range, noting its association with outbreaks in the United States and Europe. Similarly, *Staphylococcus aureus*, particularly methicillin-resistant strains (MRSA), is frequently detected in indoor air samples, contributing to nosocomial infections in healthcare settings. The 2022 Global Burden of Disease Study estimated that *S. aureus* was the leading bacterial cause of death in 135 countries, accounting for 23% of bloodstream infection deaths in high-income regions (GBD Collaborators, 2022).

Emerging trends also point to the role of environmental factors in the spread of airborne bacteria. Dust storms, particularly in arid regions, can transport pathogens like *Pseudomonas aeruginosa* and *Bacillus* species across continents, potentially introducing diseases to new regions (Gonzalez-Martin *et al*., 2014). Climate change and urbanization further amplify these risks by altering microbial ecology and increasing human exposure in densely populated areas. The WHO's 2023 report on antimicrobial resistance underscores the growing threat of drug-resistant airborne bacteria, with 42% of *Escherichia coli* isolates showing resistance to third-generation cephalosporins in 76 countries (WHO, 2023). These trends highlight the need for global surveillance and coordinated public health interventions to address airborne bacterial diseases.

2.5.2.1. Case Studies of Epidemics Linked to Airborne Pathogens

Several notable epidemics illustrate the devastating impact of airborne bacterial pathogens. The 1976 Legionnaires' disease outbreak in Philadelphia, USA, is a seminal case, where 221 individuals were infected, and 34 died after exposure to *Legionella pneumophila* aerosolized

from a hotel's air conditioning system (Fraser *et al*., 1977). This outbreak highlighted the risks associated with poorly maintained HVAC systems and led to significant advancements in water system regulations globally.

Another critical case is the 2003-2004 outbreak of MDR-TB in South Africa's KwaZulu-Natal province, where 53 patients, primarily HIV-positive, were infected in a healthcare facility (Gandhi *et al*., 2006). The outbreak, linked to poor ventilation and overcrowding, resulted in a 98% mortality rate, underscoring the lethal synergy between TB and immunosuppression. This event prompted global calls for improved infection control measures in healthcare settings, including better ventilation and isolation protocols.

In 2011, a *Pseudomonas aeruginosa* outbreak in a neonatal intensive care unit in Belfast, Northern Ireland, demonstrated the risks of airborne transmission in hospitals. The bacterium, spread through aerosolized water droplets from sinks, infected six infants, three of whom died (Walker *et al*., 2014). This case emphasized the need for rigorous environmental hygiene in healthcare facilities to prevent nosocomial infections.

These case studies highlight the critical role of environmental sources such as water systems, HVAC units, and dust in facilitating airborne bacterial epidemics. They also underscore the importance of timely surveillance, infection control, and infrastructure improvements to mitigate outbreaks.

The burden of airborne bacterial infections in Africa is substantial, driven by socioeconomic challenges, limited healthcare infrastructure, and environmental factors. Sub-Saharan Africa bears the highest age-standardized mortality rate from bacterial pathogens, with 230 deaths per 100,000 population in 2019, according to the Global Burden of Disease Study (GBD

Collaborators, 2022). Tuberculosis is a leading contributor, with 87% of global cases occurring in 30 high-burden countries, many in Africa (WHO, 2020). The region also faces challenges from emerging drug-resistant strains, with MDR-TB and extensively drug-resistant TB (XDR-TB) complicating treatment efforts.

Other airborne bacterial infections, such as *Streptococcus pneumoniae*-related pneumonia and *Klebsiella pneumoniae* infections, contribute significantly to morbidity and mortality. In 2019, these pathogens were among the top five responsible for 54.9% of bacterial deaths globally, with a disproportionate impact in Africa due to limited access to vaccines and antibiotics (GBD Collaborators, 2022). The meningococcal meningitis belt, spanning tropical Africa from 5° to 15° north, experiences cyclic epidemics of *Neisseria meningitidis*, with 2-10 yearly outbreaks historically reported (Greenwood, 1999). Recent immunization efforts have reduced incidence, but the disease remains a public health concern.

Environmental and social factors exacerbate the burden in Africa. Overcrowding in urban slums, inadequate ventilation in public spaces, and poor sanitation facilitate the spread of airborne pathogens. For example, a 2006 avian influenza outbreak in Nigeria, linked to aerosolized *Mycobacterium avium* and other pathogens, resulted in the loss of 900,000 birds, costing an estimated $4.82 million and threatening food security (Fasina *et al*., 2008). Additionally, the intersection of airborne bacterial infections with HIV/AIDS amplifies mortality rates, as seen in TB-HIV co-infections, which account for one-third of HIV-related deaths in the region (WHO, 2020).

2.5.2.2. Nigerian Context: Reports of Airborne Bacteria in Indoor Environments

Various investigations across Nigeria have consistently documented the presence of airborne bacteria in a range of indoor environments, including hospitals, university laboratories, residential buildings, hostels, and domestic toilets. These studies typically employed passive settle-plate methods (gravitational sampling) to assess microbial contamination, and their findings have highlighted significant microbial loads, the isolation of diverse bacterial species, and the detection of health-relevant pathogens. Collectively, the evidence underscores the potential public health implications of indoor microbial pollution in Nigeria.

In healthcare settings, where vulnerable populations are most at risk, studies have revealed alarming levels of microbial contamination. At the University of Uyo Teaching Hospital, for instance, an investigation conducted between February and March 2015 across different wards reported bacterial counts ranging from 4.6 to 87.5 CFU/m^3, with the Accident and Emergency unit recording the highest load, while the Operating Theatre exhibited the lowest. Notably, higher bacterial loads were consistently recorded in the evening compared to the morning, suggesting the influence of human activity and occupancy patterns. Staphylococcus aureus was the most frequently isolated bacterium, emphasizing the heightened risk of healthcare-associated infections among patients, visitors, and staff (JALS International, 2015). Similarly, at the University of Calabar Teaching Hospital, indoor air quality assessments revealed bacterial loads classified as “intermediate” to “high” when compared with European Union standards, though still within the World Health Organization’s acceptable range (<1000 CFU/m^3). Eleven bacterial genera were identified, including *Staphylococcus aureus* (18%), *Bacillus* spp. (13%), *Pseudomonas aeruginosa* (15%), *Klebsiella pneumoniae (*10%), *Escherichia coli* (10%), and *Acinetobacter baumannii* (~8%), alongside *Streptococcus* spp., *Corynebacterium*, *Micrococcus*,

Salmonella, and *Enterobacter*. These findings underscore the multiplicity of potential pathogens in hospital air, many of which are associated with opportunistic and nosocomial infections (Upula *et al*., 2023).

Further evidence from Kaduna Metropolis General Hospital revealed similarly concerning results. Airborne bacteria isolated from wards, including Emergency, Medical, and Surgical units, comprised *Pseudomonas aeruginosa* (28.9%), *Staphylococcus aureus* (24.2%), *Klebsiella pneumoniae* (20%), *Escherichia coli* (15.6%), and *Micrococcus* spp. (11.1%). Again, the Emergency ward had the highest contamination levels, reflecting both patient influx and inadequate ventilation (Naman *et al*., 2025). In Ilorin, Adekunle *et al*. (2018) compared bacterial air quality in a tertiary hospital and a public secondary school, demonstrating the presence of *Staphylococcus aureus,* coagulase-negative staphylococci (CoNS), *Bacillus* spp., *Klebsiella* spp., *Micrococcus* spp., *Escherichia* coli, *Pseudomonas* spp. and *Acinetobacter* spp. in hospital wards. In contrast, school environments showed heavier growth of CoNS and *Bacillus* spp., though *Klebsiella* and *Acinetobacter* were also detected, illustrating the variability in bacterial profiles across different indoor environments.

Beyond hospitals, Nigerian universities have also been the focus of indoor air microbiological assessments. At Olabisi Onabanjo University, bacterial concentrations in science laboratories ranged from 236.6 to 1530 CFU/m³, with the microbiology laboratory recording the highest levels and the physics laboratory the lowest. This distribution reflects the influence of laboratory activity levels, ventilation, and occupancy patterns (Ilusanya *et al*., 2020). A similar investigation at Obong University reported comparatively lower bacterial loads, with mean concentrations of 111.75 CFU/m³ in the morning and 125.25 CFU/m³ in the afternoon. The Laboratory Animal Room exhibited the highest counts (165–201 CFU/m³). *Staphylococcus aureus* (61.5%), CoNS

(27%), and *Bacillus* spp. (11.5%) dominated the isolates, though all were within acceptable indoor limits of ≤500 CFU/m³, suggesting effective ventilation and cleanliness in these settings (Ikon *et al*., 2020). In contrast, at Rhema University hostels, a progressive increase in bacterial concentrations was observed with extended exposure periods, with some rooms reaching levels as high as 29.8×10^2 CFU/m³ after 40 minutes. Eleven species were identified, with *Staphylococcus aureus* occurring in all samples (100%), while *Escherichia coli, Staphylococcus epidermidis, Klebsiella* spp. and *Bacillus subtilis* were detected in 75% of samples. Streptococcus pyogenes (50%), *Bacillus megaterium, Bacillus cereus,* and *Serratia marcescens* were also isolated. The predominance of pathogenic species such as *S. aureus, B. cereus,* and *S. pyogenes* highlighted significant public health risks within residential university environments (Ozougwu *et al*., 2021).

Investigations within residential homes and domestic toilets have further demonstrated the widespread presence of airborne bacteria in Nigeria. In Benin City, indoor bacterial concentrations during the wet season ranged between 476.1 and 939.3 CFU/m³, compared to outdoor values of 181.1–373.2 CFU/m³, while the dry season showed lower indoor values (335.0–457.2 CFU/m³) but relatively higher outdoor concentrations (387.2–627.8 CFU/m³). Identified bacteria included Proteus mirabilis*, Pectobacterium brasiliense* and *Enterobacter sichuanensis*, reflecting both human-associated and environmental sources of contamination. Seasonal variations significantly influenced microbial distribution, with higher indoor concentrations during the wet season, likely due to reduced ventilation and increased humidity (Eghomwanre *et al*., 2023). Domestic toilets, particularly in Port Harcourt, were found to harbor high bacterial loads, with *Staphylococcus* spp. (22%), *Bacillus* spp. (20%), *Enterococcus* spp. (20%), *Escherichia coli* (16%), *Micrococcus* (15%), *Klebsiella* (3%), and *Proteus* (2%)

predominating. Importantly, toilet flushing was shown to significantly elevate airborne bacterial counts, releasing tens of thousands of CFU/m³ per hour into the environment. The study also recorded fungal contaminants such as *Aspergillus* and *Penicillium*, further underscoring the potential health risks, especially to immunocompromised individuals (Agi *et al*., 2024).

2.6 Common Airborne Bacteria in Indoor Environments

Airborne bacteria constitute a significant proportion of bioaerosols that circulate within indoor environments, including residential buildings, hospitals, schools, and public transportation. The composition and concentration of these microorganisms are influenced by factors such as human occupancy, ventilation, cleaning practices, and environmental conditions (Prussin and Marr, 2015). Among the most common airborne bacteria identified in indoor environments are *Staphylococcus aureus*, *Streptococcus pneumoniae*, *Klebsiella pneumoniae*, *Bacillus* species, *Pseudomonas aeruginosa* and coliforms. These organisms are of particular interest due to their pathogenic potential, antibiotic resistance traits, and the diseases they may cause.

2.6.1. Staphylococcus aureus

Staphylococcus aureus is a Gram-positive, facultatively anaerobic coccus that is commonly carried on the skin, nasal cavity, and mucous membranes of humans. It is one of the most frequently isolated bacteria from indoor air, particularly in environments with high human density such as hospitals, schools, and dormitories (Otter and French, 2009). Airborne dissemination occurs through skin shedding, respiratory droplets, and contaminated fomites.

Pathogenically, *S. aureus* is associated with a wide spectrum of diseases ranging from superficial skin infections (boils, abscesses, and impetigo) to severe systemic infections such as pneumonia, sepsis, endocarditis, and osteomyelitis (Tong *et al*., 2015). A particularly concerning feature is

the emergence of methicillin-resistant *Staphylococcus aureus* (MRSA), which represents a major threat in hospital indoor air environments due to its persistence on surfaces and ability to spread via aerosols (Weber *et al*., 2010). Indoor exposure increases the risk of nosocomial and community-acquired infections, especially in immunocompromised individuals.

2.6.2. Streptococcus pneumoniae

Streptococcus pneumoniae is a Gram-positive diplococcus and a leading airborne pathogen found in indoor environments, particularly in areas with poor ventilation and high human occupancy. Its natural reservoir is the human nasopharynx, and it is transmitted via respiratory droplets and aerosols generated by coughing, sneezing, or speaking (Bogaert *et al*., 2004).

This bacterium is of great clinical importance as it is the most common cause of community-acquired pneumonia. In addition, it is associated with meningitis, septicemia, otitis media, and sinusitis (O'Brien *et al*., 2009). Indoors, environments such as hostels, daycare centers, and hospital wards have been identified as hotspots for pneumococcal spread due to close human contact. Antibiotic resistance, particularly to penicillin and macrolides, has further complicated the management of pneumococcal infections (Kim *et al*., 2016). The high morbidity and mortality associated with pneumococcal diseases highlight its significance as a public health concern in relation to indoor air microbiology.

2.6.3. Klebsiella pneumoniae

Klebsiella pneumoniae is a Gram-negative, encapsulated rod belonging to the Enterobacteriaceae family. Though traditionally associated with water and soil, it is increasingly reported as a common airborne bacterium in indoor environments, especially in hospitals and industrial areas

(Podschun and Ullmann, 1998). Aerosolization occurs through contaminated surfaces, sputum droplets, and medical waste.

Pathogenically, *K. pneumoniae* is a well-recognized cause of severe pneumonia, particularly in hospitalized or immunocompromised patients. It is also implicated in urinary tract infections, septicemia, and wound infections (Paczosa and Mecsas, 2016). The organism has gained notoriety due to multidrug-resistant strains such as carbapenem-resistant *Klebsiella pneumoniae* (CRKP), which pose significant challenges to treatment (Nordmann *et al*., 2011). The ability of *K. pneumoniae* to survive in indoor aerosols and colonize respiratory tracts emphasizes its role as a serious airborne pathogen of concern.

2.6.4. Bacillus species

Species of the genus *Bacillus* are Gram-positive, aerobic or facultatively anaerobic, and spore-forming rods. Due to their spore-forming ability, *Bacillus* species are resilient in harsh environmental conditions, making them common inhabitants of indoor air. Their spores can persist for long periods and easily disperse via air currents (Nicholson *et al*., 2000).

Most *Bacillus* species are environmental saprophytes; however, some are pathogenic. For instance, *Bacillus anthracis* causes anthrax, while *Bacillus cereus* is linked to foodborne illnesses and opportunistic infections (Logan, 2012). In indoor settings, non-anthrax *Bacillus* species are often considered contaminants, but they can be opportunistic pathogens in immunocompromised individuals, causing bacteremia, respiratory infections, and wound infections (Drobniewski, 1993). Their persistence in air highlights the importance of considering spore-formers in indoor microbial assessments.

2.6.5. Pseudomonas aeruginosa

Pseudomonas aeruginosa is a Gram-negative, aerobic, opportunistic bacterium with significant clinical and environmental relevance. It thrives in moist environments such as sinks, drains, and humidifiers, from where it can aerosolize and persist in indoor air (Moradali *et al*., 2017).

Clinically, *P. aeruginosa* is a leading cause of hospital-acquired infections, particularly ventilator-associated pneumonia, bloodstream infections, urinary tract infections, and wound infections (Lister *et al*., 2009). It is particularly dangerous to immunocompromised individuals and patients with cystic fibrosis, where chronic colonization of the respiratory tract can occur. The bacterium's high intrinsic resistance to antibiotics, combined with its ability to acquire new resistance mechanisms, makes it a critical priority pathogen in healthcare settings (Breidenstein *et al*., 2011). In indoor environments, its detection signals potential contamination sources that could exacerbate infection risks.

2.6.6. Coliforms and Other Opportunistic Bacteria

Coliforms, including *Escherichia coli* and *Enterobacter* species, are Gram-negative facultative anaerobic rods commonly used as indicators of fecal contamination. Although primarily associated with water and soil, they are frequently detected in indoor air, particularly in areas with poor sanitation or wastewater leakage (Grisoli *et al*., 2009). Their presence in indoor environments suggests possible contamination routes from surfaces, fomites, or aerosolized wastewater. *E. coli*, though often commensal, includes pathogenic strains capable of causing gastrointestinal diseases, urinary tract infections, and septicemia (Croxen *et al*., 2013). Other opportunistic bacteria, such as *Acinetobacter* species, are also common in indoor air and have been linked to outbreaks of respiratory and bloodstream infections in healthcare facilities (Peleg

et al., 2008). These organisms are of great concern in hospitals, where immunocompromised patients may develop life-threatening infections.

2.6.7. Pathogenic Potential and Associated Diseases

The pathogenic potential of airborne bacteria in indoor environments lies in their ability to colonize, infect, and cause diseases ranging from mild respiratory or skin infections to life-threatening systemic illnesses. Vulnerable populations—including the elderly, children, and immunocompromised individuals—are particularly at risk. Indoor exposure to airborne bacteria is associated with respiratory diseases (e.g., pneumonia, bronchitis, tuberculosis-like illnesses), gastrointestinal disturbances, urinary tract infections, wound infections, and septicemia (Douwes *et al*., 2003).

Moreover, the growing prevalence of antimicrobial resistance among these bacteria exacerbates their pathogenic potential. Multidrug-resistant strains of *S. aureus*, *K. pneumoniae*, and *P. aeruginosa* are particularly worrisome, as they significantly limit treatment options and increase morbidity and mortality rates. The circulation of such organisms in indoor air highlights the importance of continuous surveillance, improved ventilation, sanitation, and the implementation of infection prevention and control measures.

2.7 Antimicrobial Resistance in Airborne Bacteria

Antimicrobial resistance (AMR) in airborne bacteria arises through genetic and environmental mechanisms. Bacteria develop resistance via mutations in chromosomal genes or acquisition of resistance genes through horizontal gene transfer (HGT) mechanisms such as conjugation, transformation, and transduction. Mobile genetic elements like plasmids, transposons, and integrons facilitate the spread of resistance genes. Environmental stressors, including sub-lethal

antibiotic concentrations in indoor settings, promote selective pressure, enhancing resistance. Bioaerosols, carrying bacteria from human, animal, or environmental sources, can harbor resistance genes, spreading them through air circulation (Pruden *et al*., 2013).

Studies have identified antibiotic-resistant bacteria in indoor air environments, particularly in healthcare facilities, households, and crowded public spaces. Methicillin-resistant *Staphylococcus aureus* (MRSA) and multidrug-resistant *Pseudomonas aeruginosa* have been detected in hospital air samples, often linked to ventilation systems and patient shedding (Mirhoseini *et al*., 2016). Indoor dust and aerosols serve as reservoirs for resistance genes, with studies showing high prevalence of β-lactamase and tetracycline resistance genes in urban indoor environments (Gilbert *et al*., 2010). In Nigeria, research on indoor air in hospitals and markets has reported resistant strains of *Escherichia coli* and *Klebsiella pneumoniae*, highlighting local transmission risks (Ogunlesi *et al*., 2020).

AMR in airborne bacteria poses significant public health challenges. Inhalation of resistant pathogens increases risks of difficult-to-treat respiratory infections, particularly in immunocompromised individuals. Hospitals face heightened infection control challenges, as airborne resistant bacteria can contaminate sterile environments, leading to nosocomial infections. Poor ventilation and overcrowding exacerbate transmission, especially in resource-limited settings. Effective infection control requires improved air filtration, regular disinfection of ventilation systems, and monitoring of indoor air quality. Public health strategies must prioritize surveillance of airborne AMR to mitigate outbreak risks (WHO, 2014).

Globally, the rise of AMR in airborne bacteria is linked to overuse of antibiotics, poor sanitation, and global travel, which facilitate gene dissemination. The World Health Organization reports

increasing resistance in airborne pathogens like *Mycobacterium tuberculosis*, with multidrug-resistant tuberculosis (MDR-TB) cases rising by 3% annually (WHO, 2023). In Nigeria, rapid urbanization and inadequate healthcare infrastructure amplify AMR spread in indoor environments. Studies indicate a growing prevalence of resistant *Staphylococcus* and *Enterobacteriaceae* in Nigerian hospitals and public transport systems (Ogunsola and Mehtar, 2019). Emerging solutions include advanced air purification technologies and stricter antibiotic stewardship programs to curb resistance development.

2.9 Control and Mitigation of Airborne Bacterial Contamination

Airborne bacterial contamination represents a significant public health challenge, particularly in high-density environments such as student residences, where shared spaces and close interpersonal contact facilitate the transmission of infectious pathogens. Effective control and mitigation strategies are essential to reduce the risk of disease outbreaks and maintain a safe living environment. This chapter provides an in-depth examination of four critical areas for managing airborne bacterial contamination: ventilation and air filtration systems, cleaning, disinfection, and waste management, personal protective measures and behavioral practices, and public health policies and guidelines for student residences. Each section integrates evidence from peer-reviewed studies and authoritative guidelines to provide a comprehensive framework for infection control.

2.9.1 Ventilation and Air Filtration Systems

Ventilation and air filtration systems are pivotal in mitigating airborne bacterial contamination by reducing the concentration of infectious aerosols in indoor environments. Inadequate ventilation can lead to the accumulation of pathogens, increasing the risk of respiratory infections. The World Health Organization (WHO, 2020) underscores that proper ventilation is a

fundamental component of infection prevention and control (IPC), as it dilutes and disperses airborne bacteria, thereby lowering transmission risks.

Natural ventilation, achieved through open windows and doors, promotes air exchange and is a cost-effective method for improving indoor air quality (IAQ). However, its efficacy is limited by external factors such as climate, building design, and urban settings. In student residences, where natural ventilation may be insufficient, mechanical ventilation systems, such as heating, ventilation, and air conditioning (HVAC) systems, play a critical role. These systems regulate airflow and maintain consistent IAQ. A study by Li *et al*. (2007) demonstrated that increasing ventilation rates in indoor settings reduced airborne bacterial concentrations by up to 50%, significantly lowering the transmission of pathogens like *Mycobacterium tuberculosis*.

High-efficiency particulate air (HEPA) filters are highly effective in capturing bacterial aerosols, with a removal efficiency of 99.97% for particles as small as 0.3 micrometers (ASHRAE, 2021). In student residences, integrating HEPA filters into HVAC systems or using portable air purifiers can substantially reduce airborne bacterial loads. Additionally, ultraviolet germicidal irradiation (UVGI) systems, which inactivate bacteria by damaging their DNA, have been shown to enhance air quality when combined with filtration systems (Memarzadeh, 2011). For instance, a study by Escombe *et al*. (2009) found that UVGI reduced the transmission of tuberculosis in high-risk settings by 70%.

Despite their effectiveness, ventilation and filtration systems face challenges, including high installation and maintenance costs, energy consumption, and the need for regular filter replacement. In resource-constrained settings, these barriers may limit adoption. However, cost-effective solutions, such as portable HEPA purifiers, have shown promise in smaller spaces like

dormitories (Cheek *et al*., 2021). Regular maintenance and monitoring of ventilation systems are also critical to ensure optimal performance and prevent the growth of bacteria within ducts or filters.

2.9.2 Role of Cleaning, Disinfection, and Waste Management

Cleaning, disinfection, and waste management are essential strategies for controlling airborne bacterial contamination, as surfaces can serve as reservoirs for pathogens that may become aerosolized through human activity or air movement. The Centers for Disease Control and Prevention (CDC, 2020) emphasizes that routine cleaning and disinfection of high-touch surfaces are critical for reducing environmental contamination and preventing airborne transmission.

Cleaning removes dirt and organic matter, reducing the microbial load on surfaces, while disinfection targets specific pathogens using chemical agents such as quaternary ammonium compounds, hydrogen peroxide, or bleach solutions. In student residences, high-touch surfaces, including doorknobs, communal tables, and bathroom fixtures, require frequent disinfection to prevent cross-contamination. A study by Dancer (2014) found that systematic cleaning of shared spaces reduced the environmental presence of methicillin-resistant *Staphylococcus aureus* (MRSA) by up to 70%, subsequently decreasing the risk of airborne transmission. The use of electrostatic sprayers and fogging systems can further enhance disinfection by ensuring even coverage of surfaces (Rutala and Weber, 2019). Improper waste management can exacerbate bacterial contamination by creating breeding grounds for pathogens. In student residences, organic waste, such as food scraps, can harbor bacteria like *Escherichia coli* and *Salmonella*, which may become aerosolized during handling or disposal. The WHO (2014) recommends segregated waste disposal systems, secure storage, and regular waste collection to minimize

contamination risks. Implementing clearly labeled bins for organic, recyclable, and hazardous waste can improve compliance among residents.

Challenges in cleaning and waste management include inconsistent adherence to protocols, limited resources, and lack of training for custodial staff. Standardized cleaning schedules, coupled with staff training on IPC protocols, can enhance effectiveness. Additionally, the use of environmentally friendly disinfectants can minimize health risks associated with chemical exposure while maintaining efficacy (Rutala and Weber, 2019).

2.9.3 Personal Protective Measures and Behavioral Practices

Personal protective measures and behavioral practices are critical components of a comprehensive strategy to mitigate airborne bacterial contamination in student residences. These interventions focus on reducing the emission and inhalation of infectious aerosols and preventing indirect transmission through contaminated surfaces or hands. The effectiveness of these measures relies heavily on consistent adherence, which can be challenging in communal living environments.

The use of personal protective equipment, particularly face masks, is a proven method for reducing the spread of airborne bacteria. Masks such as surgical masks or N95 respirators filter out bacterial aerosols, protecting both the wearer and others in close proximity. The Centers for Disease Control and Prevention (CDC, 2020) recommends mask-wearing in crowded indoor settings, especially during outbreaks of respiratory infections like influenza or tuberculosis. In student residences, where individuals share common areas such as dining halls and study rooms, masks can significantly reduce transmission risks. A study by Cowling *et al*. (2010) found that consistent mask use in communal living settings reduced the incidence of influenza-like illnesses

by up to 60%. Additionally, eye protection, such as face shields, may be warranted in specific scenarios, such as during outbreaks of conjunctivitis-causing bacteria, to prevent transmission via mucosal surfaces.

Behavioral practices, including hand hygiene and respiratory etiquette, are foundational to infection control. Regular handwashing with soap and water for at least 20 seconds reduces the transfer of bacteria from contaminated surfaces to the respiratory tract or other individuals. Respiratory etiquette, such as covering the mouth and nose with a tissue or elbow during coughing or sneezing, minimizes the release of infectious aerosols. Educational campaigns targeting students can reinforce these behaviors. For example, Aiello *et al*. (2010) demonstrated that a hand hygiene intervention in university dormitories reduced the incidence of upper respiratory infections by approximately 20%. Promoting vaccination compliance, particularly for vaccine-preventable bacterial infections like meningococcal disease, is another critical behavioral practice in student residences, where outbreaks can spread rapidly due to close contact (Bruce *et al*., 2001).

Compliance with personal protective measures and behavioral practices can be low among students due to factors such as lack of awareness, perceived inconvenience, or social pressures. To address these challenges, residence halls can implement peer-led education programs, provide accessible PPE (e.g., free mask distribution), and integrate health promotion into orientation activities. Creating a culture of health consciousness through signage, workshops, and student-led initiatives can sustain long-term adherence.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

This study was carried out in selected student residential hostels located outside University of Benin (UNIBEN), Benin City, Edo State, Nigeria. Benin City, the capital of Edo State, lies within the rainforest belt of southern Nigeria and is characterized by a tropical climate with distinct wet and dry seasons. These climatic conditions are known to influence the abundance and diversity of airborne microorganisms. The selected hostels are typical student residential facilities around the University, characterized by high student occupancy, communal living arrangements, and varying levels of ventilation. These environmental and demographic factors make the hostels potential hotspots for airborne microbial contamination and transmission.

3.2 Study Design

A cross-sectional study design was employed for this research. Airborne bacterial samples were collected from the indoor environments of the selected student residences over a three-week period. Sampling was conducted during peak occupancy hours in the morning and evening, when student activities such as movement, conversations, and gatherings were most intense, thereby increasing the likelihood of airborne bacterial dispersal. The design allowed for the determination of the types and loads of airborne bacteria present in different sections of the hostels, providing valuable insights into their potential public health significance.

3.3 Sampling Sites

Airborne bacterial samples were collected from two student residential area around the University of Benin (Osasogie and Ekosodin). Within each hostel, three specific sampling points were identified to capture variations in microbial load across different environments:

1. **Hostel Rooms** – where students spent most of their time, often in close proximity, and with limited ventilation.
2. **Corridors/Common Areas** – characterized by high student traffic and frequent interactions.
3. **Bathrooms/Toilet Areas** – areas with high humidity and potential for increased microbial proliferation.

The selection of these sampling sites was based on occupancy rate, ventilation type (natural or limited airflow), and frequency of human activity, all of which influence airborne microbial load.

3.4 Sample Collection Method

Airborne bacterial sampling was carried out using the settle plate method as described by the American Public Health Association (APHA, 2017). Sterile Petri dishes containing Nutrient Agar (NA) for total heterotrophic bacterial count was prepared, labeled, and transported aseptically to the sampling sites. At each sampling point, the plates were exposed at a height of approximately 1 meter above the ground (representing the average human breathing zone) and at least 1 meter away from walls or obstructions. Each plate was exposed for 15 minutes to allow airborne bacteria to settle onto the culture medium. Control plates, which were not exposed, were included to ensure the sterility of the media. After exposure, all plates were immediately covered, sealed with parafilm, and placed into sterile containers. Samples were transported to the Microbiology Laboratory, Faculty of Life Sciences, University of Benin, within one hour of collection for incubation and further microbiological analysis.

3.5 Sterilization of Materials

Materials such as Petri-dishes, pipette, glass containers (conical flask, round bottom flask) and bottles were washed, drained and dried. They were wrapped with aluminum foil and sterilized in a hot-air oven at 160^{o}C for an hour. They were allowed to cool after sterilization before usage. An aseptic working environment was achieved with the use of Bunsen burner flame and disinfection of work surfaces with alcohol.

3.5.1 Preparation and Sterilization of media

Materials used include; Glass wares such as test tubes, beakers, conical flasks, Petri-dishes, McCartney bottles, Sterile cotton swabs, Sterile gloves, Normal saline, Sterile sampling containers, stirring glass rod and measuring cylinder. Media and Biochemical test reagents and Gram's staining kit . All glassware which include MacCartney bottles, Petri dishes, test tubes,conical flasks, measuring cylinders and pipettes, were sterilized at 160 ^{o}C for 1 hr in a hot-air-oven before use. The media used in this study were sterilized at 121 ^{o}C for 15 min in an autoclave. Agar media, agar slant and biochemical reagents were prepared freshly and refrigerated at 3-4 ^{o}C. Aseptic conditions were ensured during inoculation and subculturing.

3.5.1.1 Preparation of Nutrient agar

Twenty eight grams (28 g) of nutrient agar was dissolved in 1000 ml of distilled water in a conical flask corked with cotton wool and foil paper and allowed to dissolve in 1000 ml of distilled water in a conical flask. The medium will be the placed in an autoclave to sterilize it for 15 minutes at 121 °C. After sterilization, the flask will be allowed to cool.

3.5.1.2. Preparation of Citrate agar

Twenty-four point twenty-eight (24.28)grams of agar was dissolved in 1000 ml distilled water and heated to boiling, to dissolve the medium completely. It was then mixed properly and distributed in conical flasks. The medium was sterilized by autoclaving at 15 lbs pressure (121 °C) for 15 mins and then left to cool before dispension on sterile petri dishes.

3.5.1.3 Preparation of Triple Sugar Iron agar

Sixty-four point six (64.6) g of powder was dissolved in 1L of distilled water and then heated to properly dissolve the mixture. The mixture was autoclaved to sterilize the agar before it is dispensed into tubes and sterilized again at 121 °C for 15 mins. The agar was then left to solidify with short slant and good butts.

3.6 Bacterial Enumeration

Following the air sampling exercise, all exposed nutrient agar plates were transported aseptically to the microbiology laboratory for incubation. The plates were incubated at a temperature of 37°C for 24 to 48 hours to allow for optimal bacterial growth. After incubation, distinct bacterial colonies on each plate were visually enumerated. The number of airborne bacteria was then expressed as colony-forming units per cubic meter of air **(**cfu/m^3**)** using a standard formula for settle plate enumeration:

$$\text{Cfu/ml} = \frac{a\,x\,10{,}000}{\text{p x t x } 0.2}$$

Where:

- a = number of colonies counted on the agar plate
- p = surface area of the plate (in cm^2); for a 90 mm Petri dish, p = 63.6 cm^2
- t = time of exposure in minutes **(**15 minutes**)**
- 0.2 = sedimentation constant for passive air sampling

This calculation provided a standardized estimate of bacterial load in the bathroom air of the hostels, expressed in CFU/m^3.

3.6.1 Subculturing of Pure Isolates

After colony counting, well-isolated colonies with distinct morphologies were selected and subcultured onto fresh Nutrient Agar plates to obtain pure cultures. These pure cultures were then subjected to further identification tests, such as biochemical and morphological characterization.

BACTERIAL IDENTIFICATION

The bacterial isolates were characterized based on colonial morphological characteristics such as colony shape, size, elevation, optical activity, margination and pigmentation on nutrient agar and MacConkey agar. Biochemical tests were also carried out to further identify the bacterial isolates.

3.7.1 Gram staining

Smears of the bacterial isolates were prepared and heat fixed on clean grease free slides. The smears were stained for one minute with crystal violet. This was washed out with distilled water. The slides were flooded with dilute Grams' iodine solution for one minute. This was washed off with distilled water and the smears were decolorized with 95% alcohol for 30 seconds and rinsed off with distilled water. The smears were then counter stained with safranin solution for one

minute. Finally, the slides were washed off with distilled water, air dried and observed under oil immersion objective (Cheesbrough, 2005).

Potassium Hydroxide (KOH) test

Two drops of a 3% potassium hydroxide (KOH) solution were placed on a clean glass slide, after which a loopful of pure bacterial growth was emulsified in the solution by stirring in a circular motion. During mixing, the loop was occasionally lifted to observe the formation of a string in the mixture. The development of a viscous and mucoid consistency indicated a Gram-negative bacterium, whereas no reaction (absence of string formation) was interpreted as indicative of a Gram-positive bacterium (Roberts and Sandle, 2008).

3.8. BIOCHEMICAL TEST

3.8.1 Catalase Test

This is a test to detect the presence or absence of catalase enzyme. The catalase enzyme catalyses the breakdown of hydrogen peroxide to release free oxygen gas and the formation of water. A few drops of freshly prepared 3% hydrogen peroxide were added onto the bacterial isolates smeared on a slide. The production of gas bubble indicated catalase enzyme positive (Cheesbrough, 2005).

3.8.2 Oxidase Test

A piece of filter paper was wet with a few drops of the dilute (1%) solution of oxidase reagent (tetramethyl-pphenylenediamine-dihydrochloride) which was prepared by standard procedure. A bit of growth from the nutrient agar slant was obtained using sterilized platinum wire loop and smeared on the wet piece of paper. Development of an intense purple color by the cells within 30 seconds indicates a positive oxidase test (Cheesbrough, 2005).

3.8.3 Citrate Utilization Test

This test is based on the ability of some organisms to utilize citrate as a sole source of carbon. This was carried out by inoculating the test organism in test tube containing Simon's citrate medium and this was incubated at 37°C for 24 - 48 hr. The development of deep blue colour after incubation indicates a positive result (Cheesbrough, 2005).

3.8.4 Indole Test

Indole test is performed to determine the ability of the organism to split tryptophan molecule into indole. This test is performed to help differentiate species of the family enterobacteriaceae. Kovac's reagent which contains hydrochloric acid, dimethyl-aminobenzaldehyde and amyl alcohol is used. The broth was inoculated with the test organism and incubated for 18 hours at 37°C. 5ml of Kovac's reagent was then added down the inner wall of the tube. Development of bright red colour at the interface of the reagent and the broth within seconds after adding the reagent was indicative of the presence of indole and a positive result.

3.8.5. Triple sugar iron (TSI) agar test

The Triple Sugar Iron (TSI) test is an ability to test an organism's capability to ferment sugars and to produce hydrogen sulphide (H_2S) or gas (O_2), or both. The test was used primarily to differentiate members of the *Enterobacteriaceae* family based on their sugar fermentation patterns and from other Gram-negative rods. An agar slant prepared of a TSI agar was used in carrying out this test in a sterile test tube at a slanted angle. The slanted medium was inoculated with TSA pure culture using a straight inoculation needle by stabbing first through the center to the bottom of the tube and streaking the agar slant's surface. After inoculations, the test tubes were covered with foil paper and left at an ambient temperature of 36°C to incubate for 24 hours. Reactions on test tubes were examined, and sugar fermentations were indicated by the

production of H_2S, gas and a change in colours from red (alkaline) to yellow (acid). When an alkaline/acid (red top/yellow bottom) slant reaction appeared, it only indicated dextrose (glucose) fermentation. When an acid/acid (yellow top/yellow bottom) slant reaction appeared, it showed the fermentation of dextrose, lactose and/or sucrose. The appearance of an alkaline/alkaline (red top/red bottom) slant reaction represented the absence of sugar fermentation. The blackening of the medium in the slant indicated H_2S production. Bubbles, cracks, or bottom-raised space in the slanted agar indicated gas production (formation of CO_2 and H_2) (Fawole and Oso, 2007).

3.9. Antibiotic susceptibility test

The identified colonies of bacteria were used to determine the susceptibility and resistance of bacterial isolates, which were subjected to standard antibacterial susceptibility testing (AST) to decipher their resistance or susceptibility to common antibiotics used for treatment within the locality. The standard discs were produced by Oxoid, UK, which was used to execute the disc diffusion method employed in this study. For this assay, a fully grown bacterial culture (from 18-24 hours) was cultured on MHA. The inoculum corresponding to 1.5 x 10^8 cells/ml McFarland standard was streaked using a sterile loop onto the MHA plates before the introduction of antibiotic discs and were added with extreme care to the plates with the aid of sterile forceps. The susceptibility results were recorded after incubation for 24 hours at 37 ºC. Following the standard or rules of AST established in 2017 by CLSI (Clinical Laboratory Standards Institute). The inhibition zone around each disc (measured using a meter rule in diameter) was assessed and interpreted based on the 2020 CLSI standard as Resistant (R), Intermediate resistant (I) and Sensitive (S) (Odonkor and Addo, 2011)

3.10. Multiple Antibiotic Resistance (MAR) Index

This index is obviously a good tool which identifies the region where the isolates were obtained. Whether they are from places of high or low risks or from arears where antibiotics are abused. This tool becomes necessary for health risk assessment. According to Davis and Brown (2016), an index of ≥ 0.2 and above is indicative of a 'high-risk' contamination source. In this study the MAR index was determined by employing the methods delineated by Chitanand*et al.* (2010). The formula below was used to decipher MAR index of bacterial isolates.

$$MAR\ index = \frac{y}{nx}$$

$$where\ y = number\ of\ resistance\ scored,$$

$$n = number\ of\ isolates\ and$$

$$x = total\ number\ of\ antibioitics$$

It is a general established rule that MAR index greater than 0.2 is indicative of the fact that the bacterium originates from areas where antibiotics have been abused (or regularly used) or worse still from areas of high-risk source of contamination.

CHAPTER FOUR

4.1. RESULTS

Table 4.1 and Figure 4.1 presents the mean total bacterial counts of airborne samples collected from two residential areas within UNIBEN: Ekosodin and Osasogie, over a three-week period. The lowest bacterial load was recorded in Osasogie during Week 3 ($2.1 \pm 0.20 \times 10^3$ CFU/m³), while the highest was observed in Ekosodin during Week 2 ($5.4 \pm 0.35 \times 10^3$ CFU/m³). Ekosodin generally exhibited higher bacterial counts across the sampling weeks, likely due to higher population density and poor ventilation. Osasogie recorded moderate bacterial loads, with its peak value in Week 1 ($3.8 \pm 0.30 \times 10^3$ CFU/m³).

Table 4.2 presents the cultural, morphological, and biochemical characteristics of the bacterial isolates recovered from the air samples. The isolates were identified as *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella* sp., *Proteus* sp., *Bacillus* sp. and *Pseudomonas aeruginosa*.

The distribution of bacterial isolates across the two residential areas is shown in Table 4.3. *Escherichia coli* and *Staphylococcus aureus* were the most widely distributed, occurring in air samples from both Ekosodin and Osasogie. *Klebsiella* sp. and *Proteus* sp. were detected in both sites, while *Pseudomonas aeruginosa* and *Bacillus* sp. were more restricted.

The frequency of occurrence of the bacterial isolates is presented in Figure 4.2. *E. coli* had the highest frequency of occurrence (25%), followed by *S. aureus* (20%) and *Klebsiella sp.* (18.3%). *Proteus sp.* accounted for 15%, *Bacillus sp.* 11.7%, while *Pseudomonas aeruginosa* was the least frequent (10%).

The antibiotic susceptibility profiles of the bacterial isolates are shown in Tables 4.5a and 4.5b. Among Gram-positive isolates, *Staphylococcus aureus* was resistant to ampicillin, amoxicillin,

and cotrimoxazole, but sensitive to ciprofloxacin, pefloxacin, and gentamicin. *Bacillus* sp. exhibited no resistance, remaining largely sensitive to fluoroquinolones (ciprofloxacin and pefloxacin), aminoglycosides (gentamicin and streptomycin), and erythromycin, while showing intermediate responses to some beta-lactams. For Gram-negative isolates, *Escherichia coli* was resistant to ampicillin, amoxicillin, and cotrimoxazole, but sensitive to ciprofloxacin, gentamicin, and streptomycin. *Pseudomonas aeruginosa* exhibited multidrug resistance, with resistance to ampicillin, amoxicillin, pefloxacin, and cotrimoxazole, though it remained sensitive to ciprofloxacin and gentamicin. *Klebsiella* sp. showed resistance to ampicillin and amoxicillin, but was sensitive to ciprofloxacin, gentamicin, and streptomycin. Overall, fluoroquinolones (ciprofloxacin and pefloxacin) and aminoglycosides (gentamicin and streptomycin) were the most effective antibiotics, whereas beta-lactams (ampicillin and amoxicillin) and cotrimoxazole were largely ineffective.

The Multiple Antibiotic Resistance (MAR) indices of the bacterial isolates are presented in Table 4.6. The MAR index values ranged from 0.00 to 0.40, with *Pseudomonas aeruginosa* recording the highest index (0.40), indicating resistance to four of the antibiotics tested. *Staphylococcus aureus* and *Escherichia coli* both had MAR indices of 0.30, while *Klebsiella* sp. showed a lower value of 0.20. In contrast, *Bacillus* sp. exhibited a MAR index of 0.00, indicating no resistance to the tested antibiotics.

Table 4.1: Mean Total Bacterial Counts (×10³ CFU/m³) of Air Samples from Student Residential Areas Over Three Weeks

Weeks	Ekosodin	Osasogie
Week 1	4.6 ± 0.32	3.8 ± 0.30
Week 2	5.4 ± 0.35	3.2 ± 0.28
Week 3	4.9 ± 0.29	2.1 ± 0.20

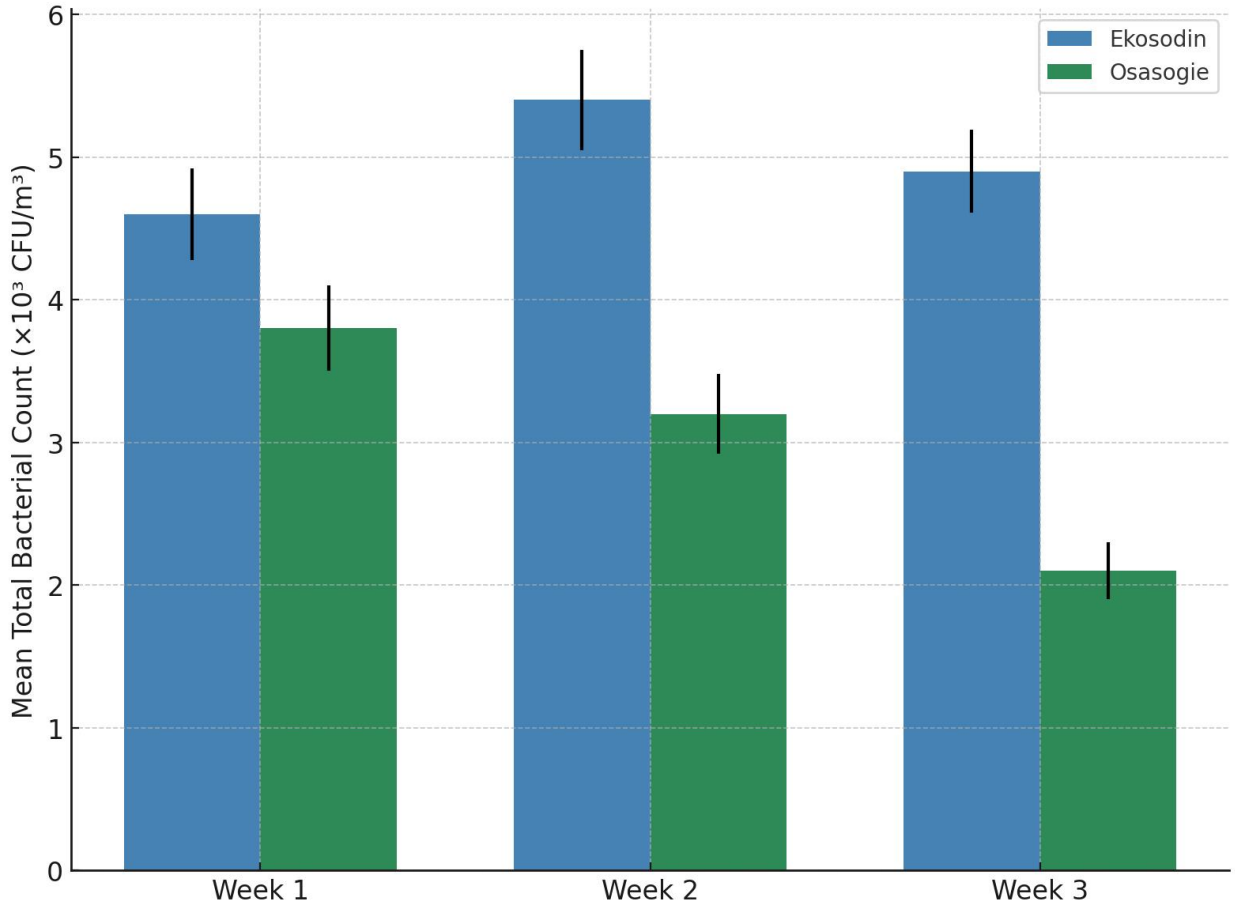

Figure 4.1. Total Bacterial Count (×10³ CFU/m³) of Air Samples from Student Residential Areas Over Three Weeks

Table 4.2: Cultural, Morphological and Biochemical Characteristics of Bacterial Isolates

Characteristics	1	2	3	4	6	7
Elevation	Raised	Flat	Flat	Flat	Flat	Flat
Margin	Entire	Undulate	Entire	Irregular	Irregular	Irregular
Colony Colour	Golden yellow	Cream	Cream	Colourless	Greenish (pigmented)	White
Colony Shape	Circular	Irregular	Circular	Irregular	Irregular	Irregular
Colony Size	Medium	Large	Large	Large	Medium	Large
Gram Stain	+	–	–	–	–	+
Cell Type	Cocci	Rod	Rod	Rod	Rod	Rod
Arrangement	Clusters	Disperse	Disperse	Disperse	Disperse	Chains
Gram Reaction Color	Purple	Pink	Pink	Pink	Pink	Purple
KOH String Test	–	+	+	+	+	–
Catalase	+	+	+	+	+	+
Indole	–	+	–	+	–	–
Citrate	+	–	+	+	+	+
Oxidase	–	–	–	–	+	–
Glucose	+	+	+	+	+	+
Sucrose	–	–	+	+	–	+
Lactose	–	+	+	–	–	–
Gas Formation	–	+	+	+	+	–
H_2S Formation	–	–	–	+	–	–
TSI (Slant/Butt)	K/A	A/AG	A/AG	K/A (H_2S + G)	K/A	K/A
Identity	*Staphylococcus aureus*	*Escherichia coli*	*Klebsiella* sp.	*Proteus* sp.	*Pseudomonas aeruginosa*	*Bacillus* sp.

Keys:
(+) Positive test; (–) Negative test
(A) Acid; (K) Alkaline; (G) Gas; (H_2S) Hydrogen sulphide
KOH = Potassium hydroxide test
TSI = Triple sugar iron test

Table 4.3: Distribution of Bacterial Isolates Across Ekosodin and Osasogie

Bacterial Isolates	Ekosodin	Osasogie
Escherichia coli	+	+
Klebsiella sp.	+	+
Staphylococcus aureus	+	+
Pseudomonas aeruginosa	+	–
Proteus sp.	+	+
Bacillus sp.	–	+

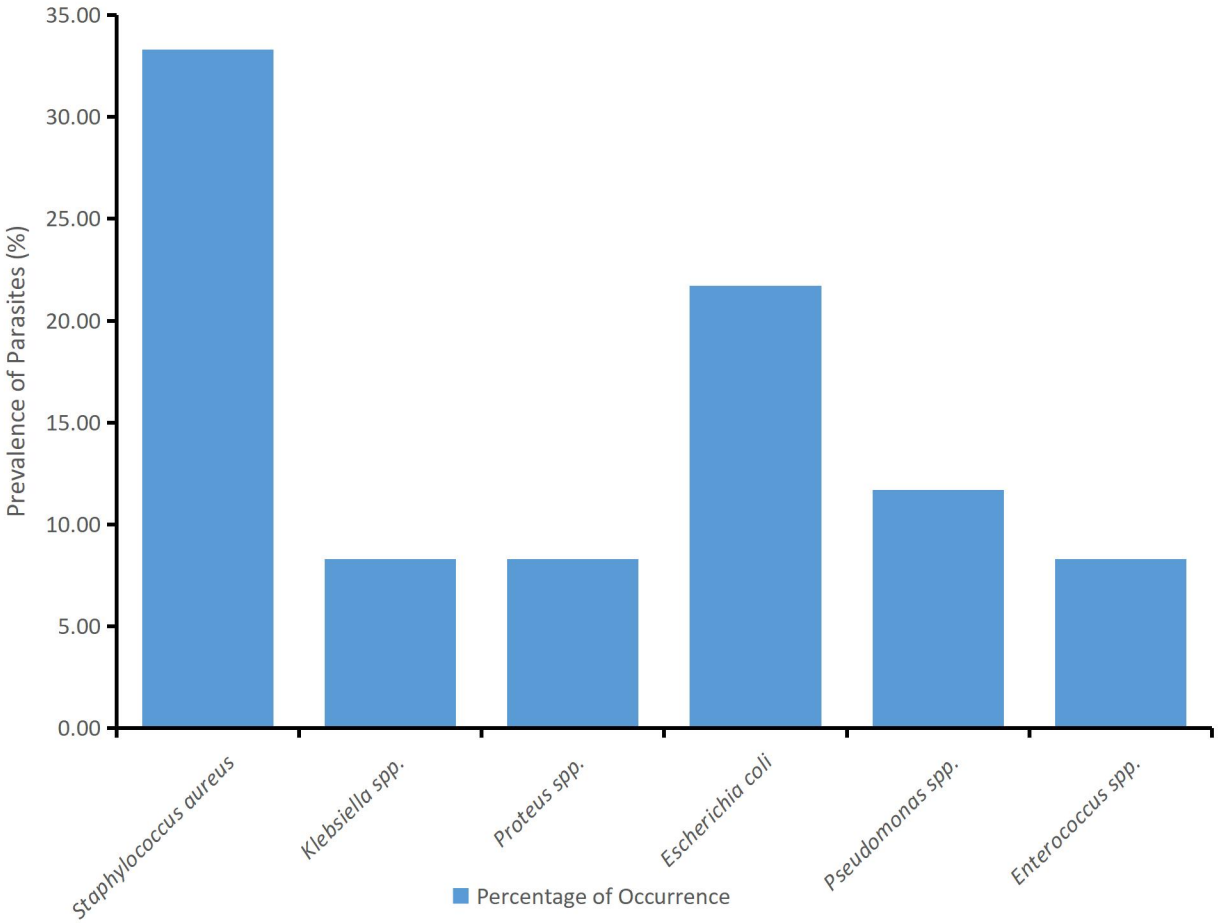

Figure 4.2. Percentage Frequency of Occurrence of Bacteria isolates

Table 4.5a: Antibiotic Sensitivity Test for Gram-Positive Bacteria

Bacteria Isolates	PEF	CN	APX	Z	AM	R	CPX	S	SXT	E
Staphylococcus aureus	19 (S)	17 (S)	11 (R)	15 (I)	10 (R)	12 (I)	23 (S)	14 (I)	11 (R)	12 (I)
Bacillus sp.	22 (S)	18 (S)	16 (I)	17 (S)	14 (I)	13 (I)	21 (S)	18 (S)	15 (I)	17 (S)

Table 4.5b: Antibiotic Sensitivity Test for Gram-Negative Bacteria

Bacteria Isolates	PEF	CN	APX	Z	AM	R	CPX	S	SXT	E
Escherichia coli	15 (I)	18 (S)	10 (R)	13 (I)	9 (R)	12 (I)	22 (S)	17 (S)	12 (R)	14 (I)
Pseudomonas aeruginosa	11 (R)	16 (S)	9 (R)	14 (I)	10 (R)	11 (R)	20 (S)	16 (I)	10 (R)	13 (I)
Klebsiella sp.	14 (I)	17 (S)	11 (R)	15 (I)	9 (R)	13 (I)	21 (S)	18 (S)	13 (I)	15 (I)

Keys:

- 0–10 mm = Resistant (R)
- 11–16 mm = Intermediate (I)
- ≥17 mm = Sensitive (S)
- PEF: Pefloxacin (10 µg), CN: Gentamicin (10 µg), APX: Ampicillin (30 µg), Z: Azithromycin (30 µg), AM: Amoxicillin (30 µg), R: Rifampicin (20 µg), CPX: Ciprofloxacin (10 µg), S: Streptomycin (10 µg), SXT: Cotrimoxazole (30 µg), E: Erythromycin (15 µg)

Table 4.6: Multiple Antibiotic Resistance (MAR) Index of Airborne Bacterial Isolates

Bacteria Isolate	Number of R Antibiotics	MAR Index
Staphylococcus aureus	4	0.40
Bacillus sp.	0	0.00
Escherichia coli	3	0.30
Pseudomonas aeruginosa	5	0.50
Klebsiella sp.	2	0.20

CHAPTER FIVE

DISCUSSION

Airborne microorganisms are an important component of indoor air quality and play a crucial role in determining the health risks associated with human occupancy in residential and institutional settings. Student residential areas, such as those in universities, are particularly vulnerable to microbial contamination due to overcrowding, inadequate ventilation, poor sanitation, and shared living spaces. The presence of airborne bacteria in such environments is not merely of academic concern but has direct implications for the spread of infectious diseases, especially respiratory tract infections, skin conditions, and opportunistic infections in immunocompromised individuals (Qian *et al*., 2014; Nazaroff, 2016; Osaghae *et al.,* 2025). The present study assessed the bacterial air quality of student residential residences within the University of Benin, specifically Ekosodin and Osasogie. The findings provide valuable insights into the levels of bacterial contamination, diversity of bacterial species, and their antimicrobial resistance patterns, which collectively reflect the potential risks posed to public health.

The mean total bacterial counts obtained from the two residential areas ranged between 2.1×10^3 CFU/m³ (Osasogie, Week 3) and 5.4×10^3 CFU/m³ (Ekosodin, Week 2). These values far exceed the recommended acceptable microbial limit for indoor air, which is 500 CFU/m³ according to the World Health Organization (WHO, 2009) and the American Conference of Governmental Industrial Hygienists (ACGIH, 1999). High bacterial loads in indoor environments are often associated with overcrowding, poor ventilation, and unhygienic conditions (Dutta *et al*., 2017). The higher counts recorded in Ekosodin compared to Osasogie may be attributed to higher population density, poor waste management, and limited airflow, all of which create favorable conditions for microbial persistence and dispersal (Fekadu and Tolosa, 2021). These patterns are

consistent with the findings of Aniekwu and Madubuko (2024), who investigated the microbial quality of air in the Keystone Male Hostel at the University of Benin. Their study documented bacterial loads as high as 26.5×10^2 CFU/m³ (equivalent to 2,650 CFU/m³) in overcrowded rooms accommodating six occupants, whereas rooms with fewer residents recorded negligible microbial levels. This comparison highlights the strong influence of population density and ventilation on indoor air quality, reinforcing the observations made in the present study. Elevated bacterial concentrations in indoor air pose serious risks as they increase the chances of inhalation and direct contact with pathogenic and opportunistic bacteria. Prolonged exposure can lead to respiratory illnesses, allergic reactions, and aggravation of pre-existing conditions such as asthma (Mandal and Brandl, 2011).

Six bacterial species were isolated, namely *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella* sp., *Proteus* sp., *Pseudomonas aeruginosa*, and *Bacillus* sp. These isolates represent a mix of pathogenic and opportunistic organisms with varying degrees of public health significance. The dominance of *E. coli* (25%) and *S. aureus* (20%) is consistent with findings from similar indoor air studies, where enteric and skin-associated bacteria were frequently detected in high-occupancy areas (Qudiesat *et al*., 2009; Ekhaise and Ogboghodo, 2011).

The presence of *E. coli* and *Klebsiella* sp. indicates fecal contamination and poor sanitation practices within the residential settings (Degu *et al*., 2019). Similarly, *S. aureus* reflects human shedding through skin and nasal secretions, posing risks of skin infections, food poisoning, and respiratory illnesses (Tong *et al*., 2015). Opportunistic pathogens such as *Pseudomonas aeruginosa* and *Proteus* sp. are notable for their involvement in nosocomial infections, especially among immunocompromised individuals (Alves *et al*., 2014). The recovery of *Bacillus* sp., though less frequent, is relevant because some species such as *Bacillus cereus* are capable of

producing toxins associated with foodborne illnesses (Kotiranta *et al*., 2000). The predominance of *E. coli* (25%) and *S. aureus* (20%) aligns with reports from indoor air studies in Nigeria and other developing countries where overcrowding, inadequate sanitation, and humid climatic conditions favor the persistence of these organisms (Ekhaise *et al*., 2010; Odebode *et al*., 2020).

The antibiotic susceptibility testing revealed varying resistance patterns across the bacterial isolates. Among Gram-positive isolates, *S. aureus* demonstrated resistance to ampicillin, amoxicillin, and cotrimoxazole but was sensitive to fluoroquinolones (ciprofloxacin and pefloxacin) and aminoglycosides (gentamicin and streptomycin). This aligns with global reports highlighting the diminishing efficacy of beta-lactams against *S. aureus* due to widespread resistance mechanisms, including beta-lactamase production (Lakhundi and Zhang, 2018). This pattern resembles the spread of community-associated methicillin-resistant *S. aureus* (CA-MRSA), which often displays multidrug resistance (David and Daum, 2010).

For Gram-negative bacteria, *E. coli* and *Klebsiella* sp. were resistant to ampicillin, amoxicillin, and cotrimoxazole but susceptible to ciprofloxacin and gentamicin. This is concerning as it reflects the global trend of Enterobacteriaceae exhibiting high resistance to first-line antibiotics, likely driven by the misuse of antibiotics in both healthcare and community settings (WHO, 2020). *Pseudomonas aeruginosa* displayed multidrug resistance, including resistance to four antibiotics, though ciprofloxacin and gentamicin retained activity. This is consistent with its well-documented ability to resist multiple classes of antibiotics via efflux pumps, biofilm formation, and enzyme production (Breidenstein *et al*., 2011).

Interestingly, *Bacillus* sp. exhibited no resistance, maintaining sensitivity to most antibiotics tested. While this suggests limited clinical concern for the isolates recovered in this study, its presence in the indoor environment should not be overlooked due to potential pathogenic strains.

The MAR index values ranged from 0.00 (for *Bacillus* sp.) to 0.40 (for *P. aeruginosa*). Values greater than 0.20 are considered indicative of bacteria originating from high-risk environments where antibiotics are frequently misused (Krumperman, 1983). The MAR indices recorded for *S. aureus* (0.30), *E. coli* (0.30), and *P. aeruginosa* (0.40) suggest that these airborne bacteria may have been exposed to antibiotic selective pressure, possibly through human activity and environmental contamination in residential areas. This finding aligns with studies in Nigeria and elsewhere that report high MAR indices for bacterial isolates from community and hospital environments (Igbinosa *et al*., 2017; Olalekan *et al*., 2020).

The detection of antibiotic-resistant airborne bacteria in student residences raises significant public health concerns. First, it highlights the role of indoor air as a potential reservoir and transmission pathway for antimicrobial-resistant pathogens. Students living in overcrowded and poorly ventilated hostels may be at risk of respiratory and systemic infections caused by these airborne pathogens. Secondly, the circulation of multidrug-resistant bacteria in community settings complicates infection management, as infections may not respond to commonly available antibiotics. This scenario can escalate into outbreaks, especially in high-density residential communities such as universities (Osaghae *et al*., 2025).

Moreover, airborne transmission provides a route for rapid dissemination of resistant bacteria beyond clinical settings, underscoring the One Health implications of antimicrobial resistance (Holmes *et al*., 2016). Thus, interventions such as improved sanitation, proper ventilation,

periodic disinfection of hostels, and antibiotic stewardship programs are essential to mitigate the risks identified in this study.

5.2 Conclusion

This study has demonstrated that the indoor air of student residential areas in Benin City harbors a wide range of airborne bacteria, with microbial loads varying across locations and sampling weeks. The bacterial counts were consistently higher in Ekosodin than in Osasogie, reflecting differences in population density, ventilation, and sanitary conditions. In some instances, the recorded mean bacterial counts exceeded acceptable limits for indoor air quality, highlighting a potential risk for respiratory discomfort, allergic reactions, and opportunistic infections among residents. The bacterial isolates identified included both environmental organisms such as *Bacillus* sp. and clinically relevant pathogens including *Staphylococcus aureus*, *Klebsiella pneumoniae* and *Pseudomonas aeruginosa*, some of which exhibited multiple antibiotic resistance. These findings underscore the public health significance of airborne microorganisms in student residential environments, where overcrowding and poor hygiene can create favorable conditions for microbial proliferation and disease transmission.

5.3 Recommendations

1. **Improvement of Ventilation Systems:** Adequate natural and mechanical ventilation should be prioritized in student hostels to reduce the accumulation of airborne bacteria.
2. **Regulation of Occupancy Levels:** Policies should be enforced to prevent overcrowding in hostel rooms, as high density directly correlates with elevated bacterial counts.
3. **Regular Sanitation and Disinfection:** Routine cleaning schedules, including the disinfection of shared surfaces and common areas, should be institutionalized to minimize microbial reservoirs.

4. **Health Education and Awareness:** Students should be sensitized on personal hygiene, the importance of keeping living spaces clean, and the risks associated with poor indoor air quality.
5. **Monitoring and Policy Implementation:** University authorities should establish regular microbial air quality assessments in hostels and enforce compliance with environmental health standards.
6. **Further Research:** Additional studies should incorporate fungal isolates and extend sampling to other hostels and seasons to provide a more comprehensive understanding of indoor microbial ecology.

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