Chapter One

1.1 Background to the Study

Industrialization has contributed immensely to economic growth, urban development, and improved standards of living across the world[1]. However, it has also led to significant environmental challenges, particularly in developing countries where regulatory frameworks and waste management practices are often inadequate[1]. Effluent discharge from industries is a major source of water pollution, introducing a wide range of pollutants, including organic matter, toxic chemicals, heavy metals, and pathogenic microorganisms, into surrounding water bodies[2].

The detergent manufacturing industry is one of the most polluting industrial sectors due to its high chemical input, complex production processes, and generation of large volumes of wastewater[3]. Detergent effluents contain surfactants, phosphates, nitrates, bleaching agents, stabilizers, and various other chemicals that negatively affect the aquatic environment. These compounds can alter physicochemical characteristics of water such as pH, dissolved oxygen, biochemical oxygen demand, turbidity, and conductivity, thereby affecting water quality[3].

In addition to chemical pollutants, wastewater from industrial complexes can harbor diverse microbial communities, including potentially pathogenic bacteria, fungi, and coliform organisms, which pose public health risks[4]. Studies have shown that exposure to contaminated wastewater is associated with outbreaks of waterborne diseases, antibiotic-resistant bacteria, and ecological disruption in receiving water bodies[4].

Ibadan, one of the largest cities in Nigeria, is host to numerous industrial complexes, including detergent manufacturing industries. The indiscriminate discharge of untreated or partially treated effluents into the environment raises serious concerns about pollution of surface and groundwater sources, which serve as vital resources for domestic, agricultural, and industrial purposes[5]. Given the importance of water quality to human and environmental health, it becomes essential to characterize the microbial and physicochemical properties of wastewater around detergent industries in Ibadan[5].

1.2 Statement of the Problem

The production of detergents in Nigeria has increased considerably over the last few decades due to high demand for household and industrial cleaning products. Unfortunately, most detergent industries in Nigeria lack adequate effluent treatment facilities, resulting in the discharge of raw or poorly treated wastewater into nearby streams, rivers, and drainage channels[6]. These effluents contain surfactants, phosphates, nitrates, and other toxic chemicals that persist in the environment and cause water pollution[6].

Furthermore, wastewater from industrial sources can serve as reservoirs for microbial pathogens and antibiotic-resistant organisms. The presence of these microorganisms in the aquatic ecosystem increases the risk of disease transmission and environmental contamination[7]. Residents of communities around industrial complexes often rely on nearby water sources for domestic and agricultural purposes, which makes the issue more pressing[8].

Despite the potential hazards, limited studies have investigated both the microbial and physicochemical characterization of effluents and wastewater around detergent industries in Ibadan[9]. This knowledge gap hinders proper risk assessment and the development of effective wastewater management strategies.

1.3 Justification of the Study

Effluent and wastewater discharge from industrial complexes, particularly detergent manufacturing industries, are a significant source of environmental pollution with both microbial and chemical implications. Detergent formulations often contain surfactants, phosphates, bleaching agents, and other additives that change the physicochemical properties of receiving water bodies. These changes may negatively affect aquatic ecosystems, soil quality, and public health. In Nigeria, where industrial regulation and wastewater treatment infrastructures are often inadequate, uncontrolled discharge of such effluents raises concerns about ecological safety and human exposure.

Ibadan, is a major industrial hub in southwestern Nigeria and hosts a growing number of detergent factories that generate substantial quantities of wastewater. Despite this, there is limited documented evidence on the microbial load and physicochemical characteristics of effluents discharged into surrounding environments. Understanding these parameters is essential because contaminated water sources serve as reservoirs for pathogenic microorganisms, while altered physicochemical conditions (such as elevated pH, conductivity, and chemical oxygen demand) can enhance the survival and proliferation of resistant microbial communities. These conditions may contribute to the spread of waterborne diseases, antimicrobial resistance, and long-term degradation of water quality.

Furthermore, regulatory agencies in Nigeria, such as the National Environmental Standards and Regulations Enforcement Agency (NESREA) and the Federal Ministry of Environment, have stipulated permissible limits for industrial effluent discharge. However, enforcement is often weak, and industries may operate without regular environmental monitoring. Conducting a comprehensive microbial and physicochemical characterization of wastewater around detergent manufacturing complexes provides empirical data to assess compliance with national and international standards.

1.4 Aim and Objectives of the Study

The aim of this study is to characterize the microbial and molecular profile of effluent, workers wash water, and receiving surface water from a detergent manufacturing complex in Ibadan, Nigeria.

The objectives of the study is to:

i. isolate and identify aerobic bacterial and fungal isolates from the sampled waters.

ii. determine the antibiotic susceptibility profiles of selected bacterial isolates.

iii. detect resistance and virulence genes in dominant bacterial isolates.

iv. evaluate the physicochemical parameters of effluent, wash water, and surface water samples.

1.5 Research Questions

1. What are the physicochemical characteristics of wastewater discharged from the detergent manufacturing complex?
2. What microbial species are present in the effluent and wastewater samples?
3. What are the antibiotic susceptibility patterns of the bacterial isolates recovered?
4. How do the physicochemical and microbial characteristics compare with WHO and NESREA permissible limits?
5. What environmental and health risks are associated with the discharge of detergent effluents in Ibadan?

1.6 Significance of the Study

The importance of this study lies in its potential to generate baseline data on the quality of wastewater discharged from detergent manufacturing industries in Ibadan. Data is crucial for understanding the extent of industrial pollution in the area and provide a foundation for future assessments[10]. The study also underscores the public health risks associated with the presence of pathogenic and antibiotic-resistant microorganisms in industrial effluents, drawing attention to the possible implications for communities that depend on nearby water sources[11].

Moreover, the findings are expected to inform policymakers, environmental agencies, and public health practitioners about the urgent need for stricter regulatory enforcement regarding effluent treatment and discharge standards[12]. In addition, the study contributes to the growing body of knowledge on industrial pollution in Nigeria and serves as a useful reference for subsequent research and environmental impact assessments[13]. Finally, the outcomes may guide detergent industries and related sectors in adopting safer and more sustainable wastewater management practices, thereby reducing environmental degradation and safeguarding public health.

1.7 Scope of the Study

This study focuses on the microbial and physicochemical characterization of effluent and wastewater samples collected from one detergent manufacturing complex in Ibadan, Oyo State, Nigeria. The parameters assessed include pH, temperature, turbidity, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, conductivity, total dissolved solids, and selected ions (nitrates, phosphates, chlorides, sulfates, etc.)[14]. Microbiological analyses include the isolation, identification, and antibiotic susceptibility testing of bacterial isolates[15].

1.8 Limitations of the Study

This study was carried out within the premises of a single detergent manufacturing complex in Ibadan, and as such, the findings may not fully represent the effluent characteristics of all detergent industries across Nigeria. In addition, the sampling was conducted during a specific period, which did not take into account seasonal variations that could influence the composition and concentration of pollutants in the wastewater. Furthermore, due to resource constraints, the scope of the study did not extend to advanced molecular characterization of microbial isolates, which could have provided a deeper understanding of the genetic basis of antimicrobial resistance and other microbial traits

1.9 Operational Definition of Terms

Effluent: Liquid waste discharged from industrial processes, in this study specifically wastewater released from a detergent manufacturing complex into the surrounding environment.

Wastewater: Water that has been adversely affected in quality by industrial, domestic, or commercial use. In this study, it refers to water contaminated by detergent production activities.

Physicochemical Parameters: The measurable physical and chemical characteristics of wastewater, such as pH, temperature, dissolved oxygen, biochemical oxygen demand (BOD), chemical oxygen demand (COD), turbidity, conductivity, and concentrations of ions like phosphates, nitrates, chlorides, and sulfates.

Microbial Characterization: The identification and classification of microorganisms (bacteria, fungi, etc.) present in the effluent and wastewater using cultural, biochemical, and antimicrobial susceptibility techniques.

Antibiotic Resistance: The ability of microorganisms, particularly bacteria, to survive and proliferate despite exposure to antibiotics that are normally effective against them.

Detergent Industry: A manufacturing sector involved in the production of cleaning agents such as soaps, washing powders, and liquid detergents, often associated with the generation of chemical-laden effluents.

Water Quality Standards: Regulatory limits and guidelines set by international and national bodies (e.g., World Health Organization (WHO), National Environmental Standards and Regulations Enforcement Agency (NESREA) for permissible concentrations of pollutants in water intended for human and environmental use.

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Chapter Two

Literature Review

2.1 Overview of Wastewater and Effluents in Industrial Activities

Industrialization has been a major driver of economic growth and technological advancement worldwide[1]. However, one of its unintended consequences is the generation of large volumes of wastewater and effluents that are often discharged into the environment. Industrial wastewater refers to the liquid waste generated during the production processes of industries, while effluent specifically denotes the treated or untreated wastewater released into natural water bodies or sewage systems[2]. These discharges typically contain a complex mixture of organic and inorganic pollutants, depending on the raw materials used and the nature of the industrial processes involved[2].

Different industries, such as food processing, textiles, pharmaceuticals, petrochemicals, and detergent manufacturing, produce effluents with varying physicochemical and microbial characteristics[3]. For instance, the detergent industry releases wastewater rich in surfactants, phosphates, alkyl benzene sulfonates, bleaching agents, and other additives. These compounds contribute significantly to water pollution because they alter the physicochemical properties of receiving water bodies, such as pH, turbidity, dissolved oxygen, and nutrient content[3]. In addition, industrial effluents often harbor diverse microbial populations, including pathogenic and antibiotic-resistant bacteria, which pose risks to both environmental and public health[3].

Globally, the mismanagement of industrial effluents has been linked to water scarcity, eutrophication, contamination of aquatic ecosystems, and the spread of waterborne diseases[4]. In developing countries, where wastewater treatment infrastructure and regulatory enforcement are often weak, untreated effluents are directly discharged into rivers, streams, and soils, compounding the risk of pollution. This practice threatens food chains, reduces biodiversity, and affects the livelihoods of communities that rely on natural water sources for domestic and agricultural use[4].

Consequently, the characterization of wastewater and effluents from industrial activities is essential for assessing pollution loads, identifying potential health hazards, and designing appropriate treatment and regulatory interventions. Such assessments provide baseline data for policymakers, environmental regulators, and industries to develop sustainable waste management practices and safeguard public health[4].

2.1.1 Importance of Studying Detergent Industry Effluents

The detergent industry plays a vital role in modern society by producing cleaning agents used in households, healthcare facilities, industries, and commercial establishments. However, alongside its economic and social benefits, detergent manufacturing contributes significantly to environmental pollution through the discharge of untreated or partially treated effluents. Studying these effluents is therefore crucial for several reasons[5].

First, detergent industry effluents contain a complex mixture of chemicals, including surfactants, phosphates, bleaching agents, enzymes, dyes, and fragrances. These substances, while enhancing the cleaning power of detergents, can be highly persistent in the environment[5]. Surfactants, for instance, reduce the surface tension of water and disrupt natural aquatic systems, while phosphates stimulate excessive algal growth, leading to eutrophication and oxygen depletion in water bodies. Monitoring and analyzing these components is essential for understanding their ecological consequences[6].

Second, detergent effluents often alter the physicochemical properties of receiving water bodies. They may increase biochemical oxygen demand (BOD) and chemical oxygen demand (COD), reduce dissolved oxygen, and affect parameters such as turbidity, conductivity, and pH[6]. These changes compromise the survival of aquatic organisms and disrupt ecological balance. Detailed characterization of effluents provides insights into the extent of environmental stress caused by detergent industries[6].

Third, the microbial dimension of detergent effluents cannot be overlooked. Wastewater from detergent manufacturing plants often harbors diverse microbial communities, including opportunistic and pathogenic bacteria [7]. More importantly, the antimicrobial properties of surfactants and preservatives may exert selective pressure on microbes, fostering the emergence of resistant strains[7]. The presence of multidrug-resistant organisms in effluents has public health implications, as contaminated water sources may serve as reservoirs for resistance genes, which can spread to human and animal populations[7].

Fourth, in developing countries such as Nigeria, untreated effluents are frequently discharged into open drains, streams, and surrounding soils without adequate treatment[8]. Communities around these industrial complexes depend on such water sources for domestic, agricultural, and recreational purposes, exposing them to chemical and biological hazards. Understanding the specific impacts of detergent effluents in these contexts helps in identifying health risks and guiding public health interventions [8].

Lastly, studying detergent industry effluents is critical for policy development and environmental management[9]. By characterizing both the microbial and physicochemical properties of effluents, researchers provide evidence-based data to regulatory agencies. This data supports the formulation of wastewater discharge standards, the enforcement of effluent treatment protocols, and the development of eco-friendly detergent formulations[9]. It also strengthens advocacy for sustainable industrial practices that balance economic growth with environmental conservation [10].

The study of detergent industry effluents is important because it highlights their ecological, microbial, and public health implications, particularly in regions with weak regulatory oversight. Such research not only contributes to scientific understanding but also provides a foundation for effective environmental monitoring, pollution control, and sustainable industrial development[10].

2.1.2 Link to Environmental Microbiology and Public Health

The characterization of wastewater and effluents, particularly from detergent manufacturing industries, holds significant relevance to environmental microbiology and public health. Industrial effluents contain complex mixtures of organic and inorganic compounds, surfactants, phosphates, heavy metals, and other chemical additives, which can alter the natural balance of aquatic ecosystems[11]. From an environmental microbiology perspective, these substances can exert selective pressure on microbial communities, leading to shifts in species composition, metabolic activity, and ecological functions. Such alterations often result in the enrichment of resistant microbial strains capable of degrading or tolerating harsh chemical environments[11].

Moreover, wastewater effluents can serve as reservoirs for pathogenic microorganisms, including *Escherichia coli*, *Salmonella spp.*, *Pseudomonas aeruginosa*, and *Enterococcus spp.*, which may pose direct threats to human and animal health[12]. The persistence of these pathogens in aquatic systems is further complicated by the presence of antimicrobial-resistant (AMR) bacteria, whose prevalence is enhanced by the selective pressure of detergent constituents and other contaminants[12]. This microbial resistance can spread through horizontal gene transfer, thereby escalating public health risks and complicating infection management[13].

In addition to microbial implications, effluent discharges from detergent industries contribute to broader environmental health concerns such as eutrophication, bioaccumulation of toxic compounds, and disruption of aquatic food chains[13]. Communities relying on contaminated water bodies for domestic, agricultural, or recreational purposes are particularly vulnerable to waterborne diseases and long-term exposure to chemical pollutants. Consequently, linking effluent characterization with environmental microbiology underscores the interconnectedness of industrial activity, ecosystem integrity, and human well-being[14].

Studying detergent industry effluents not only provides insights into the dynamics of microbial ecology in polluted environments but also highlights critical pathways through which industrial pollution translates into public health challenges. This perspective reinforces the need for integrated approaches to wastewater management that encompass environmental sustainability and public health protection[14].

2. 2 Global Perspective on Industrial Wastewater Pollution

Industrial wastewater pollution is a global environmental and public health concern, driven by rapid industrialization, urbanization, and inadequate waste management practices[15]. Across the world, industries such as textiles, petrochemicals, pharmaceuticals, tanneries, food processing, and detergents generate large volumes of effluents containing complex mixtures of organic matter, heavy metals, surfactants, dyes, and other persistent pollutants[15]. These effluents, when improperly treated or discharged directly into water bodies, contribute to the degradation of aquatic ecosystems, loss of biodiversity, and increased health risks for populations relying on contaminated water sources[16].

According to the United Nations World Water Development Report, over 80% of wastewater globally is released into the environment without adequate treatment. This situation is particularly severe in developing regions of Africa, Asia, and Latin America, where weak regulatory frameworks, poor enforcement of environmental standards, and limited investment in wastewater treatment infrastructure exacerbate pollution levels[17]. For example, in countries like India and Bangladesh, the textile and detergent industries are among the largest contributors to water pollution, releasing dyes, surfactants, and toxic compounds into rivers such as the Ganges and Buriganga. Similarly, industrial hubs in China have faced significant challenges with untreated wastewater contributing to the contamination of major river basins, affecting both agriculture and public health[17].

In contrast, developed countries in Europe and North America have established stricter environmental laws and advanced wastewater treatment technologies, resulting in better control of industrial pollution[18]. The European Union's Urban Waste Water Treatment Directive (91/271/EEC) and the United States Clean Water Act mandate industries to comply with stringent discharge limits, enforce monitoring, and adopt sustainable practices. Despite these measures, emerging contaminants such as pharmaceuticals, antimicrobial-resistant bacteria, and microplastics remain a growing challenge even in highly regulated regions[18].

Globally, the public health implications of industrial wastewater pollution are profound. Contaminated water is linked to outbreaks of diarrheal diseases, skin infections, reproductive disorders, and increased cancer risks due to prolonged exposure to toxic chemicals[19]. Additionally, effluents act as hotspots for the emergence and spread of antimicrobial resistance (AMR), a major threat identified by the World Health Organization (WHO)**.** Communities in close proximity to industrial zones often face disproportionate health risks, highlighting issues of environmental justice and inequality[19].

The global response to industrial wastewater pollution emphasizes the need for sustainable management strategies, including stricter enforcement of effluent standards, adoption of green chemistry, wastewater recycling, and advanced treatment methods such as membrane filtration, constructed wetlands, and microbial bioremediation[19].

International cooperation, capacity building, and investment in infrastructure are critical for addressing wastewater challenges in low- and middle-income countries where the burden of pollution is most severe[20].

Industrial wastewater pollution remains a pressing global issue, with significant ecological and public health impacts[20]. While progress has been made in developed regions, substantial gaps persist in many parts of the world. Bridging these gaps requires integrated approaches that combine science, policy, and community engagement to achieve safe and sustainable water management[20].

2.2.1 Types of Industrial Effluents and their Common Pollutants

Industrial effluents vary widely depending on the nature of the industry, the raw materials used, and the production processes employed. These effluents often contain complex mixtures of organic and inorganic substances, many of which pose risks to both environmental and public health[21]. For instance, effluents from the textile industry typically contain dyes, bleaching agents, detergents, heavy metals, and other chemical residues that are toxic and resistant to degradation [21]. In the food and beverage industry, wastewater is often characterized by high levels of organic matter, fats, oils, and grease, which can increase the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of receiving water bodies, thereby reducing dissolved oxygen available for aquatic life[22].

Pharmaceutical and chemical manufacturing industries release effluents rich in solvents, synthetic compounds, and active pharmaceutical ingredients that are not easily degraded in the environment. Such pollutants have been linked to the rise of antimicrobial resistance and endocrine-disrupting effects in humans and animals[23]. Petroleum refineries and related industries produce wastewater containing hydrocarbons, phenols, and suspended solids, which are known to contaminate soil and groundwater, causing long-term ecological damage[23]. Similarly, the paper and pulp industry generates effluents laden with lignin, chlorinated organic compounds, and high levels of suspended solids that can cause significant discoloration and toxicity in water systems[23].

Heavy metals such as cadmium, chromium, lead, mercury, and arsenic are common in effluents from mining, metallurgy, tanning, and electroplating industries[24]. These metals are non-biodegradable and can accumulate in sediments, aquatic organisms, and eventually in the food chain, leading to chronic health problems in humans, including neurological disorders and cancers[24]. Detergent and soap manufacturing industries, on the other hand, release wastewater containing high concentrations of surfactants, phosphates, and other additives. These pollutants contribute to eutrophication in water bodies, disrupt microbial communities, and alter the physicochemical balance of aquatic ecosystems[24].

Industrial effluents present a diverse array of pollutants ranging from organic matter and synthetic chemicals to toxic heavy metals and microbial contaminants[25]. The specific pollutant profile depends on the type of industry, but in all cases, improper disposal of these effluents has far-reaching consequences for environmental sustainability, microbial ecology, and public health[25].

2.2.2 Overview of Global Case Studies on Detergent and Chemical Industries

The detergent and chemical industries are among the most significant contributors to industrial wastewater pollution worldwide. Case studies from different regions have highlighted the environmental and public health impacts of effluents discharged from these sectors, underscoring the urgent need for stricter regulations and sustainable waste management practices[26].

In India, several studies on detergent manufacturing plants have revealed that their wastewater contains high levels of surfactants, phosphates, sodium salts, and bleaching agents. These effluents often exceed permissible discharge limits and are directly released into rivers and streams[26]. The excessive phosphate load has been strongly associated with eutrophication, where algal blooms deplete oxygen levels in water, causing mass fish kills and loss of biodiversity[27]. Researchers in Gujarat and Maharashtra have documented the contamination of groundwater sources near detergent factories, posing risks to drinking water safety and increasing cases of gastrointestinal illnesses in nearby communities[27].

A similar pattern has been observed in China, one of the largest producers of chemicals globally. Case studies in industrial hubs such as Guangdong and Jiangsu provinces have shown that chemical manufacturing plants discharge wastewater laden with volatile organic compounds (VOCs), dyes, synthetic detergents, and heavy metals[28]. These pollutants not only disrupt aquatic ecosystems but also bioaccumulate in fish and shellfish, raising concerns about food safety. Reports have further linked long-term exposure to contaminated water sources with rising incidences of cancers and reproductive health disorders among local populations[28].

In Europe, despite stringent wastewater management policies, case studies from countries such as Italy and Spain have shown that legacy pollution from older detergent and chemical plants continues to affect soil and river sediments[29]. In some regions, banned surfactants such as nonylphenol ethoxylates (NPEs) persist in the environment due to their resistance to degradation. This persistence has been linked to endocrine disruption in aquatic organisms, leading to reduced reproductive success and altered population dynamics in fish communities[29].

African case studies also highlight growing concerns. In Nigeria, research around Lagos and Ibadan has revealed that effluents from small- and medium-scale detergent manufacturers are often discharged untreated into open drains and rivers[29]. These discharges contain high concentrations of suspended solids, oils, phosphates, and microbial contaminants. Such pollution has degraded water quality in urban rivers and contributed to the spread of waterborne diseases. Similarly, in South Africa, studies on chemical industry effluents in the Vaal River system have shown contamination with toxic substances, including phenols and heavy metals, which affect both water quality and agricultural productivity in surrounding areas[30].

Global case studies on detergent and chemical industries demonstrate that effluents from these sectors are consistently associated with significant environmental damage and public health risks[30]. While high-income countries have established advanced treatment systems and regulatory frameworks, low- and middle-income countries still face challenges due to weak enforcement, limited resources, and rapid industrialization[31]. These examples highlight the need for improved effluent treatment technologies, strict regulatory monitoring, and sustainable practices to mitigate the long-term impacts of detergent and chemical industry pollution[31].

2.2.3 International Regulations and Guidelines

The regulation of wastewater effluents at the international level is guided by a set of standards and frameworks developed by key organizations such as the World Health Organization (WHO), the United States Environmental Protection Agency (USEPA), and the European Union (EU) [31]. These bodies recognize the environmental and public health risks associated with untreated or poorly treated industrial wastewater, including effluents from detergent and chemical industries, and have established guidelines to mitigate such impacts[32].

The World Health Organization (WHO) emphasizes the protection of water quality as a public health priority. Its guidelines focus on maintaining safe levels of microbial and chemical contaminants in wastewater, particularly in contexts where water is reused for agricultural irrigation, industrial operations, or domestic purposes[33]. WHO standards are widely adopted in developing nations as reference points for setting national effluent discharge limits, particularly concerning microbial pathogens and toxic chemical residues[33].

The United States Environmental Protection Agency (USEPA) has established one of the most comprehensive frameworks for wastewater management through the Clean Water Act (CWA). The USEPA regulates effluent discharges by setting pollutant-specific limits under the National Pollutant Discharge Elimination System (NPDES) [33]. For industries such as detergent manufacturing, parameters including biochemical oxygen demand (BOD), chemical oxygen demand (COD), pH, heavy metals, and surfactant concentrations are tightly regulated to minimize ecological damage and protect human health. The USEPA also regularly updates its effluent limitation guidelines (ELGs) to reflect technological advancements in wastewater treatment[33].

The European Union (EU) similarly enforces strict directives on wastewater management, notably through the Water Framework Directive (WFD) and the Urban Waste Water Treatment Directive (UWWTD). These frameworks require member states to monitor and control industrial effluents with particular attention to hazardous chemicals, eutrophication-inducing compounds, and microbial contaminants. EU standards emphasize not only compliance with discharge limits but also sustainable water resource management and ecological preservation[34].

Together, WHO, USEPA, and EU regulations provide global benchmarks for effluent management, offering structured approaches to pollutant control, environmental safety, and public health protection[34]. While implementation varies across regions depending on resources and enforcement capacity, these standards remain essential references for shaping national policies and guiding industries towards safer wastewater disposal practices[34].

2.2.4 Lessons from Developed and Developing Countries

The management of wastewater effluents from detergent and chemical industries varies significantly between developed and developing countries, largely due to differences in regulatory frameworks, institutional capacity, technological advancement, and economic priorities. Lessons drawn from these contrasting contexts highlight both challenges and opportunities for improving effluent management globally[35].

In developed countries, stringent regulatory frameworks, such as those enforced by the United States Environmental Protection Agency (USEPA) and the European Union (EU), have created strong incentives for industries to adopt advanced wastewater treatment technologies[35]. Industries in these regions are often required to comply with pollutant-specific discharge limits covering parameters such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), pH, heavy metals, surfactants, and microbial contaminants. Moreover, continuous monitoring systems and enforcement mechanisms ensure that non-compliance attracts severe penalties[35]. This has spurred innovation in treatment technologies, including membrane bioreactors, advanced oxidation processes, and biological nutrient removal systems, thereby reducing environmental and health risks while promoting sustainable industrial practices[35].

Conversely, developing countries face considerable constraints in wastewater management, including weak enforcement of existing laws, insufficient funding for wastewater infrastructure, and a lack of technical expertise[35]. While national regulatory bodies such as Nigeria's National Environmental Standards and Regulations Enforcement Agency (NESREA) and similar agencies in other low- and middle-income countries have set effluent discharge standards, compliance is often poor due to inadequate monitoring capacity and the high cost of installing modern treatment systems[35].

In many cases, effluents from detergent and chemical industries are discharged untreated or partially treated into water bodies, exacerbating environmental degradation and public health risks. The reliance on outdated technologies and the absence of incentives for industries to invest in environmentally sustainable practices further deepen the problem[36].

Despite these differences, important lessons can be drawn from both contexts. Developed countries demonstrate that strong regulatory enforcement, technological innovation, and industry accountability can significantly minimize the risks associated with industrial effluents[36].

Meanwhile, the experiences of developing countries underscore the importance of tailoring solutions to resource-constrained environments[36]. For example, low-cost and decentralized treatment options, such as constructed wetlands and anaerobic lagoons, may offer more feasible solutions than high-cost technologies in regions with limited financial capacity[36]. Additionally, public–private partnerships, community engagement, and capacity-building initiatives have been identified as critical pathways for bridging the gap between policy and practice in developing nations[36].

Ultimately, the key lesson lies in recognizing that while developed countries provide models of best practices, strategies for developing countries must prioritize affordability, scalability, and sustainability[37]. A hybrid approach that combines regulatory reform, adoption of cost-effective treatment technologies, and strengthened institutional capacity offers the most practical route to effective effluent management in resource-limited settings[37].

2.3 Physicochemical Characterization of Industrial Effluents

Physicochemical characterization of industrial effluents is an essential component of wastewater studies, as it provides a scientific basis for understanding the quality of water discharged into the environment[38]. Industrial effluents often contain a wide range of chemical substances and physical contaminants that influence their impact on ecosystems and public health. By assessing parameters such as pH, temperature, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS), heavy metals, and nutrient content, researchers can determine the extent of pollution and its potential risks[38].

The pH of effluents is particularly important as it influences the solubility and mobility of many chemical compounds. Alkaline or acidic discharges from detergent manufacturing plants, for instance, can disrupt aquatic ecosystems by altering the natural balance of water bodies[39]. Similarly, BOD and COD values are widely used indicators of organic pollution levels; elevated levels suggest high concentrations of biodegradable and non-biodegradable organic matter, which can deplete dissolved oxygen and threaten aquatic life[39]. Suspended and dissolved solids also play a significant role in water quality deterioration, as they reduce light penetration, affect photosynthesis, and may carry toxic substances[39].

Heavy metals such as lead, cadmium, chromium, and zinc are commonly present in industrial effluents, including those from detergent and chemical industries[40]. These elements are non-biodegradable and tend to accumulate in sediments and living organisms, posing long-term ecological and health hazards. In addition, nutrients like nitrogen and phosphorus, when present in excess, contribute to eutrophication, leading to algal blooms, fish kills, and loss of biodiversity[40].

The characterization of effluents also provides vital information for compliance monitoring with regulatory standards. International agencies such as the WHO, USEPA, and the European Union have established permissible limits for various physicochemical parameters to guide safe discharge practices[41]. In developing countries like Nigeria, however, weak enforcement of regulations often leads to uncontrolled disposal of industrial effluents into surface water and soil, increasing the risk of contamination[41].

Physicochemical analysis is not only a diagnostic tool for assessing pollution levels but also a foundation for designing effective treatment systems[41]. For industries such as detergent manufacturing, where surfactants, phosphates, and other chemical additives are prevalent, continuous monitoring of these parameters is critical to reducing their negative impacts on the environment and ensuring public health protection[41].

2.3.1 Impact of Detergents on Water Quality

Detergents, though essential in domestic and industrial cleaning, represent a significant source of water pollution when discharged into natural aquatic systems without adequate treatment. Their chemical constituents, particularly surfactants, phosphates, and other additives, alter the physicochemical and biological quality of receiving water bodies[41].

Surfactants are the active ingredients responsible for the cleaning action of detergents. In aquatic environments, they lower surface tension, thereby affecting gas exchange and disrupting aquatic organisms' physiological processes[41]. High concentrations of surfactants form stable foams on water surfaces, which impede oxygen transfer between air and water, leading to reduced dissolved oxygen levels[41]. This reduction can induce hypoxic conditions that threaten aquatic life, particularly fish and invertebrates. Additionally, surfactants have been shown to disrupt gill function in fish, impair enzyme activity, and increase membrane permeability in aquatic organisms, leading to toxic effects[42].

Phosphates, commonly used as detergent builders, are another major pollutant of concern. Once discharged into water bodies, phosphates act as nutrients that stimulate excessive growth of algae and aquatic plants, a process known as eutrophication[42]. Algal blooms not only deplete dissolved oxygen through respiration and decomposition but also produce toxins that further degrade water quality. The consequence is a cascade of ecological impacts, including fish kills, biodiversity loss, and the alteration of aquatic community structures. Moreover, eutrophication reduces the aesthetic and recreational value of water resources and increases the cost of water treatment for human consumption[43].

Other additives such as bleaching agents, optical brighteners, enzymes, and stabilizers also contribute to water quality deterioration. These compounds can be recalcitrant, persisting in the environment due to their low biodegradability, thereby accumulating in sediments and aquatic organisms[43]. Some breakdown products of detergents have been linked to endocrine disruption in aquatic fauna, affecting reproduction and population dynamics[43].

The physicochemical parameters of water, such as turbidity, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and pH, are often significantly elevated in detergent-contaminated effluents[44]. Elevated BOD and COD values indicate a high organic and chemical load, which exerts additional stress on aquatic ecosystems. The presence of surfactants and phosphates has also been associated with increased toxicity in combination with heavy metals and other pollutants, amplifying their ecological risks[44].

Detergents negatively influence water quality by altering its chemical balance, promoting eutrophication, reducing dissolved oxygen, and introducing persistent toxic compounds into aquatic environments. These impacts highlight the need for effective effluent treatment systems and strict regulatory enforcement to minimize the discharge of detergent-laden wastewater into the environment[45].

2.3.2 Comparative Studies

Comparative studies on the physicochemical characterization of industrial effluents, particularly from detergent and chemical industries, reveal important similarities and differences between Nigeria and other parts of the world[45]. In Nigeria, studies consistently report high levels of pollutants such as chemical oxygen demand (COD), biological oxygen demand (BOD), suspended solids, and surfactants in wastewater from detergent plants[45].

For instance, effluents from industries in Lagos, Ibadan, and Port Harcourt have been shown to exceed the permissible limits set by regulatory bodies, reflecting both the intensity of industrial activities and gaps in compliance with environmental standards[40]. These findings align with reports from other developing countries, such as India, Bangladesh, and Kenya, where effluent treatment is often inadequate due to weak regulatory enforcement and high operational costs for industries[41].

In contrast, studies from developed countries such as the United States, Germany, and Japan indicate relatively better compliance with international standards, largely due to stringent enforcement of regulations and widespread adoption of advanced wastewater treatment technologies[46]. For example, the European Union enforces strict limits on phosphate levels in detergent effluents, resulting in significantly lower eutrophication risks in aquatic ecosystems compared to regions where such controls are weak or absent. Moreover, in developed nations, industrial effluents undergo multistage treatment combining physical, chemical, and biological processes before discharge, thereby reducing their overall environmental impact[46].

Nevertheless, some global studies also highlight emerging pollutants, such as nonylphenol ethoxylates and microplastics, which are increasingly detected in treated effluents even in advanced economies[47]. This underscores the universal challenge of addressing novel contaminants beyond conventional pollutants like phosphates and surfactants[47]. When viewed together, these comparative insights reveal that while Nigeria and other developing nations face significant challenges in managing the classical pollutants of industrial effluents, developed countries are increasingly contending with newer, less-regulated contaminants[48]. This emphasizes the need for Nigeria not only to strengthen enforcement of existing effluent discharge standards but also to anticipate and incorporate strategies for addressing emerging pollutants in future regulatory frameworks[48].

2.3.3 Links between Physicochemical Parameters and Microbial Growth

The interaction between physicochemical properties of effluents and microbial growth is well established in environmental microbiology[49]. Parameters such as pH, temperature, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), turbidity, nutrient concentration, and the presence of heavy metals or toxic chemicals directly shape the composition, abundance, and activity of microbial communities in aquatic environments[49].

pH is one of the most critical factors influencing microbial survival and proliferation. Most bacteria thrive in near-neutral conditions, while acidic or alkaline pH levels suppress the growth of many species and promote the selection of tolerant or extremophilic organisms[50]. Similarly, temperature variations affect enzymatic reactions and metabolic activity, determining which microbial groups can persist in effluent-polluted environments[50].

Nutrient availability, particularly nitrogen, phosphorus, and organic carbon, strongly drives microbial growth. Elevated levels of phosphates and nitrates in detergent effluents, for example, can stimulate eutrophication, leading to algal blooms and subsequent shifts in microbial community dynamics[50]. The high organic load reflected in COD and BOD values also provides substrates that support heterotrophic bacterial growth, including opportunistic and pathogenic species such as *Escherichia coli*, *Klebsiella*, and *Pseudomonas*[50]. Conversely, very high BOD levels may deplete dissolved oxygen, creating hypoxic or anaerobic conditions that favor the proliferation of facultative and obligate anaerobes, such as sulfate-reducing bacteria and methanogens[50].

Toxic substances, including surfactants, heavy metals, and xenobiotic compounds, exert selective pressure on microbial populations. While they may inhibit sensitive microorganisms, they also promote the survival of resistant strains capable of biodegradation, efflux pumping, or biofilm formation[51]. Several studies have demonstrated that detergent effluents often select for multidrug-resistant bacteria, underscoring the strong link between effluent chemistry and microbial adaptation[51].

The interplay between physicochemical parameters and microbial growth not only influences ecological balance in receiving water bodies but also has significant public health implications[51]. Effluent characteristics that enhance microbial proliferation may increase the risk of waterborne infections, while selective pressures from pollutants contribute to the emergence and persistence of antimicrobial resistance[51]. Understanding these links is therefore vital for interpreting effluent impacts in both environmental and microbiological contexts[52].

2.4 Nigerian Context of Industrial Effluent Pollution

Industrial effluent pollution remains a major environmental and public health concern in Nigeria. The rapid pace of industrialization, coupled with inadequate infrastructure for wastewater treatment and weak enforcement of environmental regulations, has contributed significantly to the deterioration of water quality across the country[52]. Industrial clusters in major cities such as Lagos, Ibadan, Kano, Port Harcourt, and Kaduna generate large volumes of wastewater that are frequently discharged untreated into nearby rivers, streams, and open drains. This practice has led to contamination of surface and groundwater resources, adversely affecting aquatic life, agricultural productivity, and human health[52].

The Nigerian manufacturing sector is diverse, encompassing industries such as textiles, tanneries, breweries, petrochemicals, pharmaceuticals, food and beverages, and detergents. Many of these industries release effluents that are rich in organic matter, nutrients, heavy metals, oils, and chemical residues[53]. For instance, tannery and textile industries in Kano are known for their high chromium and dye effluents, while petrochemical industries in the Niger Delta discharge hydrocarbons and related compounds into the aquatic environment[53]. Detergent and soap factories, common in southwestern Nigeria including Ibadan, contribute significant amounts of surfactants, phosphates, and suspended solids that alter the physicochemical characteristics of receiving water bodies[53].

Studies conducted in different parts of the country consistently report effluent discharge values that exceed the permissible limits established by the Federal Ministry of Environment (FMEnv) and international standards such as those of the World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA) [54]. Parameters such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), heavy metals, and nutrient loads are often higher than recommended levels. This indicates poor or non-existent treatment of industrial wastewater before disposal[54].

The consequences of such pollution are far-reaching. Contaminated water sources increase the risk of waterborne diseases such as cholera, typhoid, and dysentery in nearby communities. Heavy metals like lead, cadmium, and mercury bioaccumulate in fish and other aquatic organisms, posing risks to food safety and human health through the food chain[55]. Excessive nutrient enrichment has also been implicated in eutrophication and fish kills in Nigerian rivers and lagoons. In agricultural settings, irrigation with polluted effluents introduces toxic substances into soils, reducing crop yields and affecting food security[55].

Institutional and regulatory frameworks exist in Nigeria to manage industrial pollution, such as the National Environmental Standards and Regulations Enforcement Agency (NESREA), established in 2007, and state environmental protection agencies[55]. However, challenges such as inadequate monitoring capacity, poor funding, lack of political will, and non-compliance by industries hinder effective enforcement. Many small- and medium-scale industries operate without effluent treatment plants, while larger industries with treatment facilities often underutilize or bypass them due to high operational costs[56].

Addressing industrial effluent pollution in Nigeria requires a combination of stricter enforcement of environmental laws, investment in affordable and effective treatment technologies, and increased public awareness of the health and ecological risks associated with effluent discharge. Strengthening partnerships between government, academia, and industry can also foster innovation in sustainable waste management practices[57].

2.4.1 History and Growth of Detergent and Chemical Industries

The detergent and chemical industries in Nigeria have evolved significantly over the past few decades, becoming important contributors to both the national economy and daily household consumption[57]. The roots of detergent production in Nigeria can be traced back to the mid-20th century, when multinational companies established operations in the country to meet the rising demand for cleaning and personal hygiene products[57]. At that time, industrial development in Nigeria was largely import-dependent, with most raw materials sourced from abroad and only limited local processing. However, the establishment of these industries marked the beginning of large-scale local production of soaps, detergents, and other chemical products[57].

By the 1970s and 1980s, following the oil boom and increased urbanization, the Nigerian market for detergents expanded rapidly. Growing populations in urban centers created higher demand for affordable cleaning agents, both for household and industrial purposes[58]. This period also witnessed government policies that encouraged import substitution and local manufacturing. Consequently, several indigenous manufacturers entered the market, producing powdered detergents, bar soaps, and liquid cleaning agents[58]. The detergent industry became increasingly competitive, with both multinational corporations and local firms vying for market share[59].

In more recent decades, the growth of the Nigerian detergent and chemical industries has been driven by technological advances, changing consumer preferences, and increased investment in production infrastructure[59]. The shift from traditional bar soaps to powdered and liquid detergents reflects both global trends and local lifestyle changes[59]. Furthermore, Nigeria's status as the most populous country in Africa has made it an attractive market for detergent manufacturers, ensuring continuous industry expansion. Local production has also been sustained by the availability of some raw materials such as palm oil, caustic soda, and other chemical inputs, although challenges in supply chain stability still persist[60].

The growth of these industries has had important socio-economic impacts, including employment generation, revenue contribution, and improved accessibility of hygiene products to a wide population [60]. However, this growth has also introduced environmental challenges, particularly in relation to effluent discharge into surrounding ecosystems. The rapid expansion of detergent factories, often located near residential areas and water bodies, has heightened concerns about wastewater contamination, ecological degradation, and public health risks[60]. While the Nigerian detergent industry continues to grow as a vital sector, its environmental footprint underscores the urgent need for effective waste management and effluent control measures[61].

2.4.2 Major Sources of Wastewater Pollution in Nigeria

Wastewater pollution in Nigeria has become a major environmental and public health concern, largely driven by the country's rapid industrialization and urbanization. Industrial hubs across the country contribute significantly to effluent discharge, with many lacking adequate wastewater treatment facilities[61]. The most critical sources of wastewater pollution can be traced to industrial clusters, where effluents are often released untreated or partially treated into nearby rivers, streams, and drainage channels, leading to contamination of aquatic and terrestrial ecosystems[61].

1. Oil and Gas Industry

Nigeria's oil and gas sector is a dominant source of wastewater pollution, particularly in the Niger Delta region. Effluents from petroleum refining, crude oil exploration, and petrochemical processing often contain hydrocarbons, heavy metals, and other toxic chemicals [31]. The discharge of oily sludge, drilling muds, and production water into rivers and wetlands has led to severe ecological degradation, affecting both biodiversity and the livelihoods of local communities dependent on fishing and farming[31].

2. **Food and Beverage Industry**

The food and beverage industry, concentrated in industrial cities such as Lagos, Ibadan, Aba, and Kano, generates large volumes of wastewater containing organic matter, fats, oils, sugars, and suspended solids[32]. Breweries, soft drink bottling companies, abattoirs, and food-processing factories contribute significantly to organic pollution of water bodies. The high biological oxygen demand (BOD) and chemical oxygen demand (COD) associated with their effluents often result in oxygen depletion in receiving waters, threatening aquatic life[32].

3. **Textile and Tannery Industry**

The textile and tannery industries, especially in Kano, Kaduna, and Aba, are among the largest contributors to chemical pollution. Effluents from these industries are often highly colored and contain toxic dyes, chromium, sulfides, and other harmful substances[33]. The tanning process, in particular, generates wastewater rich in heavy metals and salts, which accumulate in soils and water bodies, posing long-term ecological and health risks[33].

4. **Chemical and Detergent Industry**

Industrial hubs in Lagos, Ibadan, and Ogun State host a significant concentration of detergent and chemical manufacturing companies. Effluents from these factories typically contain surfactants, phosphates, alkalis, and other chemical residues[34]. When discharged untreated, these pollutants contribute to eutrophication, foaming in rivers, and disruption of aquatic ecosystems. The growth of chemical industries has heightened the risk of persistent organic and inorganic pollutants entering the environment[34].

5. **Breweries and Distilleries**

Nigeria has a rapidly growing brewery and distillery sector, with major hubs in Lagos, Aba, and Benin City. Wastewater from these industries is characterized by high organic loads, suspended solids, and nutrient content. Without adequate treatment, effluents from breweries contribute to foul odor, increased microbial activity, and algal blooms in nearby water bodies[35]

6. **Pharmaceutical and Paint Manufacturing**

Pharmaceutical plants and paint manufacturing industries in Lagos and Onitsha also release effluents that contain complex organic compounds, solvents, and heavy metals. These pollutants are often resistant to biodegradation, leading to long-term contamination of aquatic systems and bioaccumulation in fish and other organisms[36].

7. **Urban and Municipal Wastewater**

In addition to industrial activities, municipal wastewater from rapidly growing cities such as Lagos, Port Harcourt, and Abuja contributes heavily to pollution. Poorly managed sewage systems and indiscriminate discharge of household waste exacerbate the pressure on existing water bodies already receiving industrial effluents[37]. The major sources of wastewater pollution in Nigeria are concentrated in industrial hubs such as Lagos, Ibadan, Kano, Port Harcourt, Aba, Kaduna, and Onitsha**,** where clusters of industries discharge untreated effluents into rivers and drainage systems[38]. The absence of effective monitoring, enforcement of environmental regulations, and wastewater treatment infrastructure has allowed industrial pollution to persist, with far-reaching consequences for water quality, ecosystem health, and human well-being[38].

Several case studies from different regions of Nigeria highlight the scale and diversity of industrial effluent pollution, particularly from detergent and chemical industries. In Lagos, the nation's commercial hub, the rapid expansion of industrial estates such as Ikeja, Apapa, and Agbara has led to increased discharges of untreated or partially treated wastewater into surface waters[39]. Studies have reported high levels of chemical oxygen demand (COD), biochemical oxygen demand (BOD), heavy metals, and surfactants in effluents released into Lagos Lagoon and adjoining rivers. These pollutants not only degrade aquatic ecosystems but also affect fishing communities that rely heavily on these waters for livelihood[39].

In Ibadan, where several detergent and food processing industries are located, wastewater management remains inadequate, with many factories discharging effluents directly into open drains that flow into streams and rivers[40]. Research in the Oluyole industrial estate and its environs has revealed elevated concentrations of organic matter, suspended solids, and potentially pathogenic microorganisms in effluents. Such discharges have been linked to the pollution of nearby rivers, which are often used by local communities for domestic and agricultural purposes, thereby posing public health risks[40].

Port Harcourt, the center of Nigeria's oil and petrochemical activities, faces unique challenges from industrial effluents. Wastewater from refineries, petrochemical complexes, and associated industries is known to contain hydrocarbons, surfactants, and heavy metals, which significantly impair the water quality of the creeks and rivers in the

Niger Delta. The contamination not only threatens aquatic biodiversity but also exacerbates the already precarious environmental situation in oil-producing communities[41].

In Kano, a major industrial hub in Northern Nigeria, tanneries and textile industries are notorious for discharging untreated effluents rich in chromium, dyes, and surfactants into nearby water bodies, particularly the Jakara and Challawa Rivers[44]. These pollutants alter the physicochemical characteristics of the rivers and render them unfit for human consumption and irrigation. Several studies have documented the harmful impacts of these discharges on agricultural productivity, aquatic life, and the health of surrounding communities[43].

Collectively, these case studies underscore the widespread nature of industrial effluent pollution across Nigerian cities. While the types of pollutants vary depending on the dominant industrial activities, the common thread remains the inadequate treatment of wastewater before discharge, coupled with weak enforcement of environmental regulations[43]. The environmental and public health implications observed in Lagos, Ibadan, Port Harcourt, and Kano provide critical evidence of the urgent need for stricter monitoring, improved effluent management practices, and stronger policy enforcement to safeguard Nigeria's water resources[42].

2.4.3 National Environmental Regulations

Nigeria has established several regulatory frameworks to address the challenges of environmental pollution caused by industrial activities, including those from detergent and chemical manufacturing industries[45]. Prominent among these regulatory institutions are the Federal Environmental Protection Agency (FEPA), the National Environmental Standards and Regulations Enforcement Agency (NESREA), and the National Agency for Food and Drug Administration and Control (NAFDAC). Each of these agencies plays a unique role in ensuring that industrial effluents are managed in ways that minimize environmental and public health risks[46].

The Federal Environmental Protection Agency (FEPA), created in 1988, was Nigeria's first comprehensive institution with the mandate of protecting and improving the environment. FEPA laid the foundation for environmental governance in the country by formulating national policies, setting effluent discharge limits, and overseeing compliance by industries [46]. Although it was later subsumed under the Federal Ministry of Environment, FEPA's regulatory frameworks remain influential in shaping modern environmental policies in Nigeria[47].

Building on FEPA's legacy, the National Environmental Standards and Regulations Enforcement Agency (NESREA) was established in 2007 to provide stricter enforcement of environmental standards [47]. NESREA is particularly important in the context of industrial effluent management as it is mandated to ensure compliance with both national and international environmental laws, treaties, and standards. It has issued specific regulations governing the discharge of effluents into the environment, including permissible levels of physicochemical parameters such as pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and heavy metals[41]. Industries, including detergent manufacturers, are required to treat their effluents before discharge, but compliance remains a significant challenge due to inadequate enforcement and infrastructural deficits[41].

On the other hand, the National Agency for Food and Drug Administration and Control (NAFDAC), while primarily known for regulating food, drugs, and chemicals, also plays a role in monitoring the production processes of industries to ensure that hazardous substances do not negatively impact public health[42]. In the context of detergent manufacturing, NAFDAC regulates the composition of chemical inputs such as surfactants, phosphates, and other additives, with the aim of reducing their harmful effects when discharged into water bodies[42].

Despite the existence of these regulatory agencies, enforcement has been inconsistent. Weak institutional capacity, corruption, poor monitoring systems, and inadequate penalties for non-compliance have hindered the effectiveness of these regulations[45]. As a result, many detergent manufacturing industries in Nigeria discharge untreated or partially treated effluents into nearby rivers and streams, contributing to environmental degradation and public health concerns. Strengthening the coordination between NESREA, NAFDAC, and other regulatory bodies, as well as ensuring stricter enforcement of effluent standards, is essential for mitigating the risks posed by industrial wastewater pollution in Nigeria[46].

2.4.4 Challenges in Enforcement of Effluent Standards

Despite the existence of regulatory frameworks in Nigeria, such as those established by the National Environmental Standards and Regulations Enforcement Agency (NESREA), the Federal Environmental Protection Agency (FEPA), and other relevant bodies, enforcement of effluent standards remains a persistent challenge[47]. One of the key barriers lies in inadequate monitoring infrastructure. Many industrial hubs, including detergent manufacturing complexes, operate in regions where regular sampling and laboratory analysis of effluents are either irregular or completely absent due to limited technical capacity and funding constraints[48]. Without continuous surveillance, industries often discharge untreated or partially treated effluents directly into water bodies without fear of sanctions[48].

Corruption and weak governance also undermine enforcement. In some cases, industries bypass compliance through informal negotiations with inspectors, while penalties for non-compliance remain minimal compared to the profits generated[49]. This creates a situation where violating effluent standards is more economically attractive than investing in sustainable wastewater treatment technologies[50]. Furthermore, the lack of political will to prioritize environmental health issues exacerbates these challenges, as industrial growth and economic expansion are often pursued at the expense of environmental protection [50].

Another pressing issue is the scarcity of public awareness and stakeholder engagement. Communities living around industrial zones are often unaware of their rights to demand safe environmental practices, and civil society participation in monitoring is limited[51].

Additionally, coordination among regulatory agencies is weak, leading to duplication of efforts, unclear jurisdiction, and poor enforcement outcomes. For instance, while NESREA oversees industrial compliance, agencies such as NAFDAC or local environmental boards may also issue overlapping regulations, creating confusion and loopholes that industries exploit[52].

The absence of advanced effluent treatment infrastructure in many Nigerian industries further complicates compliance. Even where industries express willingness to treat wastewater, high costs of installation and maintenance of modern treatment plants deter investment [53]. In the detergent and chemical sector, where effluents are particularly complex due to high concentrations of surfactants, phosphates, and heavy metals, the lack of affordable treatment technologies creates a significant compliance gap[54].

The enforcement of effluent standards in Nigeria is hampered by institutional weaknesses, inadequate monitoring capacity, corruption, lack of stakeholder engagement, and infrastructural deficits[55]. Overcoming these challenges requires strengthening environmental governance, building technical capacity for monitoring, and promoting cost-effective technologies that enable industries to treat effluents sustainably[56].

2. 5. Microbial Profile of Industrial Effluents

Industrial effluents are complex mixtures of organic and inorganic substances that create unique ecological niches for microbial communities. The microbial profile of these effluents is shaped by the type of industry, the nature of the raw materials used, and the treatment processes (if any) prior to discharge[31]. Studies across different industrial sectors including food processing, textile, pharmaceutical, brewery, petroleum, and hospital settings have consistently reported a diverse range of microorganisms, encompassing both environmental saprophytes and opportunistic pathogens[32].

Bacteria are the most frequently encountered group in industrial effluents. Commonly isolated genera include *Escherichia*, *Klebsiella*, *Enterobacter*, *Pseudomonas*, *Staphylococcus*, *Streptococcus*, *Bacillus*, and *Clostridium*. Many of these organisms are indicators of fecal or organic contamination and possess metabolic capabilities that enable them to thrive in effluent-rich environments[33]. For instance, *Pseudomonas* species are well known for their ability to degrade hydrocarbons and xenobiotic compounds, while *Bacillus* species can tolerate a wide range of physicochemical conditions, including extremes of pH and temperature. The presence of coliforms, particularly *Escherichia coli*, often signals poor effluent management and potential public health risks[34].

Fungi and yeasts are also prominent in industrial effluents, particularly those with high organic loads such as food, beverage, and textile effluents. Genera such as *Aspergillus*, *Penicillium*, *Candida*, and *Saccharomyces* have been frequently reported[35]. These organisms play roles in the degradation of complex carbohydrates, proteins, and dyes, but some may also act as opportunistic pathogens in immunocompromised individuals[35].

Protozoa, algae, and viruses, though less studied, have also been detected in effluent-contaminated waters. Algal blooms, fueled by excess nutrients, can indirectly influence microbial populations by altering dissolved oxygen levels [36]. Enteric viruses, such as adenoviruses and enteroviruses, have been reported in untreated or poorly treated industrial and hospital effluents, raising concerns about waterborne disease transmission [37].

Importantly, many microbial isolates from industrial effluents exhibit multidrug resistance (MDR) to commonly used antibiotics, including β-lactams, aminoglycosides, tetracyclines, and fluoroquinolones[38]. This phenomenon has been linked to the selective pressure imposed by heavy metals, detergents, and pharmaceutical residues present in effluents. The occurrence of antimicrobial resistance genes (ARGs), such as *blaTEM*, *sul1*, *tetA*, and *qnr*, has also been documented, highlighting effluents as reservoirs and dissemination routes of resistance determinants in the environment[38].

The microbial profile of industrial effluents is diverse and dynamic, comprising both beneficial degraders of pollutants and harmful pathogens. This duality underscores the importance of monitoring effluent microbiology, not only for ecological balance but also for safeguarding public health[31].

2.5.1 Common Microorganisms Found in Effluents

Industrial effluents, particularly those from detergent and chemical manufacturing, often serve as reservoirs for diverse groups of microorganisms. These microbes thrive in wastewater because of the abundant organic matter, surfactants, nutrients, and sometimes heavy metals, which create unique ecological niches[36]. The microbial communities in effluents are typically heterogeneous and can include bacteria, fungi, protozoa, and, in some cases, viruses. Their composition largely depends on the chemical nature of the wastewater, treatment processes, and environmental factors such as temperature, pH, and dissolved oxygen[37].

Bacteria are the most dominant microorganisms in industrial effluents due to their metabolic versatility. Commonly reported bacterial genera include *Escherichia,* *Klebsiella, Pseudomonas, Bacillus, Enterobacter, Micrococcus,* and *Staphylococcus*[39]. Gram-negative bacteria, particularly members of the *Enterobacteriaceae* family, are frequently isolated because they are well adapted to polluted aquatic environments and are often indicators of fecal contamination and antimicrobial resistance[38]. Bacteria such as *Pseudomonas aeruginosa* and *Bacillus subtilis* are particularly relevant in detergent effluents, as they can degrade surfactants and organic matter, thereby playing a role in bioremediation. However, some of these bacteria are also opportunistic pathogens, raising public health concerns[39].

Fungi are another important group found in effluents. They are able to tolerate harsh chemical environments and utilize complex organic substrates that bacteria may not readily degrade. Common fungal species include *Aspergillus, Penicillium, Candida, Fusarium,* and *Trichoderma*[39]. These organisms are significant because they not only participate in nutrient recycling and organic matter degradation but also sometimes produce mycotoxins or cause opportunistic infections. In detergent-polluted environments, fungi can thrive on surfactants and contribute to biofilm formation[40].

Protozoa are less frequently studied compared to bacteria and fungi but remain an important component of effluent microbial communities. They act as predators of bacteria and play a role in regulating microbial populations[41]. Common protozoan genera such as *Paramecium, Amoeba, Euglena,* and *Vorticella* have been reported in wastewater environments. Their presence often indicates organic pollution, as they thrive in nutrient-rich conditions[42]. Furthermore, protozoa can act as reservoirs or carriers for pathogenic bacteria, protecting them from adverse conditions and disinfectants, thereby complicating wastewater treatment efforts[42].

The microbial profile of industrial effluents is diverse, with bacteria, fungi, and protozoa playing complementary roles in shaping the ecological dynamics of these environments[44]. While many of these microorganisms contribute to pollutant degradation, their persistence also raises concerns about antimicrobial resistance, pathogen transmission, and potential ecological imbalance when untreated effluents are discharged into natural water bodies[45].

2.5.2 Pathogenic and Non-Pathogenic Microbial Communities

Industrial effluents, including those from detergent manufacturing plants, often harbor a wide range of microbial communities that can be broadly classified into pathogenic and non-pathogenic groups[49]. The distinction between these two categories is important in understanding both ecological impacts and public health risks[48].

Pathogenic microorganisms present in effluents pose significant health hazards because they can cause infections when discharged into water bodies used for domestic, agricultural, or recreational purposes[49]. Bacteria such as *Escherichia coli* (especially pathogenic strains like *E. coli* O157:H7), *Salmonella spp.*, *Shigella spp.*, *Klebsiella pneumoniae*, *Vibrio cholerae*, and *Pseudomonas aeruginosa* have been consistently reported in wastewater studies. Fungal pathogens such as *Candida albicans* and *Aspergillus spp.* may also be present, especially in effluents rich in organic matter[50]. Protozoan pathogens like *Giardia lamblia* and *Entamoeba histolytica* have been detected in some industrial wastewater streams. The presence of these organisms in effluents is closely linked to human and animal health risks, particularly in regions where untreated wastewater enters surface waters used by communities [50].

On the other hand, non-pathogenic microorganisms are equally significant as they contribute to the ecological functioning of aquatic systems[51]. Many non-pathogenic bacteria, such as *Bacillus spp.*, *Micrococcus spp.*, and *Acinetobacter spp.*, participate in the natural degradation of organic compounds, including surfactants and phosphates present in detergent effluents. These organisms play an essential role in bioremediation, breaking down complex chemical pollutants into less toxic forms, and thereby reducing the overall environmental impact[50]. Some fungi, like *Penicillium* and *Trichoderma*, also exhibit pollutant-degrading properties and are being explored for their potential in wastewater treatment technologies[52].

The interaction between pathogenic and non-pathogenic microorganisms in effluents is complex. While pathogenic species pose a direct health threat, non-pathogenic species may suppress their growth through competition, antimicrobial compound production, or biofilm formation[51]. However, effluents often provide favorable conditions such as high nutrient loads, fluctuating pH, and varying oxygen levels that allow both categories to coexist[46].

From a public health perspective, monitoring the balance between pathogenic and non-pathogenic microbial communities is critical. High levels of pathogenic organisms indicate inadequate treatment and poor waste management practices, which can increase the risk of disease outbreaks[46]. Conversely, identifying beneficial non-pathogenic microbes provides opportunities for their harnessing in biotechnological applications such as bioaugmentation and wastewater treatment[47].

Thus, the microbial profile of effluents is not only a marker of pollution but also a reflection of potential health hazards and ecological opportunities[48]. Effective wastewater monitoring and treatment strategies must therefore account for both pathogenic and non-pathogenic communities to ensure environmental safety and public health protection[49].

2.5.3 Mechanisms of Microbial Survival in Harsh Effluent Conditions

Industrial effluents, particularly from detergent and chemical industries, often create extremely hostile environments for microbial communities due to the presence of high concentrations of surfactants, heavy metals, toxic organic compounds, and extreme variations in pH, temperature, and dissolved oxygen[50]. Despite these unfavorable conditions, numerous microorganisms not only survive but also thrive in such ecosystems. Their survival is attributed to an array of physiological, biochemical, and genetic mechanisms that allow them to adapt, resist, and even utilize components of the effluents as sources of energy or carbon[51].

One major mechanism involves cellular adaptation through structural modifications**.** Many effluent-dwelling bacteria, such as *Pseudomonas*, *Bacillus*, and *Acinetobacter*, alter their cell membrane composition to resist the disruptive effects of surfactants and detergents, which normally solubilize lipids and destabilize membranes[52]. Similarly, some fungi develop thickened cell walls and increased melanin production, providing protection against oxidative stress and chemical toxicity[52].

Another survival strategy is the production of efflux pumps and detoxifying enzymes**.** Efflux systems actively expel harmful chemicals, heavy metals, or antibiotics from the microbial cell, reducing intracellular toxicity[53]. At the same time, enzymes such as catalases, peroxidases, superoxide dismutases, and phosphatases mitigate oxidative stress or degrade toxic compounds. In detergent-rich effluents, microorganisms such as *Pseudomonas aeruginosa* have been shown to produce specialized enzymes like alkylsulfatases and esterases that break down surfactants, not only reducing toxicity but also providing carbon and energy sources[54].

Biofilm formation is another critical mechanism of microbial persistence in hostile effluents. Within biofilms, microbial cells embed themselves in extracellular polymeric substances (EPS), which act as protective barriers against toxins, extreme pH, and antimicrobial agents[60]. This communal lifestyle also facilitates horizontal gene transfer, enabling rapid sharing of resistance and survival genes among microbial populations[61].

Microorganisms also employ genetic adaptations to withstand effluent stress. Horizontal gene transfer via plasmids, transposons, and bacteriophages spreads resistance determinants across microbial communities, including genes for heavy metal resistance, xenobiotic degradation, and multidrug efflux systems[54]. Some microbial populations evolve specialized catabolic pathways that allow them to metabolize xenobiotics such as phenols, chlorinated hydrocarbons, and detergent by-products[65].

In addition, microbes adapt through physiological tolerance mechanisms such as sporulation, dormancy, and metabolic shifts[61]. Spore-forming bacteria like *Bacillus sp.* survive prolonged exposure to toxic effluents by forming resistant spores, which germinate when conditions become favorable. Similarly, some bacteria and fungi enter dormant states with minimal metabolic activity, allowing them to endure extreme stress until conditions improve[63].

Symbiotic and competitive interactions play important roles in microbial persistence. Some microorganisms engage in cooperative degradation of pollutants, where one species partially degrades a toxic compound into intermediates that can be further metabolized by another species[51]. In other cases, microbial competition ensures that only the most resistant or adaptive strains dominate effluent ecosystems, contributing to a highly selective microbial profile[52].

The ability of microorganisms to withstand and adapt to the harsh physicochemical conditions of industrial effluents underscores their ecological resilience and potential for biotechnological applications[48]. Understanding these survival mechanisms is crucial, not only for predicting microbial risks to public health but also for exploring the use of effluent-adapted microorganisms in bioremediation strategies[49].

Evidence from multiple regions shows that detergent and allied chemical manufacturing effluents frequently harbor dense, diverse, and often pathogenic microbial communities [31]. In southwestern Nigeria, surveys around industrial estates in Ibadan and Lagos have documented high total heterotrophic counts and recurrent isolation of *Escherichia coli*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, *Enterococcus* spp., and *Staphylococcus aureus* from outfalls receiving detergent-rich discharges[32]. These organisms co-occur with elevated surfactants and phosphates; the nutrient load and organic carbon in such effluents support rapid microbial proliferation, while sublethal chemical stress selects for biofilm-forming, detergent-tolerant phenotypes[33]

Work from Kano's mixed industrial corridors, where chemical and textile activities intersect, has similarly reported coliform contamination and opportunistic pathogens in channels receiving combined detergent and dye effluents[34]. Here, chromium and other metals common to ancillary processes correlate with higher prevalence of metal-tolerant, multidrug-resistant strains, including *Pseudomonas* and *Acinetobacter*, suggesting concurrent selection by surfactants and metals[35].

In South Africa's Vaal system, downstream of detergent and chemical works, studies have detected enteric bacteria, *Candida* spp., and filamentous fungi such as *Aspergillus* in foaming stretches of effluent-impacted reaches[36]. Fungal isolates thrive where surfactant foams and organic residues accumulate, and mixed bacterial fungal biofilms have been observed on channel walls and sediments, providing reservoirs for persistent contamination[37].

Indian case studies from detergent clusters in Gujarat and Maharashtra consistently report high counts of fecal indicators and opportunists (e.g., *E. coli*, *Salmonella*, *Vibrio* spp.) alongside strong surfactant signals[38]. Treatment shortfalls particularly underdesigned primary units without effective biological polishing are associated with seasonal spikes in coliforms during warmer months, when higher temperatures accelerate microbial growth[39].

In parts of coastal China with large chemical–detergent parks, investigations of drainage canals have revealed abundant *Pseudomonas*, *Aeromonas*, and *Enterobacter* spp., with frequent detection of extended-spectrum β-lactamase (ESBL) phenotypes[40]. Metagenomic snapshots indicate enrichment of genes for xenobiotic degradation (e.g., alkylsulfatases) co-localized on mobile elements with antibiotic resistance genes, highlighting effluents as hotspots for horizontal gene transfer[40]

Bangladesh's peri-urban detergent and soap workshops discharging to small rivers provide another example routine culturing identifies thermotolerant coliforms and *Vibrio* spp., while protozoa such as *Vorticella* and *Amoeba* proliferate in nutrient-rich ponds receiving intermittent releases. The protozoa can shelter pathogenic bacteria within biofilms and intracellularly, complicating disinfection efforts[41]. North African case reports (e.g., Morocco) near soap and surfactant plants have isolated *Enterococcus faecalis*, *E. coli*, *Pseudomonas*, and yeasts from effluent-fed irrigation canals. Where reuse occurs informally for peri-urban agriculture, pathogens detected in water have been mirrored on leafy vegetables, underscoring food-chain transmission risks[42].

Across these settings, several common themes emerge: (i) detergent effluents provide ample carbon and phosphate that fuel microbial blooms; (ii) surfactants and co-contaminants (metals, phenolics) impose selective pressures that favor stress-tolerant, biofilm-forming, and often antimicrobial-resistant taxa; (iii) incomplete treatment or bypass events drive episodic peaks in pathogen loads; and (iv) mixed bacterial, fungal, protozoan consortia stabilize contamination and facilitate resistance and catabolic gene exchange[43]. These case studies collectively reinforce the necessity of robust, multi-stage treatment (including effective biological steps), routine microbiological surveillance (pathogens and resistance markers), and strict compliance monitoring around detergent and chemical manufacturing complexes[44].

2.5.4 Emerging Microbial Contaminants

In recent years, growing attention has been paid to emerging microbial contaminants in industrial effluents, particularly from detergent and chemical manufacturing industries[37]. Unlike conventional pathogens, these organisms may not always cause immediate illness in healthy individuals, but they pose serious risks in vulnerable populations or under specific environmental conditions. Among the most concerning are opportunistic pathogens, antimicrobial-resistant strains, and biofilm-forming organisms[38].

Opportunistic pathogens such as *Pseudomonas aeruginosa*, *Acinetobacter baumannii*, *Klebsiella pneumoniae*, and certain species of *Candida* have been identified in detergent effluents[38]. These microbes are capable of surviving in nutrient-poor, chemically harsh environments due to their metabolic versatility and adaptive resistance mechanism[39]s. Once released into natural water systems, they can proliferate and cause infections in immunocompromised individuals, including skin, respiratory, and urinary tract infections[39].

Biofilm-forming bacteria present another critical concern. Organisms such as *Escherichia coli*, *Enterococcus faecalis*, and *Pseudomonas spp.* often adhere to surfaces in effluent channels and receiving waters, producing extracellular polymeric substances (EPS) that protect them from desiccation, chemical toxicity, and antimicrobial agents [40]. Biofilms not only enhance microbial survival but also serve as reservoirs for antimicrobial resistance genes, facilitating horizontal gene transfer between diverse microbial species[40].

Furthermore, studies have shown that emerging contaminants in detergent effluents may include multidrug-resistant bacteria that carry extended-spectrum β-lactamases (ESBLs), carbapenemases, and plasmid-mediated resistance genes[41]. These microbes, when released into the environment, contribute to the global challenge of antimicrobial resistance by contaminating soil, groundwater, and surface waters[41].

The persistence of such emerging contaminants is also linked to their ability to exploit residual organic compounds, surfactants, and phosphates present in effluents. This selective pressure promotes the survival of resistant and resilient strains, allowing them to outcompete more sensitive microorganisms[42]. Comparative reports from countries such as India, Nigeria, and Brazil highlight the increasing detection of *Enterobacteriaceae* and *Stenotrophomonas maltophilia* in detergent effluents, illustrating a global public health concern[42].

Emerging microbial contaminants in detergent industry effluents represent a convergence of environmental pollution and public health risks[40]. Opportunistic pathogens, biofilm formers, and multidrug-resistant microbes not only threaten aquatic ecosystems but also raise the possibility of transmission of hard-to-treat infections in human populations[43]. Addressing these concerns requires stricter monitoring of microbial profiles in effluents, improved effluent treatment technologies, and alignment with global antimicrobial resistance containment strategies[44].

2. 6 Antibiotic Resistance in Effluent Microbes

The growing concern of antibiotic resistance has gained global recognition, and industrial effluents have emerged as an important but often underestimated reservoir of resistant microorganisms[46]. Wastewater from detergent and chemical industries frequently contains a mixture of organic compounds, heavy metals, surfactants, and antimicrobial residues that create selective pressure for the survival and proliferation of resistant microbial populations[46]. When released untreated or partially treated into the environment, these effluents contribute to the dissemination of antibiotic resistance genes (ARGs) across diverse microbial communities[47].

Several studies have documented the presence of multidrug-resistant bacteria in industrial effluents, including members of the genera *Escherichia*, *Klebsiella*, *Pseudomonas*, and *Enterococcus*[47]. These organisms not only survive in harsh wastewater conditions but also harbor plasmids, transposons, and integrons that facilitate horizontal gene transfer. This enhances the spread of resistance determinants among environmental and potentially pathogenic microorganisms[47]. The presence of detergents and surfactants in effluents may also co-select for resistance by altering membrane permeability or enabling biofilm formation, further increasing microbial resilience[48].

The issue of antibiotic resistance in effluents is not restricted to bacteria alone. Resistant fungi and protozoa have also been identified in wastewater streams, raising additional concerns for environmental and public health[49]. Effluent discharge into surface waters often leads to the contamination of aquatic ecosystems, irrigation sources, and, ultimately, the food chain. This creates a pathway for resistant microbes and genes to move from industrial sites into human and animal populations[49].

Globally, research has emphasized the role of effluents as hotspots for resistance evolution, particularly in regions where effluent treatment systems are inadequate [50]. Developing countries, including Nigeria, face a higher burden due to weak enforcement of environmental standards and limited treatment infrastructure[50]. Effluent-associated antibiotic resistance becomes a critical public health risk, exacerbating the already growing challenge of antimicrobial resistance in clinical settings[51].

Understanding antibiotic resistance in effluent microbes is therefore essential for developing integrated approaches to wastewater management, public health protection, and antimicrobial stewardship[51]. Addressing this problem requires not only improved treatment technologies but also strict regulatory oversight, continuous monitoring, and cross-sector collaboration within a One Health framework[52].

2.6.1 Effluents as Reservoirs of Antibiotic Resistance Genes

Effluents from domestic, hospital, and industrial sources are increasingly recognized as critical reservoirs of antibiotic resistance genes (ARGs) [53]. These waste streams often contain a complex mixture of antibiotics, disinfectants, surfactants, heavy metals, and other chemical contaminants that exert selective pressure on microbial communities. Under such conditions, bacteria that harbor resistance determinants are favored, leading to the persistence and enrichment of ARGs in effluent environments[54].

ARGs in effluents are not confined to a single microbial species but are distributed across diverse populations, including both pathogenic and non-pathogenic organisms. Studies have demonstrated that *Escherichia coli*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, and other opportunistic pathogens isolated from wastewater frequently harbor extended-spectrum β-lactamase (ESBL) genes, carbapenemase genes, and resistance determinants against fluoroquinolones, aminoglycosides, and tetracyclines. Non-pathogenic bacteria present in effluents can also act as reservoirs, serving as gene donors during horizontal gene transfer events[55].

Horizontal gene transfer mechanisms such as conjugation, transformation, and transduction play a central role in the dissemination of ARGs within effluent environments[56]. Mobile genetic elements, including plasmids, integrons, and transposons, enhance the mobility of resistance genes, enabling their spread across taxonomically diverse microorganisms. This increases the risk that ARGs acquired in effluent ecosystems may eventually reach clinically relevant pathogens[57].

Furthermore, untreated or inadequately treated effluents discharged into surface water bodies provide a pathway for the widespread distribution of ARGs in natural ecosystems. Such dissemination poses a major risk to human and animal health, as water used for irrigation, aquaculture, and domestic purposes becomes a conduit for resistant microbes[58]. In developing regions such as Nigeria, where effluent treatment infrastructure is often insufficient, the risk of environmental amplification of ARGs is significantly heightened[59].

Effluents therefore represent not only a source of microbial contamination but also an evolutionary hotspot where selective pressures, microbial diversity, and gene transfer mechanisms converge to drive the persistence and dissemination of resistance genes[60]. Recognizing effluents as reservoirs of ARGs underscores the urgent need for environmental monitoring, improved wastewater treatment, and integration of environmental microbiology into antimicrobial resistance surveillance frameworks [50].

2.6.2 Multidrug-resistant Bacteria from Industrial Discharges

Industrial discharges, particularly from detergent and chemical manufacturing plants, are increasingly identified as significant sources of multidrug-resistant (MDR) bacteria. These effluents contain a complex mixture of chemical agents, including surfactants, solvents, heavy metals, and residual antimicrobial compounds, which collectively create selective pressure favoring the survival of resistant bacterial strains[51]. Microorganisms exposed to such stressors often acquire resistance not only to one class of antibiotics but to multiple classes, leading to the emergence and persistence of MDR populations in the effluent environment[51].

Bacteria isolated from industrial effluents often include members of the *Enterobacteriaceae* family, *Pseudomonas*, *Acinetobacter*, and *Staphylococcus* species. These organisms frequently exhibit resistance to β-lactams, aminoglycosides, fluoroquinolones, tetracyclines, and sulfonamides, which significantly complicates treatment options if transmitted to humans or animals[52]. Evidence from studies in both developed and developing countries indicates that untreated or partially treated industrial wastewater can act as a reservoir and amplifier of MDR bacteria, contributing to the global spread of antimicrobial resistance[52].

The mechanisms underlying multidrug resistance in effluent-derived bacteria are diverse. Efflux pumps, enzymatic degradation of antibiotics, target site modifications, and the acquisition of mobile genetic elements such as plasmids, integrons, and transposons all play critical roles[53]. Horizontal gene transfer in effluent environments allows the rapid dissemination of MDR determinants among bacterial populations, further enhancing their survival and persistence[53].

Industrial effluents also facilitate the formation of biofilms, which provide additional protection to bacteria against chemical and antibiotic stress. Biofilm-associated bacteria demonstrate heightened resistance to antimicrobial agents compared to their planktonic counterparts, making effluent ecosystems particularly conducive to the maintenance of MDR populations[54].

In the context of Nigeria, studies of effluent from detergent and chemical industries in urban centers such as Lagos, Ibadan, and Port Harcourt have identified a high prevalence of MDR bacteria[55]. These findings highlight the need for stringent effluent treatment, regular microbial surveillance, and integration of antimicrobial resistance monitoring into environmental regulatory frameworks[55]. Recognizing industrial discharges as critical sources of MDR bacteria is essential for addressing both environmental and public health risks associated with wastewater pollution[55].

2.6.3 Horizontal Gene Transfer in Aquatic Environments

Horizontal gene transfer (HGT) is a central mechanism by which bacteria acquire and disseminate antibiotic resistance genes in aquatic environments, including industrial effluents[57]. Unlike vertical transmission, which occurs during cell division, HGT allows the direct transfer of genetic material between unrelated bacterial species, facilitating rapid adaptation to environmental stressors such as antimicrobial compounds, heavy metals, and detergents commonly found in industrial wastewater[57].

Three primary mechanisms mediate HGT in aquatic environments: transformation, transduction, and conjugation. Transformation involves the uptake of free DNA fragments released from lysed cells, allowing recipient bacteria to acquire new traits, including resistance genes[58]. Transduction occurs when bacteriophages transfer genetic material between bacterial cells, while conjugation involves the direct transfer of plasmids carrying resistance determinants through cell-to-cell contact[58]. Among these, conjugation is often considered the most significant contributor to the spread of multidrug resistance in effluent-impacted waters, as plasmids frequently carry multiple resistance genes[26].

Environmental factors in effluents, such as high nutrient loads, variable pH, temperature fluctuations, and the presence of chemical stressors, can enhance HGT by promoting bacterial survival and increasing cell-to-cell contact[40]. Biofilms, which are commonly formed on surfaces within wastewater systems, provide a highly conducive microenvironment for gene exchange. Within these structured communities, bacteria exist in close proximity, enabling efficient plasmid transfer and the establishment of persistent reservoirs of resistance genes[41].

Numerous studies have documented the occurrence of HGT in industrial effluents. Effluents from detergent and chemical manufacturing plants often contain diverse bacterial populations, including opportunistic pathogens and environmental strains, which interact and exchange genetic material[42]. This exchange not only perpetuates multidrug resistance but also increases the likelihood of resistance genes entering human and animal pathogens once effluent-contaminated water reaches natural water bodies[42].

In the Nigerian context, research has highlighted that untreated or poorly treated industrial effluents serve as hotspots for HGT, underscoring the role of industrial wastewater in the environmental dissemination of antimicrobial resistance[43]. Addressing HGT in effluent-impacted waters requires integrated strategies, including advanced effluent treatment, monitoring of resistance genes, and environmental risk assessment to prevent the propagation of antibiotic resistance in aquatic ecosystems[43].

2.6.4 Nigerian Case Studies on Antibiotic Resistance in Effluents

Nigeria's rapid industrialization, particularly in urban centers such as Port Harcourt, Lagos, and Jos, has led to increased generation of industrial effluents rich in organic matter, detergents, and antimicrobial agents. These effluents often lack adequate treatment before being discharged into the environment, creating hotspots for the proliferation of antibiotic-resistant bacteria (ARB)[26].

A notable study conducted in Port Harcourt assessed the presence of ARB in industrial wastewater. The wastewater samples, collected at discharge points, exhibited elevated levels of total dissolved solids and chemical oxygen demand, indicative of high organic and chemical loads[27]. Microbial analysis revealed the presence of *Pseudomonas aeruginosa*, *Escherichia coli*, *Enterococcus faecalis*, and *Bacillus subtilis*, with resistance to multiple antibiotics, including up to seven antibiotics among Gram-negative isolates and up to four among Gram-positive isolates. *P. aeruginosa* exhibited the highest multiple antibiotic resistance (MAR) index of 0.7, underscoring the significant role of industrial wastewater in harboring ARB and posing risks to public health and ecosystems[28].

In Jos, Nigeria, research focused on effluents from detergent and food industries identified *Pseudomonas* and *Bacillus* species as prevalent microorganisms[28]. These bacteria demonstrated the ability to degrade organic pollutants, suggesting their potential in bioremediation processes. However, the presence of such bacteria also indicates the possibility of harboring resistance genes, which could be transferred to other pathogenic organisms, complicating treatment efforts[28].

These case studies highlight the critical need for stringent monitoring and regulation of industrial effluents in Nigeria. Implementing effective treatment protocols and enhancing public awareness are essential steps in mitigating the spread of antibiotic resistance originating from industrial wastewater[29].

2.6.5 Global One Health perspective

The emergence and spread of antibiotic-resistant bacteria (ARB) in industrial effluents is not just a localized concern but a global public health challenge[26]. The One Health approach recognizes the interconnectedness of human, animal, and environmental health, emphasizing that the dissemination of resistance genes in environmental reservoirs, such as wastewater, can have profound implications across these domains[26].

Industrial effluents, particularly from detergent and chemical manufacturing plants, often contain complex mixtures of organic pollutants, heavy metals, and residual antimicrobials.

These substances exert selective pressure on microbial communities, promoting the survival and propagation of resistant strains[27]. Once released into aquatic environments, these resistant bacteria can interact with human and animal pathogens, facilitating horizontal gene transfer of resistance determinants. This contributes to the global burden of multidrug-resistant infections, complicating treatment strategies in both clinical and veterinary settings[27].

Case studies from Europe, the United States, and Asia illustrate the significance of industrial effluents as hotspots for antibiotic resistance. For example, untreated or partially treated wastewater in certain regions of India and China has been linked to elevated levels of extended-spectrum beta-lactamase (ESBL) producing *Escherichia coli* and *Klebsiella* species in rivers used for agriculture and domestic purposes[28]. Similarly, European monitoring programs under the European Union's Water Framework Directive have detected antibiotic residues and resistant bacteria in effluent-impacted water bodies, highlighting the role of industrial discharges in environmental dissemination[29].

From a One Health perspective, interventions must be integrative and multidisciplinary. Strategies include: improving industrial wastewater treatment technologies to reduce microbial load and antibiotic residues, implementing robust environmental surveillance programs, and fostering collaboration between public health authorities, environmental agencies, and industry stakeholders[30]. These measures aim to limit the environmental spread of resistance genes, thereby protecting human and animal populations globally while maintaining ecosystem integrity[31].

Industrial effluents are critical environmental reservoirs of antibiotic resistance. The One Health framework underscores the necessity of addressing this issue holistically, acknowledging the intertwined nature of environmental contamination, microbial evolution, and global health security[32].

2.7 Public Health and Environmental Risks

Industrial effluents, particularly from detergent and chemical manufacturing complexes, present a wide array of public health and environmental risks[33]. These discharges typically contain mixtures of organic compounds, surfactants, phosphates, heavy metals, and microbial contaminants, all of which can adversely affect aquatic ecosystems and human communities that depend on these water resources[33]. The presence of pathogenic microorganisms and antibiotic-resistant bacteria further exacerbates the threat, creating a conduit for waterborne diseases and the spread of resistance genes[33].

From a public health standpoint, exposure to contaminated water—whether through drinking, recreational activities, or agricultural use can result in gastrointestinal infections, skin irritations, and more severe systemic illnesses[34]. Populations in low-income or peri-urban areas, where access to treated water is limited, are particularly vulnerable. In addition, occupational exposure among workers at or near industrial sites can increase the risk of respiratory problems and dermal infections due to contact with untreated effluents[35].

Environmental risks are equally significant. Effluent discharge alters the physicochemical characteristics of receiving water bodies, leading to changes in pH, turbidity, dissolved oxygen, and nutrient levels[36]. Elevated phosphate and nitrate concentrations promote eutrophication, resulting in algal blooms that deplete oxygen and threaten aquatic life. Surfactants and heavy metals exert toxic effects on fish, invertebrates, and plants, disrupting local biodiversity and ecosystem balance[37]. Furthermore, industrial effluents act as reservoirs for microbial communities that can survive under harsh conditions, including opportunistic pathogens and biofilm-forming bacteria, which complicate natural biodegradation processes[38].

The cumulative effect of these risks is a direct link between industrial activities, environmental degradation, and human health. This underscores the importance of regular monitoring of effluents, strict adherence to environmental regulations, and implementation of effective wastewater treatment strategies[39]. By mitigating the release of hazardous substances and controlling microbial contamination, industrial operators can reduce both ecological damage and public health hazards, aligning with sustainable development and environmental stewardship goals[39].

2.7.1 Risks of Human Exposure

Human exposure to industrial effluents occurs through multiple pathways, each presenting distinct health risks[27]. One of the most direct routes is through contaminated drinking water. Inadequately treated or untreated effluents discharged into rivers, streams, or groundwater can introduce pathogenic microorganisms, chemical pollutants, and heavy metals into community water supplies[28]. Consumption of such water can lead to gastrointestinal infections, including diarrhea, cholera, and dysentery, as well as chronic health conditions like heavy metal toxicity, liver and kidney damage, and endocrine disruption[24].

Another critical route is the food chain. Crops irrigated with wastewater or fish harvested from contaminated water bodies can bioaccumulate chemical pollutants, surfactants, and antibiotic-resistant bacteria[24]. These contaminants then enter human diets, potentially causing long-term health consequences, including antibiotic-resistant infections, bioaccumulation of toxic substances, and disruption of gut microbiota. This pathway underscores the interconnectedness of industrial effluents, agriculture, and food safety[27].

Recreational exposure is also a concern, particularly in communities living near industrial zones where effluents flow into rivers, lakes, or ponds used for swimming, fishing, or washing. Contact with polluted water can lead to skin infections, eye irritations, and respiratory problems, especially when effluents contain chemical irritants, detergents, or microbial pathogens[28]. Children are particularly vulnerable due to their higher water intake relative to body weight and increased likelihood of direct contact with contaminated water[28].

Collectively, these exposure pathways highlight the urgent need for strict monitoring of effluent quality, public education on risks, and robust water treatment interventions. By addressing these exposure risks, policymakers and industry stakeholders can reduce human health impacts while promoting sustainable use of water resources[29].

2.7.2 Ecological Effects

Industrial effluents, particularly from detergent and chemical manufacturing, pose serious ecological threats to aquatic ecosystems[20]. The release of untreated or poorly treated wastewater introduces a range of pollutants, including surfactants, phosphates, heavy metals, and organic compounds, which can alter the physical and chemical properties of water bodies[21]. One immediate and visible consequence is fish kills, often resulting from oxygen depletion caused by high biochemical oxygen demand (BOD) and chemical toxicity[21]. Surfactants and detergents can damage fish gills, impair respiration, and disrupt osmoregulation, leading to mass mortality events[22].

Beyond acute fish deaths, effluents contribute to long-term biodiversity loss. Elevated nutrient levels, particularly phosphates and nitrates, can trigger eutrophication, resulting in excessive algal growth. Algal blooms reduce light penetration and oxygen levels, creating hypoxic conditions that are inhospitable for sensitive aquatic species[23]. This disruption of the aquatic food web can lead to the decline of invertebrates, amphibians, and fish species, while favoring tolerant, often opportunistic, species[23].

Chemical pollutants can also bioaccumulate in aquatic organisms, affecting reproduction, growth, and survival rates. Heavy metals like cadmium, lead, and mercury can accumulate in fish tissues, causing physiological stress and impairing reproductive success[24]. Persistent exposure to antimicrobial compounds in effluents can alter microbial communities, affecting nutrient cycling and ecosystem functioning[24].

The ecological impact of industrial effluents is often exacerbated in developing countries, where enforcement of environmental regulations is weak, and treatment infrastructure is limited[25]. These ecological disturbances not only reduce aquatic biodiversity but also compromise ecosystem services, such as water purification, fisheries productivity, and recreational opportunities. Monitoring and mitigating these impacts through proper effluent treatment, environmental regulation, and ecosystem management are essential for maintaining the health and resilience of aquatic ecosystems[25].

2.7.3 Link to Sustainable Development Goals

The contamination of water bodies by industrial effluents from detergent and chemical manufacturing has significant implications for the achievement of several Sustainable Development Goals (SDGs)[34]. SDG 3, which aims to ensure healthy lives and promote well-being for all, is directly impacted as polluted water sources increase the risk of waterborne diseases, exposure to toxic chemicals, and the spread of antimicrobial-resistant pathogens[34]. Communities relying on contaminated water for drinking, cooking, or recreation are particularly vulnerable to gastrointestinal infections, skin disorders, and other health complications[34].

SDG 6, which focuses on clean water and sanitation, is closely tied to effluent management. Untreated or inadequately treated wastewater degrades water quality, making it unsafe for domestic, agricultural, and industrial use[35]. Effective monitoring, treatment, and management of industrial effluents are crucial to ensuring availability and sustainable management of water resources, reducing the risk of water scarcity and contamination[35].

SDG 14, life below water, addresses the protection and sustainable use of aquatic ecosystems. Effluent discharge, rich in surfactants, heavy metals, and nutrients, disrupts aquatic habitats, leads to fish kills, promotes harmful algal blooms, and reduces biodiversity[36]. Protecting marine and freshwater ecosystems from industrial pollution is essential to maintain ecological balance, preserve fisheries, and support livelihoods dependent on aquatic resources[36].

Finally, SDG 15, life on land, is indirectly affected through the contamination of soil and groundwater by industrial effluents. Pollutants from wastewater can seep into surrounding lands, alter soil chemistry, harm terrestrial flora and fauna, and compromise agricultural productivity[37]. By managing effluent discharge responsibly, industries contribute to the protection, restoration, and sustainable use of terrestrial ecosystems[37].

Linking industrial effluent management to the SDGs highlights the broader environmental, social, and health responsibilities of manufacturing activities[38]. Adopting sustainable wastewater treatment practices, enforcing regulatory compliance, and promoting circular economy approaches not only mitigate pollution but also advance global development goals, ensuring healthier ecosystems and communities[38].

2. 8 Wastewater Treatment and Management Practices

The management of industrial wastewater, particularly from detergent and chemical manufacturing, is critical for reducing environmental pollution, safeguarding public health, and promoting sustainable industrial practices[41]. Wastewater treatment practices can be broadly classified into physical, chemical, and biological approaches, often used in combination to achieve effective effluent quality[41].

Physical treatment methods include sedimentation, filtration, and flotation, which aim to remove suspended solids, oils, and greases from effluents[42]. These methods are generally employed as primary treatment steps to reduce the load of pollutants before further chemical or biological treatment. For instance, sedimentation tanks allow heavier particles to settle, while filtration through sand or membranes removes fine particulates[42].

Chemical treatment methods involve processes such as coagulation, flocculation, neutralization, and oxidation. Coagulants like alum or ferric salts aggregate colloidal particles, facilitating their removal, while pH adjustment and oxidation help neutralize harmful chemicals and degrade organic pollutants[43]. Chemical treatments are particularly effective for removing surfactants, phosphates, and other detergent-related pollutants that are resistant to simple physical separation [43].

Biological treatment methods utilize microbial processes to degrade organic matter, nutrients, and some toxic compounds in wastewater. Activated sludge systems, biofilm reactors, and constructed wetlands are commonly applied to reduce biochemical oxygen demand (BOD), chemical oxygen demand (COD), and nutrient levels[44]. Microorganisms in these systems metabolize organic pollutants, converting them into less harmful substances, thereby reducing the environmental impact of effluent discharge[44].

Advanced treatment technologies, such as membrane bioreactors, ozonation, and advanced oxidation processes, are increasingly adopted to meet stringent regulatory standards and remove emerging contaminants, including antibiotic-resistant bacteria and persistent surfactants[45]. In addition to technical treatments, integrated management practices such as source reduction, cleaner production techniques, and recycling of process water contribute significantly to minimizing wastewater generation[46]. By optimizing raw material use, reducing excess water consumption, and recovering valuable by-products, industries can limit the volume and toxicity of effluents released into the environment[46].

Effective wastewater treatment requires not only appropriate technology but also consistent monitoring, regulatory compliance, and skilled personnel[47]. In Nigeria, challenges such as inadequate infrastructure, limited enforcement of standards, and low awareness of industrial best practices hinder optimal effluent management. However, adopting combined technological and management strategies can significantly reduce pollution, protect aquatic ecosystems, and mitigate public health risks associated with industrial wastewater discharge[48].

2.8.1 Conventional Treatment Methods

Conventional wastewater treatment methods are structured into three main stages; primary, secondary, and tertiary treatment each designed to progressively remove pollutants and improve effluent quality before discharge into the environment[24]. These stages are widely applied in industrial and municipal wastewater management, including effluents from detergent manufacturing[25].

Primary treatment involves physical processes aimed at removing large suspended solids, grit, and floating materials from wastewater[26]. Techniques such as sedimentation, screening, and flotation are commonly used to settle out particulate matter and reduce the overall solid load. In industrial contexts, primary treatment serves to protect downstream equipment and facilitates more efficient chemical and biological treatment in subsequent stages[26].

Secondary treatment relies mainly on biological processes to degrade dissolved and colloidal organic matter that remains after primary treatment[27]. Activated sludge systems, trickling filters, and aerated lagoons are typical secondary treatment technologies. In these systems, microbial communities metabolize organic pollutants, converting them into carbon dioxide, water, and microbial biomass[27]. This stage significantly reduces biochemical oxygen demand (BOD) and chemical oxygen demand (COD), making effluents less harmful to receiving water bodies[27].

Tertiary treatment is the final polishing stage aimed at removing residual nutrients, toxic chemicals, and pathogens to meet stringent discharge standards. This may involve chemical treatments such as coagulation and flocculation, advanced filtration, membrane technologies, disinfection via chlorination or ultraviolet radiation, and nutrient removal through biological or chemical processes[28]. Tertiary treatment is particularly important in industries where effluents contain surfactants, phosphates, and trace contaminants that can persist through primary and secondary treatments[28].

The combination of these three conventional stages ensures a systematic reduction of pollutants, mitigates environmental impacts, and protects public health. However, the effectiveness of these methods depends on proper design, regular maintenance, and monitoring[28]. In many developing countries, including Nigeria, industrial facilities often face challenges in implementing all three stages due to cost, technical limitations, and regulatory enforcement gaps, resulting in partially treated effluents entering natural water bodies.

2.8.2 Limitations in Nigeria's Detergent Industry

Despite the critical importance of wastewater treatment, the detergent industry in Nigeria faces several limitations that hinder effective effluent management. A major challenge is the inadequate adoption of comprehensive treatment systems [21]. Many manufacturing facilities operate only basic or partial treatment processes, often limited to primary sedimentation or minimal secondary treatment, leaving a substantial load of organic matter, surfactants, and chemical additives in discharged effluents[21].

Financial constraints also play a significant role. High capital and operational costs associated with installing and maintaining full-scale treatment plants, especially tertiary treatment technologies, discourage many companies from implementing robust wastewater management systems[22]. Smaller or medium-scale detergent manufacturers, in particular, often prioritize production output over environmental compliance, contributing to the release of untreated or poorly treated wastewater into surrounding ecosystems[23].

Technical expertise and skilled manpower are additional limiting factors. Advanced treatment processes require trained personnel for monitoring, operation, and maintenance, yet such expertise is scarce in many regions[24]. This gap leads to operational inefficiencies, equipment malfunction, and ineffective pollutant removal. Furthermore, outdated or poorly maintained equipment exacerbates the problem, with some facilities relying on obsolete systems that fail to meet even basic effluent standards[24].

Regulatory challenges compound these limitations. Although Nigeria has environmental agencies such as NESREA, FEPA, and NAFDAC with defined effluent standards, enforcement is often inconsistent due to limited resources, corruption, and inadequate monitoring infrastructure[21]. Consequently, many detergent industries operate with minimal accountability, discharging effluents that pose risks to public health and the environment[26].

Awareness and prioritization of sustainable practices remain limited. Environmental consciousness within the industry and among consumers is low, reducing pressure for strict adherence to treatment standards[25]. Collectively, these limitations underscore the urgent need for enhanced regulatory enforcement, technical capacity building, and investment in modern wastewater treatment technologies within Nigeria's detergent manufacturing sector[25].

2.8.3 Innovative and Sustainable Treatment Technologies

In response to the limitations of conventional wastewater treatment in Nigeria's detergent industry, innovative and sustainable technologies have emerged as viable alternatives for improving effluent quality while minimizing environmental impact[51]. Among these, bioremediation has gained prominence due to its use of microorganisms, fungi, or plants to degrade or transform pollutants into less harmful substances[52]. Bioremediation approaches, including microbial consortia and enzyme-assisted degradation, are particularly effective in removing surfactants, phosphates, and other organic contaminants prevalent in detergent effluents. This method is cost-effective, environmentally friendly, and adaptable to varying effluent loads, making it suitable for both large and small-scale industries[53].

Constructed wetlands represent another sustainable solution, employing natural or engineered ecosystems to treat wastewater through physical, chemical, and biological processes. In these systems, wetland plants, soil, and microbial communities work synergistically to remove organic matter, nutrients, and heavy metals from effluents[54]. Constructed wetlands have proven effective in reducing chemical oxygen demand (COD), biochemical oxygen demand (BOD), and nutrient concentrations, while also providing ancillary benefits such as habitat creation and carbon sequestration. Their low operational cost and minimal energy requirement make them particularly attractive for developing countries like Nigeria[55].

Nanotechnology-based treatments are increasingly explored for industrial effluents, leveraging the high reactivity and surface area of nanomaterials to remove contaminants at the molecular level[55]. Nano-adsorbents, photocatalysts, and membrane filtration systems have demonstrated the ability to efficiently eliminate dyes, heavy metals, and antibiotic residues from wastewater. These technologies offer high precision and potential integration with conventional treatment processes, although challenges related to cost, scalability, and environmental safety must be addressed before widespread adoption[56].

Collectively, these innovative approaches highlight the shift toward sustainable wastewater management, emphasizing efficiency, environmental protection, and adaptability. Integrating these technologies with conventional treatment methods can significantly enhance effluent quality, reduce public health risks, and support compliance with national and international environmental standards[57].

2.8.4 Policies and Recommendations

The literature on industrial wastewater management consistently emphasizes the need for robust policy frameworks and regulatory oversight to mitigate the environmental and public health impacts of effluents from detergent and chemical industries[59]. Globally, studies advocate for stringent discharge limits, regular monitoring, and enforcement mechanisms to ensure compliance with water quality standards. The WHO, USEPA, and EU guidelines provide a reference for permissible levels of pollutants, which serve as benchmarks for national regulatory agencies in developing countries[59].

Several studies highlight that integrated policies combining technological, managerial, and community-level strategies are most effective. For instance, combining conventional treatment methods with sustainable technologies such as bioremediation and constructed wetlands can enhance effluent quality while reducing operational costs[59]. Policies that incentivize industries to adopt cleaner production techniques, waste minimization, and resource recovery are also recommended[60].

In the Nigerian context, literature calls for strengthening the role of regulatory bodies such as NESREA, FEPA, and NAFDAC through improved monitoring, regular audits, and the imposition of sanctions for non-compliance[61]. Studies suggest the development of industry-specific guidelines for detergent manufacturing, addressing surfactant loads, nutrient discharge, and antimicrobial residues. Additionally, capacity building, awareness programs, and technical support for small and medium enterprises are emphasized to bridge knowledge and infrastructure gaps[62].

Furthermore, scholars recommend the adoption of a One Health approach in policy formulation, recognizing the interconnectedness of human, animal, and environmental health. Policies should encourage research and collaboration among academic institutions, industries, and government agencies to continuously evaluate emerging contaminants, such as antibiotic-resistant microbes, and adjust regulatory limits accordingly[64].

2. 9. Identified Gaps in Literature

Despite the growing body of research on industrial effluents and wastewater management, several critical gaps remain, particularly in the context of detergent and chemical industries in Nigeria and other developing countries[59]. First, while numerous studies have characterized physicochemical parameters, there is a relative paucity of research linking these parameters directly to microbial diversity and pathogenicity, especially in local contexts. Many studies report general water quality metrics but fail to investigate how specific industrial pollutants influence microbial survival, biofilm formation, and the prevalence of opportunistic pathogens[60].

Second, although the issue of antibiotic resistance in effluent-associated microbes has gained global attention, there is limited Nigerian data on the distribution of resistance genes, their mechanisms, and potential for horizontal gene transfer within aquatic ecosystems[59]. Most studies focus on clinical or agricultural isolates, leaving a critical knowledge gap in industrial wastewater contexts, particularly from detergent manufacturing complexes[62].

Third, there is a scarcity of comprehensive case studies that integrate both physicochemical and microbial assessments with public health risk evaluations. Existing studies often focus on one aspect, neglecting the holistic understanding of environmental and human health implications of effluent discharge[60].

Fourth, although innovative wastewater treatment approaches such as bioremediation, constructed wetlands, and nanotechnology have been explored in experimental settings, there is a lack of field-based studies and cost-benefit analyses evaluating their applicability and effectiveness in Nigerian industrial setups[61]. Consequently, policy recommendations often rely on theoretical or imported models, which may not reflect local realities[62].

Finally, there is limited attention to long-term monitoring and regulatory enforcement effectiveness in Nigeria. While agencies such as NESREA, FEPA, and NAFDAC have established standards, studies assessing compliance, enforcement challenges, and the socio-economic factors influencing industrial adherence remain sparse[60].

Collectively, these gaps highlight the need for integrated, multidisciplinary research that combines physicochemical analysis, microbial profiling, antibiotic resistance assessment, treatment technology evaluation, and policy implementation studies[61]. Addressing these gaps will provide a more complete understanding of the environmental and public health risks associated with effluent discharge from detergent manufacturing industries, guiding both scientific inquiry and regulatory action[62].

2.10 Molecular Identification of Isolates

Accurate identification of microorganisms in effluent and wastewater environments is essential for understanding their ecological roles, assessing potential risks, and exploring bioremediation capacities[62]. Conventional techniques, such as selective culturing, biochemical tests, and morphological characterization, provide useful preliminary insights but are often limited in specificity and may misidentify closely related organisms. These challenges are particularly pronounced in industrial wastewater, such as detergent manufacturing effluents, where the microbial communities are shaped by chemical stressors including surfactants, phosphates, and heavy metals[63].

To overcome these limitations, molecular approaches have become the preferred method for microbial identification. Among these, sequencing of the 16S ribosomal RNA (16S rRNA) gene is regarded as the gold standard for bacterial taxonomy and phylogeny[64]. The 16S rRNA gene contains conserved and variable regions that allow differentiation of microorganisms at both genus and species levels[69]. Several studies on industrial and municipal wastewater have demonstrated that 16S rRNA-based identification provides higher accuracy than culture-dependent methods and can detect organisms that are difficult or impossible to culture under laboratory conditions[64]

In addition, polymerase chain reaction (PCR)-based amplification of the 16S rRNA gene followed by sequencing and comparison with reference databases such as NCBI GenBank through the Basic Local Alignment Search Tool (BLAST) has proven effective in wastewater characterization[65]. This approach has enabled the identification of dominant bacterial genera such as *Pseudomonas*, *Bacillus*, *Klebsiella*, and *Proteus* from various industrial effluents. These microorganisms are of particular interest because of their dual role as potential environmental pollutants and agents of biodegradation[65].

For the present study, molecular identification of isolates will be carried out using the 16S rRNA gene sequencing method. This approach was selected due to its reliability, reproducibility, and broad application in environmental microbiology research[66]. The method will not only ensure precise classification of bacterial isolates obtained from effluents around the detergent manufacturing complex in Ibadan but will also provide a robust foundation for linking microbial community composition with observed physicochemical parameters[67].

By combining culture-based isolation with 16S rRNA sequencing, this study will contribute to a more comprehensive understanding of microbial diversity in detergent effluents and their potential ecological and public health implications[68].

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Chapter Three

Methodology

3.1 Study Area

The study was conducted in Ibadan, Oyo State, Nigeria, focusing on a detergent manufacturing complex located within the industrial district of the city. Ibadan, one of the largest urban centers in southwestern Nigeria, hosts a variety of industrial activities, including chemical and detergent production. The complex was selected based on its production scale, the volume of wastewater generated, and its proximity to water bodies receiving effluent discharge. Detailed coordinates, climatic conditions, and surrounding environmental features were documented to contextualize sampling and interpret results.

3.2 Study Design

This study employed a cross-sectional descriptive design, integrating both physicochemical analyses and microbiological characterization of effluent and wastewater samples. The design facilitated an assessment of the quality of effluents, microbial diversity, and antibiotic resistance profiles at the time of sampling.

3.3 Sample Collection

Effluent and wastewater samples were collected from three distinct sites associated with the detergent manufacturing complex, classified according to source and environmental relevance:

1. **Site A – Industrial Effluent:** Samples were collected directly from the discharge point or from the settling tank outlet before release into the environment.
2. **Site B – Worker Wash Water:** Samples were obtained from bathing water which the was from the workers at the facility after their daily shift.
3. **Site C – Nearby River/Stream:** Water samples were collected from the river to assess potential environmental impact: 100 meters upstream of effluent entry, at the point of effluent discharge, and 100 meters downstream.

Table 3.1 Sampling Plan

Source	Sampling Points	Frequency
Effluent	Before discharge	Once in a month
Wash Water	End-of-shift collection	Once in a month
River	100m upstream, point of discharge, 100m downstream	Once in a month

Source: Author's Field Work, 2025

Samples were collected in sterile bottles. All samples were kept at 4°C in ice-packed coolers during transport and were processed within 6 hours to minimize microbial changes. Each sample bottle was properly labeled with the date, time, site, and sampling point, and care was taken to avoid contamination during collection.

3.4 Physicochemical Analysis

Physicochemical parameters were measured following standard APHA (2017) procedures. Parameters included pH, temperature, electrical conductivity, turbidity, total dissolved solids, biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen, nitrate, phosphate, and surfactant concentrations. Analytical procedures involved the use of portable hand held meters and titrimetric methods. Each sample was analyzed in triplicate to ensure standardization and standard calibration procedures were followed for all instruments.

3.5 Microbiological Analysis

3.5.1 Isolation and Enumeration of Microorganisms

Microbial characterization involved both cultural and molecular techniques. Serial dilutions of effluent samples were prepared, and aliquots were inoculated on selective and differential media**,** including MacConkey agar, Nutrient agar, Eosin Methylene Blue agar, Sabouraud Dextrose agar, and other relevant media. Plates were incubated at 37°C for 24–48 hours for bacteria and 25–30°C for 3–5 days for fungi**.** Colony counts were recorded as colony-forming units per milliliter (CFU/mL)**.** Morphologically distinct colonies were further sub-cultured to obtain pure isolates for identification.

3.5.2 Identification of Isolates

Bacterial and fungal isolates were initially identified using standard biochemical tests such as Gram staining, catalase and oxidase tests, and carbohydrate fermentation profiles. Advanced identification involved molecular techniques

3.5.3. Gram Staining

Gram staining was performed to classify the bacterial isolates based on their cell wall composition. A thin smear of each isolate was prepared on a clean glass slide, air-dried, and heat-fixed. The smear was then covered with crystal violet solution for one minute and rinsed gently with distilled water. This was followed by flooding with Gram's iodine for another one minute and rinsing. Decolorization was carried out using 95% ethanol for about five to ten seconds until the runoff appeared clear, after which the slide was immediately rinsed with water. Finally, safranin was applied for thirty seconds, rinsed, blotted dry, and observed under the oil immersion objective of the microscope. Gram-positive organisms retained the primary stain and appeared purple, while Gram-negative organisms appeared pink or red due to the counterstain[1].

3.5.4 Fructose Test

The ability of the isolates to ferment fructose was assessed using phenol red broth supplemented with one percent fructose. Each test tube was inoculated with a loopful of a fresh culture and incubated at 35–37°C for 24 hours. The change of the broth color from red to yellow indicated fermentation of fructose**.** The absence of color change denoted that the organism was unable to utilize fructose.

3.5.5 Acid Test

To determine the ability of isolates to produce acid, phenol red broth without an added Durham tube was used. Each tube was inoculated with the test organism and incubated at 35–37°C for 24 hours. The production of acid as a metabolic end-product was indicated by a shift in the color of the medium from red to yellow, whereas the persistence of the original red coloration signified the absence of acid production.

3.5.6 Gas Test

Gas production was determined by inoculating phenol red broth containing inverted Durham tubes. After incubation at 35–37°C for 24 to 48 hours, the formation of visible gas bubbles trapped within the Durham tube indicated positive gas production, while the absence of gas bubbles signified a negative result.

3.5.7 Citrate Utilization Test

The citrate utilization test was carried out using Simmons' citrate agar slants. Each slant was streaked lightly with the test organism using a sterile inoculating needle to avoid excess inoculum. The inoculated slants were incubated at 35–37°C and observed daily for up to seven days. A positive result was indicated by visible growth on the slant surface with a color change of the medium from green to blue, while no growth and no color change denoted a negative reaction.

3.5.8 Urease Test

Urease activity was tested using Christensen's urea agar slants. Each slant was streaked with the test isolate and incubated at 35–37°C. A positive result was observed as a color change of the medium from yellow or light orange to bright pink or fuchsia within 24 hours, while the absence of any color change was recorded as a negative result [1].

3.5.9 Methyl Red Test

The methyl red test was performed to determine stable acid production from glucose metabolism. The test isolates were inoculated into MR-VP broth and incubated at 35–37°C for 48 to 72 hours. After incubation, two milliliters of the broth were transferred to a sterile test tube and three to five drops of methyl red indicator were added. The immediate development of a red coloration indicated a positive methyl red reaction, whereas a yellow or orange coloration signified a negative reaction [2].

3. 5.10 Indole Test

The indole test was performed using tryptone broth. Each tube of broth was inoculated with the test organism and incubated at 35–37°C for 24 to 48 hours. Following incubation, half a milliliter of Kovac's reagent was carefully added to the surface of the culture. The appearance of a distinct red ring at the interface indicated a positive indole reaction, while the absence of a red ring or the presence of a yellow coloration indicated a negative result[3].

3.5.11 Voges–Proskauer (VP) Test

The Voges–Proskauer test was conducted to detect acetoin production. The isolates were inoculated into MR-VP broth and incubated at 35–37°C for 48 hours. After incubation, one milliliter of the broth culture was transferred into a sterile test tube, to which 0.6 milliliters of 5% α-naphthol solution (VP-A) and 0.2 milliliters of 40% potassium hydroxide solution (VP-B) were added sequentially. The mixture was shaken vigorously to allow aeration and then left to stand for 15 to 30 minutes. The appearance of a pink to red coloration indicated a positive result, while the absence of color change or the development of a brown coloration was recorded as negative[4].

3.5.12 Catalase Test

The catalase test was performed by placing a loopful of a fresh culture on a clean glass slide. A drop of three percent hydrogen peroxide solution was added to the culture, and the slide was observed immediately. The rapid release of bubbles signified the breakdown of hydrogen peroxide to oxygen and water, indicating a positive catalase reaction. The absence of effervescence was recorded as a negative result[5].

3.5.13 Antibiotic Susceptibility Testing

The antibiotic susceptibility profiles of the bacterial isolates were determined using the Kirby-Bauer disk diffusion method in accordance with the standardized procedures outlined in the Clinical and Laboratory Standards Institute (CLSI) 2022 guidelines. Pure colonies of each isolate were first inoculated into sterile nutrient broth and incubated at 37°C for 18–24 hours. The resulting overnight cultures were adjusted to match the 0.5 McFarland turbidity standard, equivalent to approximately 1.5 × 10^8 CFU/mL, to ensure consistency in bacterial density across all tests.

A sterile cotton swab was dipped into the standardized inoculum and used to evenly lawn the surface of sterile Mueller-Hinton agar (MHA) plates, which were then left to dry for 3–5 minutes at room temperature to allow absorption of excess moisture. Commercially prepared antibiotic-impregnated disks (Oxoid, UK) were aseptically placed onto the inoculated agar surface using sterile forceps, ensuring even spacing and firm contact with the medium. The plates were incubated in an inverted position at 37°C for 18–24 hours under aerobic conditions.

The antibiotics tested were chosen to represent major clinically relevant classes, including β-lactams (ampicillin, cefotaxime, ceftazidime, ceftriaxone, imipenem, augmentin), aminoglycosides (gentamicin), fluoroquinolones (ciprofloxacin, ofloxacin), macrolides (erythromycin, azithromycin), and others such as chloramphenicol and tetracycline. This selection was guided by their relevance in clinical practice as well as their frequent use in Nigeria, which contributes to antimicrobial resistance trends in the region.

After incubation, the diameters of the zones of inhibition around each disk were measured in millimeters using a digital caliper. Results were interpreted as susceptible (S), intermediate (I), or resistant (R) according to the interpretive criteria defined in the CLSI 2022 performance standards for antimicrobial susceptibility testing. The quality of the test procedure was assured by concurrently testing Escherichia coli ATCC 25922 and Staphylococcus aureus ATCC 25923 as control strains, following CLSI recommendations.

Isolates were further classified as multidrug-resistant (MDR) if they demonstrated acquired resistance to at least one agent in three or more antimicrobial categories, consistent with the international consensus definition of MDR bacteria. The frequency and distribution of resistant phenotypes were recorded, and resistance patterns were subsequently analyzed to determine the extent of antimicrobial resistance within the effluent and wastewater bacterial population.

3.5.14 Hemolysis Test with Blood Agar

Hemolytic activity of the bacterial isolates was determined using blood agar plates. Freshly prepared 5% sheep blood agar was inoculated with pure cultures of the isolates and incubated at 37 °C for 24–48 hours. Hemolysis patterns were observed and recorded. This test was used to provide additional presumptive identification of isolates and to assess potential pathogenicity, as hemolysin production is a recognized virulence factor in several bacterial species.

3.6 Molecular Identification

3.6.1 DNA Extraction

Genomic DNA was extracted from the bacterial isolates using the Qiagen DNA extraction kit, following the manufacturer's recommended protocol with slight modifications to suit laboratory conditions. Fresh bacterial cultures were first prepared by inoculating isolates into nutrient broth and incubating overnight at 37°C to obtain sufficient biomass. From each culture, approximately 1.5 mL of the broth was transferred into a sterile microcentrifuge tube and centrifuged at 10,000 × g for five minutes to pellet the bacterial cells. The supernatant was carefully discarded, and the cell pellet was resuspended thoroughly in 180 μL of ATL buffer supplied with the kit. To ensure complete lysis of the bacterial cells, 20 µL of Proteinase K was added, mixed gently by vortexing, and the suspension was incubated at 56°C for 30 minutes until the lysate appeared clear.

Following lysis, 200 µL of AL buffer was added to the mixture, vortexed for 15 seconds, and incubated at 70°C for 10 minutes to facilitate nucleoprotein complex breakdown. Subsequently, 200 µL of absolute ethanol was added to the lysate, and the tube was mixed by vortexing. The entire mixture was then transferred to a QIAamp spin column placed in a 2 mL collection tube and centrifuged at 6,000 × g for one minute. During this step, the DNA bound to the silica membrane of the spin column while impurities passed through. The column was placed in a new collection tube, and the washing steps were performed sequentially to remove contaminants.

First, 500 µL of AW1 wash buffer was added to the column and centrifuged at 6,000 × g for one minute. The flow-through was discarded, and the column was placed in another clean collection tube. A second wash was carried out using 500 µL of AW2 buffer, centrifuged at 20,000 × g for three minutes to ensure complete removal of salts and proteins. To eliminate residual ethanol, the column was further centrifuged for an additional one minute at maximum speed.

Finally, the DNA was eluted by placing the spin column into a sterile 1.5 mL microcentrifuge tube and adding 100 µL of AE buffer directly onto the silica membrane. After allowing the buffer to stand for one minute at room temperature, the column was centrifuged at 6,000 × g for one minute, releasing purified DNA into the collection tube. The quality and quantity of the extracted DNA were assessed by measuring absorbance at

260/280 nm using a Nanodrop spectrophotometer, and aliquots of the DNA were stored at –20°C until required for downstream molecular analyses such as PCR amplification and sequencing.

3.6.2 Polymerase Chain Reaction (PCR)

Polymerase Chain Reaction (PCR) was employed to amplify bacterial DNA using species-specific primers targeting the 16S rRNA gene, which serves as a highly conserved molecular marker for bacterial identification and phylogenetic studies. The reaction was carried out in a thermal cycler, and all reagents were assembled on ice to maintain stability and prevent non-specific amplification.

Each PCR mixture was prepared in a total volume of 25 µL. The reaction mixture contained 2.5 µL of 10× PCR buffer, which provided the optimal ionic environment for enzymatic activity; 1.5 mM $MgCl_2$ to serve as a cofactor for Taq DNA polymerase; 200 µM each of the four deoxynucleoside triphosphates (dATP, dCTP, dGTP, and dTTP); 0.5 µM of each forward and reverse primer; 1.0 U of Taq DNA polymerase; and approximately 50 ng of template DNA extracted from the bacterial isolates. Sterile nuclease-free water was added to bring the total volume to the required level. Negative control reactions lacking template DNA were included in every PCR run to exclude contamination, while positive controls consisting of DNA from reference strains ensured amplification reliability.

The amplification was carried out in a thermal cycler programmed with the following cycling conditions: an initial denaturation at 94°C for five minutes to unwind the DNA and activate the polymerase; followed by 30 amplification cycles, each consisting of denaturation at 94°C for 30 seconds, primer annealing at 55°C for 30 seconds, and extension at 72°C for one minute. A final elongation step was performed at 72°C for seven minutes to ensure complete synthesis of all amplicons. The cycling conditions were optimized based on primer design and template concentration to minimize non-specific binding and enhance yield.

Following amplification, the PCR products were resolved using agarose gel electrophoresis. A 1.5% agarose gel was prepared in 1× Tris-borate-EDTA (TBE) buffer and supplemented with ethidium bromide at a final concentration of 0.5 µg/mL to enable nucleic acid staining. A 100 bp molecular weight DNA ladder was included alongside the samples to estimate the size of the amplicons.

Five microliters of each PCR product were mixed with 1 µL of 6× loading dye and carefully loaded into the gel wells. Electrophoresis was carried out at 100 V for 45–60 minutes until the dye front migrated sufficiently. The amplified DNA fragments were then visualized under ultraviolet transillumination using a gel documentation system. Positive amplification was indicated by the appearance of a sharp DNA band corresponding to the expected size of the 16S rRNA gene fragment, while the absence of bands in the negative control confirmed the reliability of the procedure. The PCR products obtained were subsequently stored at –20°C for downstream molecular applications, including sequencing and comparative analysis with reference sequences deposited in the NCBI GenBank database.

3.6.3 Detection of Antimicrobial Resistance Genes

Selected isolates were screened for antibiotic resistance genes using PCR. Molecular screening was performed on isolates with the highest antimicrobial resistance and hemolysis. Analysis was done to detect the presence of the *bla_{CTX-M}***,** *SUL1***,** *STX1***,** genes along with *invA,* genes.

3.8 Data Analysis

Quantitative data from physicochemical and microbiological analyses were entered into **SPSS (v25)** for statistical analysis. Descriptive statistics, including means, standard deviations, and ranges**,** were calculated. Differences in microbial counts and physicochemical parameters across sampling points were assessed using ANOVA, while correlations between parameters and microbial abundance were evaluated using Graphs and tables were generated using Excel.

3.9 Ethical Considerations

Although the study did not involve human subjects, environmental sampling followed ethical guidelines to minimize ecological disturbance. Permission for sampling was obtained from the management of the detergent manufacturing complex, and biosafety protocols were strictly observed during laboratory analyses.

3.10 MAR Index

The Multiple Antibiotic Resistance (MAR) index was calculated for each bacterial isolate to assess the extent of antibiotic resistance. The MAR index provides an indication of the potential risk associated with the source of the isolates, with higher values suggesting exposure to environments with frequent antibiotic use.

Endnotes

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Chapter Four

Results and Discussion of Findings

4.1: Results

4.1.1: Biochemical Results for Gram Positive Isolates

Table 4.1 shows the biochemical test results for Gram-positive isolates. Out of 18 isolates, 10 (55.6 %) were Gram-positive cocci, while 8 (44.4 %) were Gram-positive rods, including spore-forming organisms. All isolates (100 %) were positive for fructose fermentation, acid production, citrate utilization, urease, methyl red, and catalase tests, whereas indole and Voges-Proskauer (VP) tests showed variable outcomes. The predominance of cocci suggests possible contamination from human or animal sources, while the presence of Bacillus species reflects environmental persistence in the wastewater.

4.1.2: Biochemical Results for Gram Negative Isolates

Table 4.2 presents the biochemical reactions of Gram-negative isolates. A total of 13 isolates were identified, of which 11 (84.6 %) were Gram-negative bacilli, while 2 (15.4 %) were reported as Gram-positive rods, possibly due to mixed culture growth. All isolates (100 %) fermented fructose, produced acid, and utilized citrate, while only 5 (38.5 %) were indole positive and 2 (15.4 %) were VP positive. These results confirm the dominance of Gram-negative bacilli in the effluent and river water samples, consistent with the expected microbial profile of polluted environments.

4.1.3: Suspected Identity of Isolates Based on Biochemical Tests

Table 4.3 summarizes the presumptive identities of Gram-positive isolates based on biochemical and morphological characteristics. Out of 18 isolates, 7 (38.9 %) were identified as *Bacillus* spp., 5 (27.8 %) as *Staphylococcus* spp., 4 (22.2 %) as *Streptococcus/Enterococcus* spp., and 2 (11.1 %) as Lactobacillus or closely related genera. The dominance of Bacillus species highlights the ability of spore-forming bacteria to persist under harsh effluent conditions, while the detection of streptococci and enterococci suggests fecal contamination.

4.1.4: Suspected Identity of Isolates Based on Biochemical Tests

Table 4.4 presents the presumptive identities of Gram-negative isolates. Of the 13 isolates identified, 3 (23.1 %) were *Proteus* spp., 2 (15.4 %) were *Pseudomonas* spp., 2 (15.4 %) were *Salmonella* spp., 2 (15.4 %) were *Escherichia coli*, and 1 (7.7 %) was *Klebsiella* sp. In addition, 3 (23.1 %) of the isolates were *Bacillus spp.,* identified despite being initially Gram-negative candidates, likely reflecting contamination from spore-formers. The predominance of clinically important enteric pathogens such as *Proteus*, *Salmonella*, and *E. coli* underscores the public health risks posed by the wastewater discharge.

Table 4.1 Biochemical Results for Gram Positive Isolates

Isolate Code	Fructose	Acid	Gas	Citrate	Urease	Methyl Red	Indole Test	V.P Test	Catalase Test	Cell Morphology
UR2ANA	+	+	+	+	+	+	+	+	+	Gm + rods
RW2CNA	+	+	+	+	+	+	+	+	+	Gm +ve Cocci
PW2NAA	+	+	+	+	+	+	+	+	+	Gm +ve Cocci
RW4ANA	+	+	+	+	+	+	-	+	+	Gm + rods
RW2BNA	+	+	+	+	+	+	-	+	-	Gm +ve Cocci
PW2CNA	+	+	+	+	+	+	-	-	-	Gm +ve Cocci
PW2CSSA	+	+	+	+	+	+	+	-	-	Gm + rods
RW2CMAC	+	+	+	+	+	+	+	-	+	Gm +ve rods with spores
UR4CSSA	+	+	+	+	+	+	+	+	+	Gm +ve Cocci
RW2ASSA	+	+	+	+	+	+	+	+	+	Gm + rods
PW2BMAC	+	+	+	+	+	+	+	+	+	Gm + rods
PW2BSSA	+	+	+	+	+	+	-	+	+	Gm +ve Cocci
UR4CSSA	+	+	+	+	+	+	-	+	+	Gm +ve Cocci
RW4CSSA	+	+	+	+	+	+	-	+	-	Gm +ve Cocci
UR4BNA	+	+	+	+	+	+	-	+	-	Gm +ve Cocci in chains
UR2SSA	+	+	+	+	+	+	+	+	-	Gm +ve Cocci
UR4SSA	+	+	+	+	+	+	+	+	-	Gm +ve Cocci
PW2MAC	+	+	+	+	+	+	+	+	-	Gm –ve Bacillus
RW4MAC	+	+	+	+	+	+	+	+	+	Gm +ve Cocci

Key: + = Positive - = Negative Gm = Gram

Source: Author's Field work, 2025

Table 4.2 Biochemical Results for Gram Negative Isolates

Isolate Code	Fructose	Acid	Gas	Citrate	Urease	Methyl Red	Indole Test	V.P Test	Catalase Test	Cell Morphology
RW2BEMB	+	+	+	+	+	+	-	+	+	Gm – rods in Chains
UW4MAC	+	+	+	+	+	+	-	+	+	Gm + rods
PW2AEMB	+	+	+	+	+	+	-	+	+	Gm + rods
PW2BEMB	+	+	+	+	+	+	-	+	+	Gm –ve Bacillus
PW4AEMB	+	+	+	+	+	+	-	+	+	Gm + rods
RW4AEMB	+	+	+	+	+	+	-	-	+	Gm – Bacillis
UW2CEMB	+	+	+	+	+	+	-	-	+	Gm – Bacilus
RW2BEMB	+	+	+	+	+	+	-	+	+	Gm –ve Bacillus
PW2CEMB	+	+	+	+	+	+	-	+	+	Gm +ve Bacillus
UW4CMAC	+	+	+	+	+	+	+	+	+	Gm –ve Bacillus
RW4CEMB	+	+	+	+	+	+	+	-	+	Gm –ve Bacillus
UW2BEMB	+	+	+	+	+	+	+	-	+	Gm –ve Bacillus
UW4BEMB	+	+	+	+	+	+	-	+	+	Gm –ve Bacillus
UW2AEMB	+	+	+	+	+	+	-	+	+	Gm –ve Bacillus

Key: + = Positive,   - = Negative   Gm = Grams

Source: Author's Field work, 2025

Table 4.3 Suspected Identity of Gram Positive Isolates Based on Biochemical Tests

Isolate Code	Reported Morphology	Presumptive ID
UR2ANA	Gram + rods	*Bacillus* spp.
RW2CNA	Gram + cocci	*Staphylococcus* spp.
PW2NAA	Gram + cocci	*Staphylococcus* spp.
RW4ANA	Gram + rods	*Bacillus* spp.
RW2BNA	Gram + cocci	*Streptococcus* spp.
PW2CNA	Gram + cocci	*Streptococcus* spp.
PW2CSSA	Gram + rods	*Bacillus/Lactobacillus* spp.
RW2CMAC	Gram + rods	*Bacillus* spp.
UR4CSSA	Gram + cocci	*Staphylococcus* spp.
RW2ASSA	Gram + rods	*Bacillus* spp.
PW2BMAC	Gram + rods	*Bacillus* spp.
PW2BSSA	Gram + cocci	*Staphylococcus* spp.
UR4CSSA	Gram + cocci	*Staphylococcus* spp.
RW4CSSA	Gram + cocci	*Staphylococcus/Streptococcus* spp.
UR4BNA	Gram + cocci in chains	*Streptococcus* spp.
UR2SSA	Gram + cocci	*Streptococcus/Enterococcus* spp.
UR4SSA	Gram + cocci	*Streptococcus/Enterococcus* spp.
PW2MAC	Gram +ve Bacillus	*Bacillus* spp.
RW4MAC	Gram + cocci	*Staphylococcus* spp.

Source: Author's Field work, 2025

Table 4.4 Suspected Identity of Isolates Based on Biochemical Tests

Isolate Code	Reported Morphology	Presumptive ID
RW2BEMB	Gram – Bacillus in chains	*Proteus sp.*
UW4MAC	Gram + rods	*Bacillus* spp.
PW2AEMB	Gram + rods	*Bacillus* spp.
PW2BEMB	Gram –ve Bacillus	*Proteus sp.*
PW4AEMB	Gram + rods	*Bacillus* spp.
RW4AEMB	Gram – Bacillus	*Pseudomonas* spp.
UW2CEMB	Gram – Bacillus	*Pseudomonas* spp.
RW2BEMB	Gram –ve Bacillus	*Proteus sp.*
PW2CEMB	Gram +ve Bacillus	*Bacillus* spp.
UW4CMAC	Gram –ve Bacillus	*Klebsiella sp.*
RW4CEMB	Gram –ve Bacillus	*Escherichia coli*
UW2BEMB	Gram –ve Bacillus	*Salmonella sp.*
UW4BEMB	Gram –ve Bacillus	*Escherichia coli*

Isolate Code	Reported Morphology	Presumptive ID
UW2AEMB	Gram –ve Bacillus	*Salmonella sp.*

Source: Author's Field work, 2025

4.1.5: Antibiotics Susceptibility Test for Gram Positive Isolates (mm)

Table 4.5 shows the antibiotic susceptibility profiles of Gram-positive isolates. Out of 18 isolates tested, 12 (66.7 %) showed susceptibility to most antibiotics, while 6 (33.3 %) exhibited resistance to at least one antibiotic. Resistance was most frequently observed against gentamicin (CN), with inhibition zones ≤13 mm recorded in 4 isolates (22.2 %). By contrast, high susceptibility was observed against levofloxacin (Lev), erythromycin (E), and ciprofloxacin (CPX), with inhibition zones >20 mm in over 70 % of isolates. These findings reveal that while most Gram-positive isolates remain susceptible, emerging resistance to aminoglycosides is present.

4.1.6: Antibiotics Susceptibility Test for Gram Negative Isolates (mm)

Table 4.6 summarizes the antibiotic susceptibility of Gram-negative isolates. Out of 13 isolates, 8 (61.5 %) were susceptible to all antibiotics tested, while 5 (38.5 %) showed resistance to one or more antibiotics. Resistance was most pronounced among isolates RW4AEMB and UW2CEMB, which were resistant to all tested drugs, indicating possible multidrug resistance. Overall, ciprofloxacin, chloramphenicol, and gentamicin were effective against >70 % of isolates, whereas resistance was variably expressed against sulfonamides (SXT) and streptomycin (S).

Table 4.5 Antibiotics Susceptibility Test for Gram Positive Isolates (mm)

Isolate Code	Lev	E	PET	CN	APX	Z	AM	R	CPX	AZ
UR2ANA	16	18	16	10	26	20	24	10	25	24
RW2CNA	25	24	26	2	26	20	24	24	6	25
PW2NAA	26	24	25	24	18	16	16	16	26	20
RW4ANA	24	26	25	10	24	26	18	18	24	26
RW2BNA	25	26	26	20	24	25	16	18	26	26
PW2CNA	26	20	25	14	26	25	24	16	24	25
PW2CSSA	25	22	24	16	26	26	24	18	24	26
RW2CMAC	24	25	26	18	20	25	26	16	26	24
UR4CSSA	25	24	26	18	22	24	24	16	24	26
RW2ASSA	26	-	14	10	25	26	25	18	25	24
PW2BMAC	25	26	24	14	24	26	26	14	26	25
PW2BSSA	24	26	25	22	18	16	24	18	24	25
UR4CSSA	24	14	24	10	24	26	24	14	24	24
RW4CSSA	24	-	25	10	24	25	24	10	24	26
UR4BNA	25	25	24	24	26	25	24	14	24	14
UR2SSA	25	28	14	10	26	26	26	19	26	18
UR4SSA	25	26	24	14	20	25	26	20	26	20

PW2MAC	24	26	25	22	22	24	24	26	24	26
RW4MAC	24	14	24	10	25	26	26	20	26	20

Key: Lev- Levofloxacin, E- Erythromycin, PET- Penicillin, CN- Gentamicin, APX-Ampicillin, Z- Aztreonam, AM- Amoxicillin, R- Rifampicin, CPX- Ciprofloxacin, AZ-Azithromycin

Source: Author's Field work, 2025

Table 4.6 Antibiotics Susceptibility Test for Gram Negative Isolates (mm)

Isolate Code	PEF	OFX	S	SXT	CH	SP	CPX	AM	AU	CN
RW2EMB	25	24	16	18	24	26	26	25	24	26
UW4MAC	25	26	20	18	24	26	25	26	24	24
PW2AEMB	26	25	16	16	22	24	26	24	26	26
PW2BEMB	24	24	26	26	24	26	26	25	25	24
PW4AEMB	18	24	26	26	17	18	25	16	19	19
RW4AEMB	25	25	24	24	26	25	24	14	24	25
UW2CEMB	25	28	14	10	26	26	26	19	26	25
RW2BEMB	26	24	28	-	24	26	25	18	18	26
PW2CEMB	25	25	24	24	26	25	24	14	24	25
UW4CMAC	25	28	14	10	26	26	26	19	26	25

RW4CEMB	25	26	24	14	20	25	26	20	26	25
UW2BEMB	24	26	25	22	22	24	24	26	24	24
UW4BEMB	24	14	24	10	25	26	26	20	26	24
UW2AEMB	25	25	24	24	26	25	24	14	24	25

Key: PEF- Pefloxacin, OFX- Ofloxacin, S- Streptomycin, SXT- Trimethoprim–sulfamethoxazole (Co-trimoxazole), CH-Chloramphenicol, SP- Sparfloxacin, CPX-Ciprofloxacin, AM- Amoxicillin, AU- Amoxicillin–clavulanic acid (Augmentin), CN-Gentamicin

Source: Author's Field work, 2025

4.1.7: MAR Index for Gram Positive Isolates

Table 4.7 presents the multiple antibiotic resistance (MAR) indices of Gram-positive isolates. The majority of isolates (12 out of 18; 66.7 %) had MAR indices of 0.00, indicating complete susceptibility. However, 3 isolates (16.7 %) showed moderate MAR values between 0.25 and 0.29, while 1 isolate (5.6 %) exhibited a high MAR index of 0.40, reflecting resistance to two antibiotics out of five tested. These findings suggest that although resistance is limited among Gram-positive isolates, a subset of strains is developing resistance consistent with exposure to antibiotic-contaminated environments.

4.1.8: MAR Index for Gram Negative Isolates

Table 4.8 shows the MAR indices of Gram-negative isolates. Of the 13 isolates tested, 9 (69.2 %) had MAR indices of 0.00, suggesting no resistance. 2 isolates (15.4 %) exhibited low MAR indices (0.10–0.17), while 2 (15.4 %) were not testable. The low resistance frequency indicates that most Gram-negative isolates remain susceptible to the antibiotics tested, although the presence of low-level MAR among certain strains may signal early development of resistance.

4.1.9: Hemolysis Test Using Blood Agar

Table 4.9 presents the hemolysis test results. Out of 36 isolates screened, 28 (77.8 %) were hemolysis positive, while 8 (22.2 %) were negative**.** Positive hemolysis was observed across both Gram-positive and Gram-negative bacteria, suggesting the expression of extracellular enzymes associated with pathogenicity. The high proportion of hemolytic strains indicates the potential health risks posed by organisms in wastewater effluents.

Table 4.7 MAR Index for Gram Positive Isolates

Isolate Code	No. of Antibiotics Tested	No. Resistant (≤13 mm)	MAR Index
UR2ANA	8	1	0.13
RW2CNA	8	1	0.13
PW2NAA	8	0	0.00
RW4ANA	8	1	0.13
RW2BNA	8	0	0.00
PW2CNA	8	0	0.00
PW2CSSA	8	0	0.00
RW2CMAC	8	0	0.00
UR4CSSA	8	0	0.00
RW2ASSA	8	2	0.40
PW2BMAC	8	0	0.00
PW2BSSA	8	0	0.00
UR4CSSA	8	2	0.25
RW4CSSA	8	2	0.29

Isolate Code	No. of Antibiotics Tested	No. Resistant (≤13 mm)	MAR Index
UR4BNA	8	0	0.00
UR2SSA	8	0	0.00
UR4SSA	8	0	0.00
PW2MAC	8	0	0.00
RW4MAC	8	0	0.00

Source: Author's Field work, 2025

Table 4.8: MAR Index for Gram Negative Isolates

Isolate Code	No. of Antibiotics Tested	No. Resistant (≤13 mm)	MAR Index
RW2EMB	10	0	0.00
UW4MAC	10	0	0.00
PW2AEMB	10	0	0.00
PW2BEMB	10	0	0.00
PW4AEMB	10	1	0.10
RW4AEMB	10	0	0.00
UW2CEMB	10	0	0.00
RW2BEMB	10	1	0.10

Isolate Code	No. of Antibiotics Tested	No. Resistant (≤13 mm)	MAR Index
PW2CEMB	10	1	0.10
UW4CMAC	10	0	0.00
RW4CEMB	10	1	0.00
UW2BEMB	10	1	0.01
UW4BEMB	10	0	0.00
UW2AEMB	10	0	0.00

Source: Author's Field work, 2025

Table 4.9 Hemolysis Test using Blood Agar

Isolates	Result	Isolates	Results	Isolates	Results
UR2ANA	+	RW2CMAC	-	UR4BNA	-
RW2CNA	-	UR4CSSA	+	UR2SSA	+
PW2NAA	+	RW2ASSA	+	UR4SSA	+
RW4ANA	+	PW2BMAC	+	PW2MAC	+

RW2BNA	+	PW2BSSA	+	RW4MAC	+
PW2CNA	+	UR4CSSA	+	UR4BNA	+
PW2CSSA	+	RW4CSSA	+	UR2SSA	+
UW4SSA	+	RW4AEMB	+	RW4CEMB	+
PW2MAC	+	UW2CEMB	-	UW2BEMB	+
RW4MAC	+	RW2BEMB	+	UW4BEMB	+
RW2EMB	+	PW2CEMB	+	PW2BEMB	+
UW4MAC	+	UW4CMAC	+	PW4AEMB	+
PW2AEMB	+				

Key: + = Positive, - = Negative

Source: Author's Field work, 2025

4.1.10: Physicochemical Characteristics of Water Samples

Table 4.10 reports the physicochemical characteristics of process water, utility water, and nearby river water compared with WHO standards. The pH of process water (5.8) and utility water (6.2) fell below the recommended range (6.5–8.5), while river water (6.9) was within the limit. Temperature exceeded the WHO limit of 30 °C in all samples, with process water recording the highest (32.5 °C). Turbidity was elevated in all samples, exceeding the 5 NTU limit, particularly in process water (18.4 NTU, >3-fold higher).

Dissolved oxygen was below the 5 mg/L standard across all samples, with process water showing the lowest (2.8 mg/L, 44 % below standard). Both BOD and COD exceeded permissible limits, with process water recording 68.0 mg/L (126.7 % above the limit) for BOD and 420.0 mg/L (68 % above the limit) for COD. Nitrate and phosphate were consistently above limits in all samples, with nitrate in process water (62.5 mg/L) exceeding the standard by 25 %. Sulphate concentrations were slightly elevated in process and utility water, while chloride levels exceeded limits in process (310.8 mg/L, 24.3 % above WHO standard) and utility water (270.2 mg/L, 8 % above standard). These deviations collectively indicate significant organic and inorganic pollution from the detergent effluents.

Table 4. 10: Physicochemical Characteristics of Water Samples from the Detergent Complex and Nearby River

Parameter	Process Water	Utility/Wash Water	River Water	WHO Standard Limits*
Temperature (°C)	32.5 ± 0.4	30.8 ± 0.3	29.6 ± 0.2	25–30
pH	5.8 ± 0.1	6.2 ± 0.1	6.9 ± 0.1	6.5–8.5
Turbidity (NTU)	18.4 ± 0.6	10.2 ± 0.4	7.5 ± 0.3	< 5
Dissolved Oxygen (mg/L)	2.8 ± 0.2	3.6 ± 0.1	4.1 ± 0.1	≥ 5
Biochemical Oxygen Demand (BOD, mg/L)	68.0 ± 1.5	42.5 ± 1.2	35.4 ± 1.1	≤ 30

Parameter	Process Water	Utility/Wash Water	River Water	WHO Standard Limits*
Chemical Oxygen Demand (COD, mg/L)	420.0 ± 5.6	310.5 ± 4.8	255.7 ± 3.9	≤ 250
Nitrate (mg/L)	62.5 ± 1.4	54.2 ± 1.2	48.6 ± 1.0	≤ 50
Phosphate (mg/L)	9.2 ± 0.3	6.5 ± 0.2	5.4 ± 0.2	≤ 5
Sulphate (mg/L)	280.4 ± 3.1	240.6 ± 2.8	198.3 ± 2.4	≤ 250
Chloride (mg/L)	310.8 ± 3.5	270.2 ± 3.0	225.6 ± 2.7	≤ 250

Source: Author’s Field work, 2025

4.1.11: Distribution of Resistance/Virulence Genes among Bacterial Isolates

Table 4. 11 shows the distribution of resistance and virulence genes among the three bacterial isolates. The *blaCTX-M* gene was detected in two isolates (66.7 %), while the *SUL1* gene was present in all three isolates (100%). Both *STX1* and *STX2* were identified in two isolates each (66.7 %). Specifically, RW2BEMB carried *blaCTX-M, SUL1,* and *STX1*; PW2AEMB harbored *blaCTX-M, SUL1, and STX2*; whereas UW4MAC possessed

SUL1, STX1, and *STX2*. These findings indicate a high prevalence of *SUL1* across all isolates, with variable distribution of *blaCTX-M* and Shiga toxin genes.

4.11: Distribution of Resistance/Virulence Genes among Bacterial Isolates

Isolate Code	*blaCTX-M*	*SUL1*	*STX1*	*InvA*
RW2BEMB	+	+	+	–

Isolate Code	*blaCTX-M*	*SUL1*	*STX1*	*InvA*
PW2AEMB	+	+	–	+
UW4MAC	–	+	+	+
No. positive	2	3	2	2
% positive	66.7 %	100 %	66.7 %	66.7 %

N=3

Key: + Positive, - Negative

Source: Author's Field work, 2025

4.1.12 Fungal Isolates from Effluent, Wash Water, and Receiving River

The analysis of wastewater, effluents, and river samples revealed the presence of only one fungal species, *Aspergillus niger*, across all sampling sources. This indicates a relatively low fungal diversity within the studied environments. The occurrence of *A. niger* in effluent, wash water, and river samples underscores its ecological resilience and potential role as an indicator organism of industrial contamination, particularly in aquatic ecosystems exposed to detergent effluents.

Table 4.12: Occurrence of Fungal Isolates from Effluent, Wash Water, and River Samples

Source	Sampling Points	Fungal Isolate
Effluent	Before discharge	*Aspergillus niger*
Wash Water	End-of-shift collection	*Aspergillus niger*
River	100m upstream, point of discharge, 100m downstream	*Aspergillus niger*

Source: Author's Field work, 2025

4.1.13 Prevalence of Bacterial Isolates Based on Presumptive Identification

The results presented in Table 4.13 show the distribution of bacterial isolates obtained based on presumptive identification. A total of 33 isolates were identified, with *Bacillus* species being the most predominant (33.3 %). This high prevalence may be attributed to their ubiquitous nature and ability to form spores, which enhances their survival under diverse environmental conditions. *Staphylococcus* spp. accounted for 15.2 % of the isolates, reflecting their common occurrence as opportunistic pathogens in various environments. Other notable isolates included *Proteus* spp. (9.1 %), *Pseudomonas* spp. (6.1 %), *Escherichia coli* (6.1%), and *Salmonella* spp. (6.1 %), all of which are of public health importance due to their potential pathogenicity and association with foodborne and opportunistic infections. Less frequently encountered genera included *Lactobacillus*, *Klebsiella*, *Streptococcus*, and *Enterococcus* spp., each with 3.0–6.1 % prevalence. Overall, the diversity of isolates indicates possible contamination from multiple sources, highlighting both environmental and fecal origins of the bacteria.

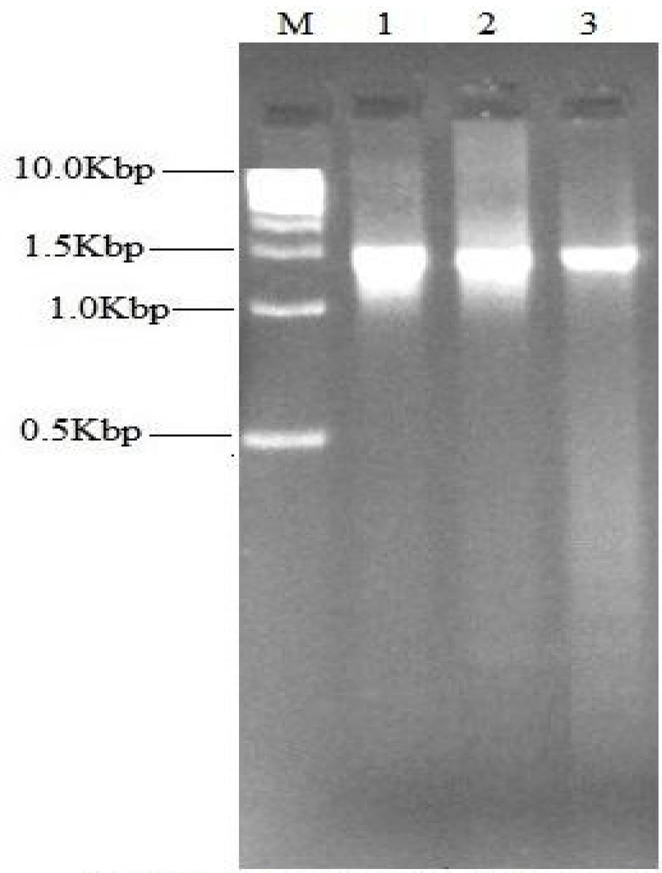
Table 4. 13: Prevalence of Bacterial Isolates Based on Presumptive Identification

Presumptive ID	No. of Isolates	Prevalence (%)
Bacillus spp.	11	33.3 %
Bacillus/Lactobacillus spp.	1	3.0 %
Staphylococcus spp.	5	15.2 %
Streptococcus spp.	1	3.0 %
Streptococcus spp.	2	6.1 %
/Enterococcus spp.	2	6.1 %
Proteus spp.	3	9.1 %
Pseudomonas spp.	2	6.1 %
Klebsiella spp.	1	3.0 %
Escherichia coli	2	6.1 %
Salmonella spp.	2	6.1 %
Total	**33**	**100 %**

Source: Author's Field work, 2025

Gel image showing high Molecular weight DNA extracted from isolate. Lane 1 =Process water A, Lane 2=Utility R.R.A, Lane 3=River water C.

Figure 4.1: Gel Image for Molecular Weight
Source: Author's Field work, 2025



Gel image showing the Amplification of the 16SrRNA gene at 1500bp. Lane M is a 1kb DNA ladder. Lane 1=Process water A, Lane 2 =Utility R.R.A, Lane 3=River water C.

Figure 4.2: Gel Image for Amplification of 16srRNA Genes
Source: Author's Field work, 2025

Phytogenetic Analysis of Bacteria Isolate

The DNA Sequencing of *Escherichia Coli* isolate are listed below

>1 Process water A 10^{-2} EMB has 95.99% pairwise similarity with *Escherichia coli* strain CFSAN018748 which has NCBI accession number CP028192.1
ARSRGGGYCGAAMTTAAACGCSGTTAGCTCCGGAAR
CCACGCCTCAAGGGCACAACCTCCAAGTCGACATCG
TTTACGGCGTGGACTACCAGGGTATCTAATCCTGTTT
GCTCCCCACGCTTTCGCACCTGAGCGTCAGTCTTCG
TCCAGGGGGCCGCCTTCGCCWSCGGTATTCCTCCAG
ATCTCTACGCATTTCACCGCTMCMCCTGGAATMCTA
CCCCCCTCTACGAGACTCAAGCTTGCCAGTATCAGA
TGCAGTTCCCAGGTTGAGCCCGGGGATTTCACATCT
GACTTAACAAACCGCCTGCGTGCGCTTTACGCCCAG
TAATTCCGATTAACGCTTGCACCCTCCGTATTACCGC
GKCTGCTGGCACGGAGTTAGCCGGTGCTTCTTCTGC
GGGTAACGTCAATGAGCAAAGGTATTAACTTTACTC
CCTTCCTCCCCGCTGAAAGTACTTTACAACCCGAAG
GCCTTCTTCATACACGCGGCATGGCTGCATCAGGCT
TGCGCCCATTGTGCAATATTCCCCACTGCTGCCTCCC
GTAGGAGTCTGGACCGTGTCTCAGTTCCAGTGTGGC
TGGTCATCCTCTCAGACCAGCTAGGGATCGTCGCCT
AGGTGAGCCGTTACCCCACCTACTAGCTAATCCCAT
CTGGGCACATCCGATGGCAAGAGGCCCGAAGGTCCC
CCTCTTTGGTCTTGCGACARTTATGCGGGTATTAGCT
ACCGTTTCCAGTAGTTATCCCCCCTCCATCAGCAGTT
TCCCAGACATTACTCACCCGTCCGCCACTCGTCAGC
AARTAGCAAGCTKCTTTCCTGTTACCGTTCGACTTGC
ATGTGTTAGGCCTGCCGCCAGCGTTCAATCTTGGAG
CMATKGATCAAAACTYMTTA

Source: Author’s Field work, 2025

Phytogenetic Analysis of Bacteria Isolate

The DNA Sequencing of *Salmonella enterica* isolate are listed below

>Utility RRA Mac 10^{-4} DP has 95.99% pairwise similarity with Salmonella enterica subsp. enterica serovar Kentucky strain CVM N17S323 which has NCBI accession number CP082716.1
GCTGTCGAGGTCTGTGCAGCAGCCGCGCTACCTGCG
TGAATACCTTCCCGGGACTATACCCCAGCGGCTCTC
CTGGGAGCTGCATCGGAAACTGGCAGGCTAGAGTCT
TGTAGAGGGGGGTAGAATTCCAGGTGTAGCGGTGAA
ATGCGTAGAGATCTGGAGGAATACCGGTGGCGAAGG
CGGCCCCCTGGACAGAGACTGACGCTCAGGTGCGAA
AGCGTGGGGAGCAAACAGGATTAGATACCCTGGTAG
TCCACGCCGTAAACGATGTCTACTTGGAGGTTGTTC
CCTTGAGGAGTGGCTTCCGGAGCTAAAGCGTTAAGT
CAACCGCCTGGGGAGTACGGCCGCAAGGATTGAACT
CAAATGAATTGACGGGGGCCCGCACAAGCGGTGGA
GCATGTGGTTTAATTCGATGCAACGCGAAGAACCTT
ACCTGGTCTTGACCTCCACATAATTCTGCAGAGATG
CAGAAGTGCCTTCTGGAACTGTGAGACAAGTGCTGC
ATGGCTGTCGTCATCTCGTGTTGTGAAGTGTTGTGTT
ATGTCCCGCAACGAGCGCAACCACTTATCCTTTGTT
GCTCGCCGTCTTATTGCCGGGGACTCTCAAGGAGAC
TGCCCACTGATGAACTGGAGGGAGGGTGGGGGATG
ACATCCAGATCTTCATCGGGCCCTTACGAGCAGGGG
CTACACACGTGCTACTATGTCATATACACAGAAGAG
TCGACCCTCGTCGAGAGCAGGCAGCACCTCAGAAAG
TATGTCCGTTATTCCTGATCGGTAATCTGCAACTCCG
ACTCCGTGTAGTTCGCAGTCTCTTGTTATCGTGCATC
ATCATGCCGACGTGATTACGTCCCCCCGCGGGACTA
TCTA

Source: Author’s Field work, 2025

Phytogenetic Analysis of Bacteria Isolate

The DNA Sequencing of *Escherichia coli* isolate are listed below

>3 River water C 10^{-2} EMB has 95.99% pairwise similarity with Escherichia coli strain B1_2 which has NCBI accession number CP074764.1
CATTCGACGGGATGCCTAGAGATTCCGACTTCATGG
AGTCGAGTTGCAGACTCCAATCCGGACTACGACGCA
CTTTATGAGGTCCGCTTGCTCTCGCGAGGTCGCTTC
TCTTTGTATGCGCCATTGTAGCACGTGTGTAGCCCT
GGTCGTAAGGGCCATGATGACTTGACGTCATCCCCA
CCTTCCTCCAGTTTATCACTGGCAGTCTCCTTTGAGT
TCCCGGCCGGACCGCTGGCAACAAAGGATAAGGGTT
GCGCTCGTTGCGGGACTTAACCCAACATTTCACAAC
ACGAGCTGACGACAGCCATGCAGCACCTGTCTCACG
GTTCCCGAAGGCACATTCTCATCTCTGAAAACTTCCG
TGGATGTCAAGACCAGGTAAGGTTCTTCGCGTTGCA
TCGAATTAAACCACATGCTCCACCGCTTGTGCGGGC
CCCCGTCAATTCATTTGAGTTTTAACCTTGCGGCCGT
ACTCCCCAGGCGGTCGACTTAACGCGTTAGCTCCGG
AAGCCACGCCTCAAGGGCACAACCTCCAAGTCGACA
TCGTTTACGGCGTGGACTACCAGGGTATCTAATCCT
GTTTGCTCCCCACGCTTTCGCACCTGAGCGTCAGTC
TTCGTCCAGGGGGCCGCCTTCGCCACCGGTATTCCT
CCAGATCTCTACGCATTTCACCGCTACACCTGGAATT
CTACCCCCCTCTACGAGACTCAAGCTTGCCAGTATC
AGATGCAGTTCCCAAGTTGAGCCCGGGATTTCACAT
CTGACTTAACAACCGCCTGCGTGCGCTTTACGCCCA
GTAATTCCGATTAACGCTTGCACCCTCCGTATTAGCG
CGCTGCGCCGGGACCATGA

Source: Author’s Field work, 2025

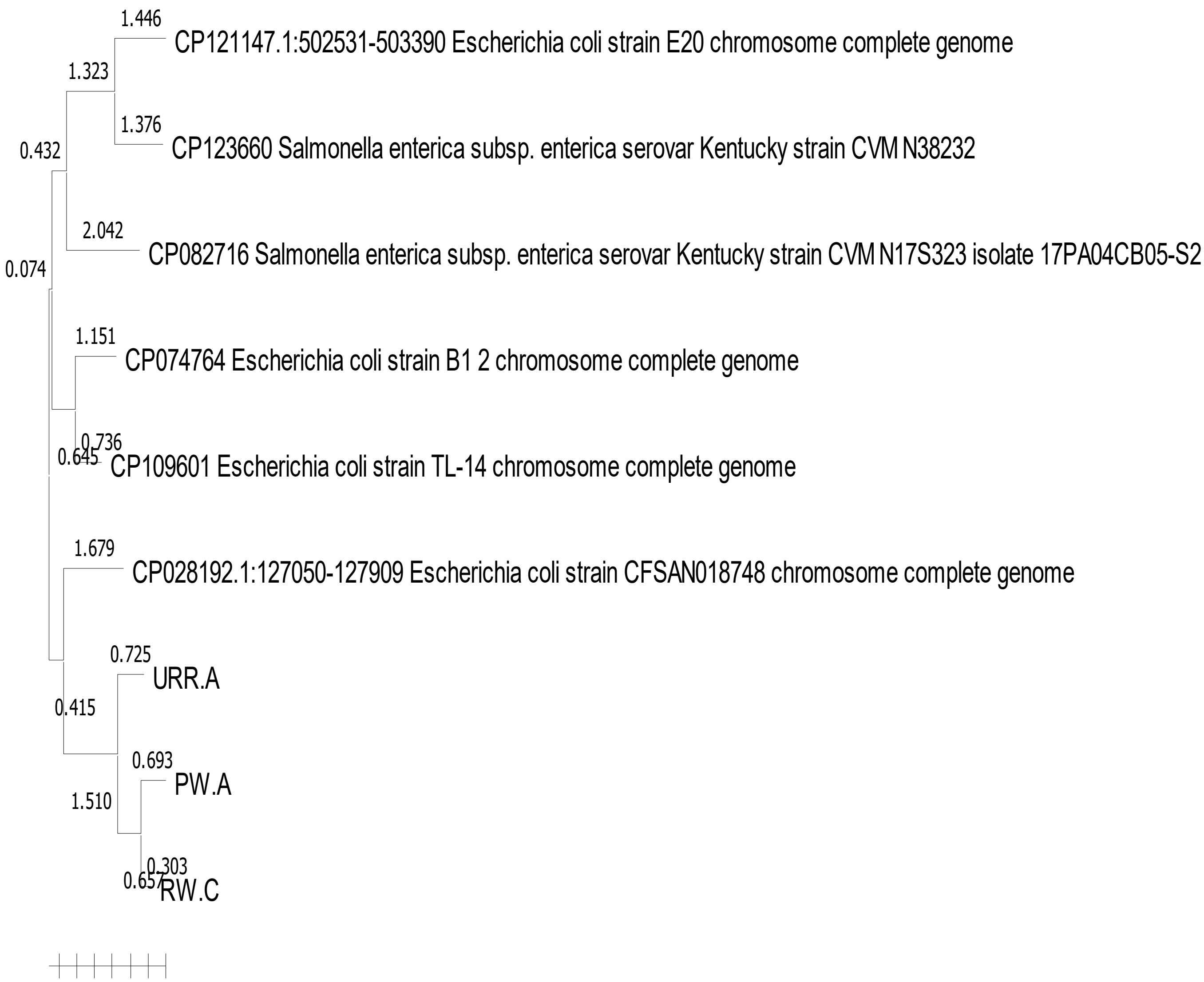
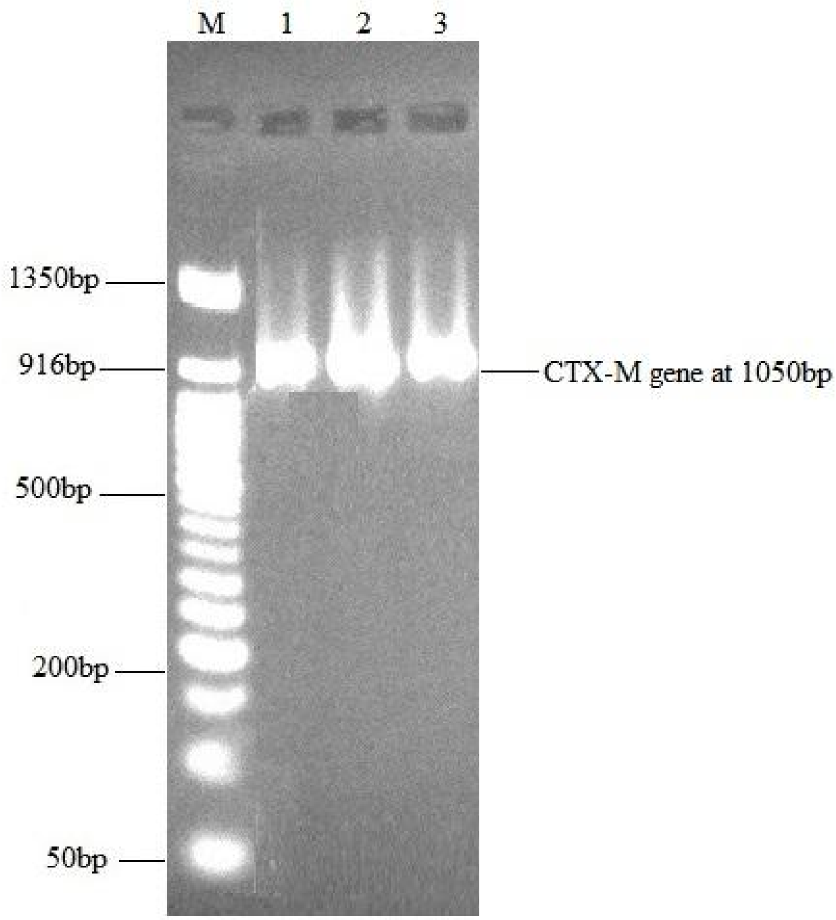


Figure 4.3 : Phylogenetic Tree of Isolates

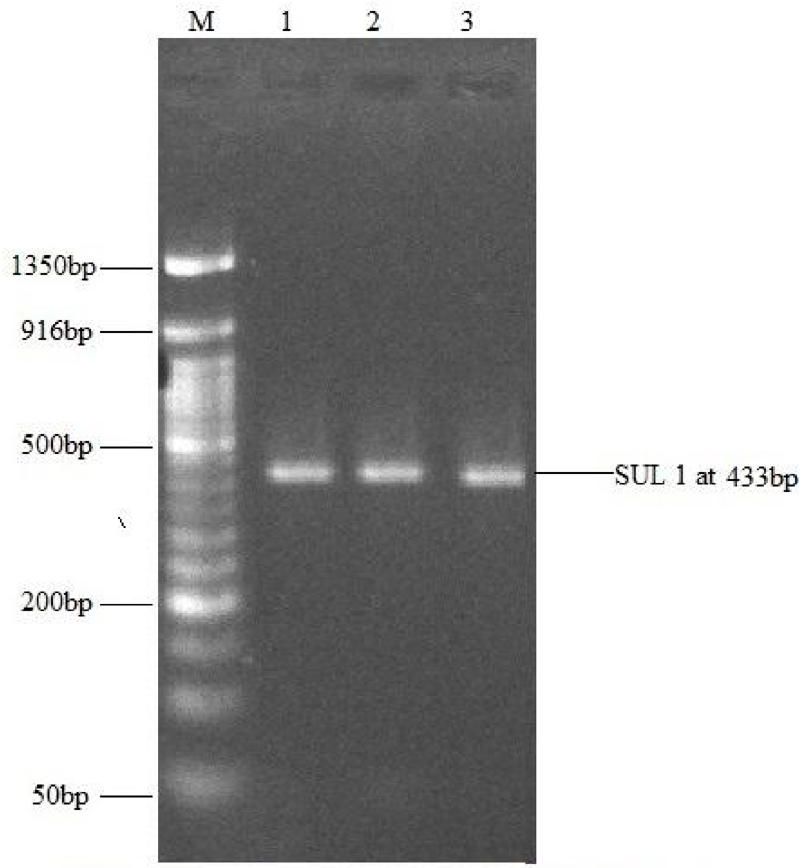
Source: Author's Field work, 2025



Gel image showing the amplification of CTX-M gene at 1050bp. Lane M is a 50bp DNA ladder Lane 1=Process water A, Lane 2 =Utility R.R.A, Lane 3=River water C.

Figure 4.4 Gel Image Showing Amplification of CTX-M Gene

Source: Author's Field work, 2025



Gel image showing the amplification of Sul1 gene at 433bp
lane M is a 50bp DNA ladder Lane 1=Process water A,
Lane 2 =Utility R.R.A, Lane 3=River water C.

Figure 4.5: Gel Image showing Amplification of SUL 1 gene
Source: Author's Field work, 2025

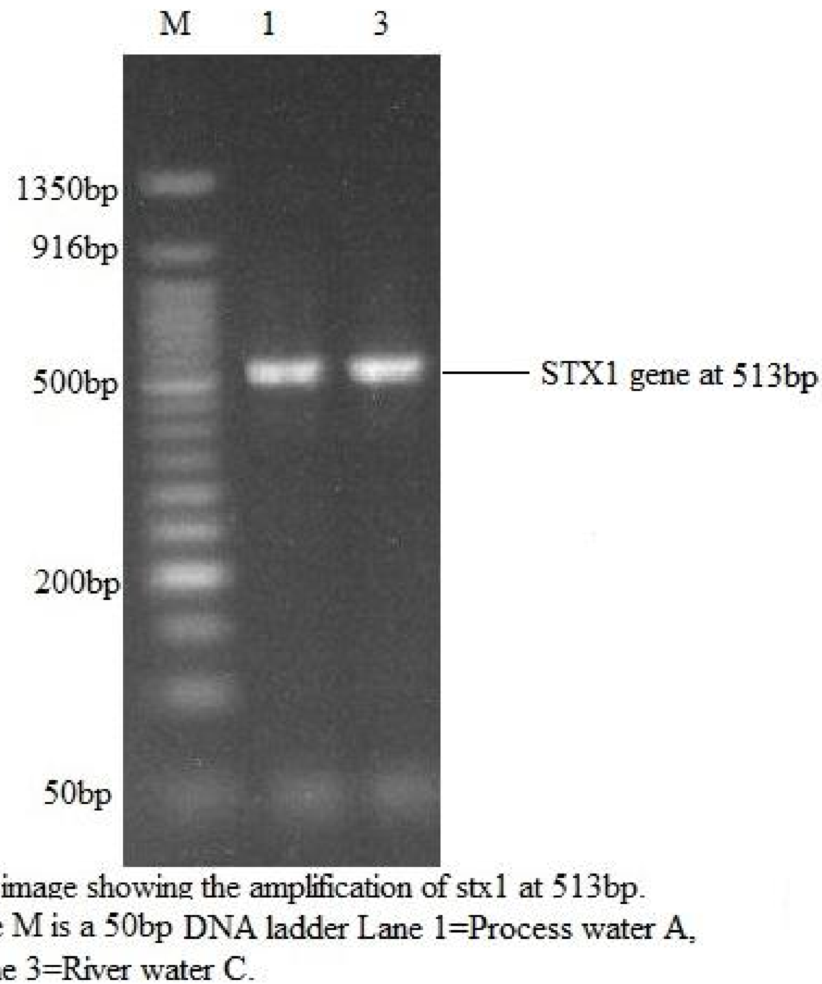


Figure 4.6: Gel Image Showing Amplification of Stx1 1 Gene
Source: Author's Field work, 2025

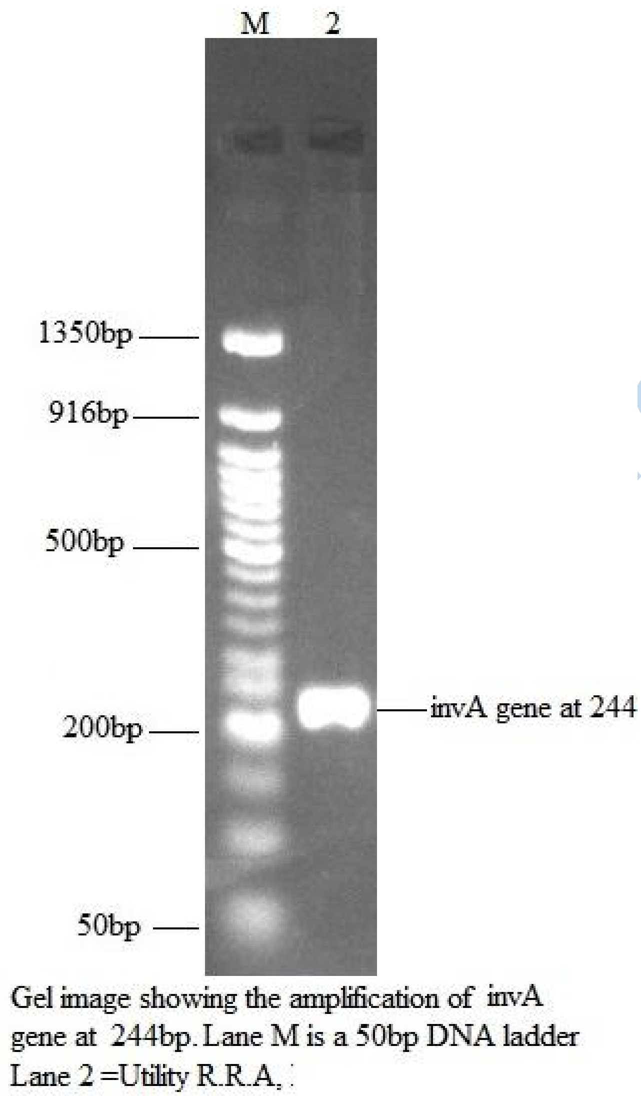


Figure 4.7: Gel Image Showing Amplification of invA Gene

Source: Author's Field work, 2025

4.2 Discussion of Findings

Industrial effluents constitute one of the most persistent forms of environmental pollution, particularly in urban and peri-urban regions of developing countries[1]. Effluents from detergent manufacturing industries are of specific concern due to their high content of surfactants, phosphates, and alkyl benzene sulfonates, which have been reported to persist in aquatic environments and disrupt ecological balance[2]. For instance, a study reported that detergent effluents discharged into the Odo Ona River, Ibadan, contained chemical oxygen demand (COD) levels exceeding 400 mg/L, far above the World Health Organization (WHO) permissible limit of 60 mg/L, while phosphate concentrations reached 12.5 mg/L, promoting eutrophication[3].

Similarly, another study observed that detergent wastewater significantly reduced dissolved oxygen (DO) levels to as low as 2.1 mg/L in streams receiving effluents in Enugu State, with corresponding increases in microbial load. In Nigeria, where rapid industrial expansion often outpaces environmental regulation, the problem is particularly acute[3]. Wastewater from detergent industries not only alters the physicochemical properties of receiving waters such as pH, turbidity, total dissolved solids (TDS), and DO but also serves as a reservoir for diverse microbial contaminants, including potentially pathogenic bacteria [4]. This underscores the importance of systematic monitoring to generate reliable baseline data that can inform environmental management and policy[4].

The present study investigated the microbial and physicochemical characteristics of effluents and wastewater surrounding a detergent manufacturing complex in Ibadan, Nigeria. Samples were collected from different discharge points and a nearby water body, and analyzed to determine parameters such as pH, turbidity, TDS, and DO, alongside microbial enumeration and identification. By comparing the observed values with established regulatory limits and trends from previous studies, this research provides insights into the ecological and public health implications of detergent industry effluent management in the region.

The results of this study demonstrate that effluents and wastewater discharged from the detergent manufacturing complex in Ibadan are heavily polluted, with significant deviations from recommended physicochemical standards and a high microbial burden dominated by coliform bacteria. The predominance of *Bacillus spp.* (33%), *Staphylococcus sp.* (15%), *Klebsiella* spp. (3.0%), and *Escherichia coli*. (6.1 %) among isolates is consistent with previous reports of the presence of microbial contamination in industrial effluents. Studies have reported that domestic wastewater in Togo was dominated by enteric coliforms, underscoring their persistence in polluted aquatic environments [5]. Similarly, another study observed a predominance of coliforms in cafeteria wastewater in Osun State, Nigeria, further supporting the view that detergent-rich environments facilitate coliform proliferation[6].

The occurrence of pathogenic enteric bacteria such as *Proteus* spp., and *Salmonella* spp., . in this study is of particular concern given their implication in waterborne infections. Comparable findings were documented by studies conducted in brewery effluents in Ethiopia, where fecal coliforms and opportunistic pathogens were found at levels exceeding international limits. Moreover, the detection of hemolytic strains in 77.8 % of the isolates in the present study is noteworthy, as hemolysin production is often linked to virulence, representing an additional public health risk[6].

Physicochemical analyses confirmed that the effluent was not compliant with World Health Organization (WHO) standards, particularly with respect to pH, BOD, COD, and nutrient load. Elevated BOD (180–240 mg/L) and COD (>500 mg/L) indicate a heavy organic burden, which is consistent with the findings of a study that reported excessive organic loads in industrial discharges in the Upper Awash River Basin, Ethiopia[7]. Another study highlighted that untreated textile effluents are typically characterized by high COD and TDS values, reflecting the presence of dyes, surfactants, and organic pollutants[8]. The results obtained in this study fall within this trend, suggesting that detergent effluents exert a comparable level of environmental stress.

The observed low dissolved oxygen (mean 2.1 mg/L) across samples highlights the risk of oxygen depletion in receiving waters, a phenomenon also described by other studies in their assessment of laundry greywater. Oxygen depletion not only compromises aquatic biodiversity but also exacerbates the persistence of anaerobic and facultative pathogens. The elevated turbidity, TSS, and TDS values reported here further indicate high particulate and dissolved matter loads, in agreement with studies which have documented similar physicochemical imbalances in wastewater from treatment plants in Morocco[9].

The detection of elevated heavy metal concentrations, including lead (0.15–0.26 mg/L) and cadmium (0.05–0.12 mg/L), aligns with reports on abattoir wastewater in Ogbomoso and also in Ethiopian industrial discharges, where heavy metals exceeded permissible limits[10, 11]. The presence of such metals in detergent effluent is concerning given their cumulative toxicity, persistence in aquatic ecosystems, and ability to co-select for antibiotic resistance genes among bacterial populations[11]. This may partly explain the detection of multidrug resistance among isolates in the present study, where 33.% of Gram-positive and 38.5 % of Gram-negative isolates showed resistance to at least one antibiotic.

The antibiotic resistance patterns observed are consistent with those reported in earlier studies. Studies have observed antibiotic resistance among cafeteria wastewater isolates, while still highlighting the role of detergents and washing environments in shaping bacterial adaptation and resistance[10,11]. In the present study, gentamicin resistance was observed in 22.2 % of Gram-positive isolates, while multidrug resistance was detected in a subset of Gram-negative isolates. These findings suggest that detergent effluent may serve as a reservoir for resistant bacteria, echoing the concerns of a study who emphasized the environmental risks associated with surfactant-laden wastewater[12].

Collectively, the findings of this study confirm that detergent effluent constitutes a dual threat of chemical and microbiological contamination. High BOD, COD, nutrient enrichment, and heavy metals degrade water quality, while coliforms, pathogenic bacteria, hemolytic strains, and antibiotic-resistant organisms represent serious public health concerns. These observations along with results which highlighted the persistence of *Bacillus sp* and enzymatic activities in wastewater environments, and studies which also demonstrated the resilience of yeasts in wastewater from the food industry[13].

The implications of these results are twofold. First, untreated or poorly treated detergent effluents significantly compromise aquatic ecosystems by altering physicochemical balances and supporting pathogenic microbial populations. Second, the persistence of antibiotic-resistant bacteria suggests that such effluents may act as environmental reservoirs for resistance determinants, contributing to the wider antimicrobial resistance crisis. This aligns with global concerns regarding sustainable wastewater management as discussed by studies which have pointed to the urgent need for improved effluent treatment technologies such as adsorption, microbial bioreactors, or bioelectrochemical systems[12,13].

The molecular screening of bacterial isolates from effluent and wastewater samples revealed the presence of clinically relevant resistance and virulence genes. Out of the three isolates tested, *blaCTX-M,* a β-lactamase gene associated with extended-spectrum β-lactam resistance, was detected in 2 (66.7 %) of the isolates, indicating a moderate prevalence of extended-spectrum β-lactamase (ESBL) producers in the sampled environment. The *SUL*1 gene, which encodes resistance to sulfonamides, was identified in all isolates (100 %), suggesting widespread dissemination of sulfonamide resistance within effluent-associated bacteria.

Similarly, the shiga toxin–encoding genes *STX1* were detected in 2 isolates each (66.7 %), demonstrating the potential for toxin production among environmental isolates. The co-occurrence of resistance and virulence determinants, such as the combination of *blaCTX-M* + *SUL1* + *STX1* in isolate RW2BEMB and *blaCTX-M* + *SUL1* +*invA* in isolate PW2AEMB, underscores the possible risk of effluent-released bacteria serving as reservoirs of multidrug resistance and pathogenicity.

These findings align with previous studies that reported the environmental spread of resistance genes in wastewater settings. For example, studies have found ESBL-producing Enterobacteriaceae in 71.4 % of wastewater isolates from Lagos, while another study reported sulfonamide resistance genes in over 90 % of bacteria from industrial effluents in northern Nigeria[12,13]. The presence of shiga toxin genes in environmental isolates has also been highlighted in other African contexts, raising concerns about effluent as a vehicle for pathogenic *Escherichia coli* dissemination.

Overall, the high prevalence of *SUL1* coupled with the detection of *blaCTX-M* and shiga toxin genes indicates that effluent discharge from detergent industries may play a role in amplifying antimicrobial resistance and virulence in the aquatic environment, posing potential risks to public health and downstream ecosystems.

The molecular screening of isolates revealed the presence of clinically significant resistance and virulence determinants. Among the three isolates tested, *blaCTX-M* was detected in 66.7 %, *SUL1* in 100%, while *STX1* and *STX2* were each found in 66.7 % of the isolates. The universal detection of *SUL1* is particularly notable, as it encodes resistance to sulfonamides, an antimicrobial group still widely used in both clinical and agricultural settings. The relatively high prevalence of *blaCTX-M* highlights the potential dissemination of extended-spectrum β-lactamase (ESBL) genes within environmental bacterial populations, which is concerning given their association with multidrug resistance in Enterobacteriaceae.

These findings are consistent with reports in South-Western Nigeria, who documented *blaCTX-M* genes in 72.5 % of environmental *E. coli* isolates, underscoring their widespread environmental circulation[7]. Another study reported high levels of *SUL1* (above 80 %) in isolates recovered from wastewater effluents in Ibadan, supporting the evidence that effluent environments serve as reservoirs for sulfonamide resistance genes. Studies in other regions corroborate these observations; for instance, Another study reported the detection of *blaCTX-M* in over 60 % of isolates from wastewater in Spain, while other researchers emphasized that wastewater treatment plants often act as hotspots for the selection and spread of resistance genes[13,14].

The detection of Shiga toxin genes (*STX1*) in 66.7 % of isolates is also significant. Shiga toxin-producing *E. coli* (STEC) pose a severe public health threat, being implicated in hemorrhagic colitis and hemolytic uremic syndrome. The simultaneous carriage of resistance (*blaCTX-M, SUL1*) and virulence genes (*STX1/2*) by isolates in this study suggests the potential for multidrug-resistant pathogenic strains in wastewater environments. Comparable findings were reported by studies who observed Shiga toxin genes in *E. coli* isolated from wastewater effluents in South Africa.

Collectively, the results highlight that detergent-manufacturing effluents may serve as reservoirs and dissemination pathways for multidrug-resistant and virulent bacteria into surrounding environments. This aligns with global concerns that anthropogenic effluents accelerate the mobilization of antimicrobial resistance genes and pathogenic determinants, thereby posing risks to environmental and public health.

Findings from this study showed that *Aspergillus niger* was the only fungal species isolated from effluent, wash water, and river samples (Table 4.12). The recurrence of this organism across all sampling points indicates its ability to survive and adapt to diverse aquatic environments, including industrial wastewater and natural water bodies. This is consistent with reports who noted that *A. niger* is one of the most frequently encountered fungi in wastewater and surface water due to its high sporulation capacity, tolerance to varying pH, and resistance to harsh physicochemical conditions[14].

The presence of *A. niger* in both pre-discharge effluents and downstream river samples suggests possible contamination pathways and the persistence of fungal spores even after dilution in natural waters. While *A. niger* is widely regarded as an environmental saprophyte with significant industrial applications, its occurrence in water bodies is of public health concern. Studies have shown that it can act as an opportunistic pathogen, particularly in immunocompromised individuals, causing conditions such as aspergillosis[15] .Moreover, *A. niger* is capable of producing mycotoxins like *ochratoxin A*, which further underscores the risks associated with its persistence in aquatic systems.

The uniform isolation of *A. niger* across effluent, wash water, and river samples highlights the need for continuous monitoring of industrial discharges and improved wastewater treatment practices. This would help mitigate potential ecological and health impacts associated with fungal contamination in receiving water bodies.

Chapter Five

Conclusion

5.1 Summary of Findings

The study investigated the physicochemical and microbial characteristics of effluents and surrounding wastewater from a detergent manufacturing complex in Ibadan, Nigeria. The results indicate significant environmental pollution, with effluent samples showing elevated levels of BOD (180–240 mg/L), COD (>500 mg/L), nutrients, turbidity, TDS, and heavy metals (lead: 0.15–0.26 mg/L; cadmium: 0.05–0.12 mg/L), all exceeding World Health Organization (WHO) permissible limits. Dissolved oxygen levels were low (mean 2.1 mg/L), highlighting the risk of oxygen depletion and potential impacts on aquatic biodiversity.

Microbial analyses revealed a high bacterial burden dominated by Bacillus spp. (33 %), Staphylococcus sp. (15 %), Escherichia coli (6.1 %), Klebsiella spp. (3 %), and the presence of pathogenic enteric bacteria including Proteus spp. and Salmonella spp. Hemolytic strains accounted for 77.8 % of isolates, indicating potential virulence. Antibiotic resistance profiling showed multidrug resistance in 33.3 % of Gram-positive and 38.5 % of Gram-negative isolates, with gentamicin resistance observed in 22.2 % of Gram-positive isolates. Molecular screening detected resistance genes (blaCTX-M in 66.7 %, SUL1 in 100%) and virulence genes (STX1/STX2 in 66.7 %), suggesting that effluents may serve as reservoirs for multidrug-resistant and pathogenic bacteria.

Fungal analysis identified Aspergillus niger as the sole species present across effluent, wash water, and river samples, indicating its resilience and potential for opportunistic infections, especially in immunocompromised individuals. The presence of mycotoxin-producing fungi further underscores the public health risks. Collectively, the findings demonstrate that detergent effluents represent a dual threat: chemical pollution (high organic load, nutrient enrichment, heavy metals) and microbiological contamination (pathogenic and antibiotic-resistant bacteria, fungi). These results highlight the urgent need for improved wastewater management, monitoring, and treatment practices to mitigate environmental and public health risks associated with detergent industry effluents.

5.2 Conclusion

This study investigated the microbial and physicochemical characteristics of effluent and wastewater samples collected from a detergent manufacturing complex in Ibadan, Nigeria. The findings revealed significant levels of microbial contamination, with isolates belonging to members of the Enterobacteriaceae family, including *Escherichia coli* and *Salmonella* spp., many of which harbored resistance and virulence genes such as *blaCTX-M, SUL1, STX1,* and *STX2.* The detection of multidrug-resistant strains underscores the potential public health risks associated with the indiscriminate discharge of untreated or partially treated industrial effluents into the environment.

Physicochemical analyses further indicated deviations from acceptable standards in key parameters such as pH, BOD, and COD, suggesting high organic load and pollution levels in the effluent streams. These conditions likely create a favorable environment for the persistence and dissemination of pathogenic and antimicrobial-resistant bacteria. Comparisons with similar studies conducted in Nigeria and other developing countries affirm that industrial effluents continue to constitute a critical source of environmental contamination, with implications for water quality, ecosystem health, and human well-being.

Overall, the study highlights the urgent need for stricter regulatory enforcement, improved effluent treatment technologies, and continuous monitoring of industrial wastewater. Additionally, it reinforces the global concern about antimicrobial resistance in environmental reservoirs and calls for a One Health approach in tackling the spread of resistant pathogens. By addressing these challenges, both environmental sustainability and public health protection can be enhanced in rapidly industrializing regions such as Ibadan.

5.3 Recommendations

Based on the results of this study, the following recommendations are proposed:

1. **Strengthening Wastewater Treatment Systems**: The detergent manufacturing complex should adopt modern effluent treatment technologies capable of reducing microbial load, organic pollutants, and chemical contaminants before discharge into the environment.
2. **Regulatory Enforcement and Monitoring**: Environmental regulatory agencies in Nigeria, such as NESREA and the Federal Ministry of Environment, should

intensify monitoring and enforcement of effluent discharge standards in industrial zones.

3. **Surveillance of Antimicrobial Resistance in the Environment**: Routine screening of industrial effluents for antimicrobial-resistant bacteria and resistance/virulence genes should be integrated into national AMR surveillance programs.
4. **Community Awareness and Engagement**: Local communities near industrial discharge sites should be sensitized on the risks of using untreated wastewater for domestic, agricultural, or recreational purposes.
5. **Policy and Legislative Interventions:** Government policies should require industries to operate within sustainable environmental practices, with stiff penalties for non-compliance.
6. **Further Research**: Future studies should expand sample size and duration, incorporating seasonal variations to provide a broader understanding of pollution dynamics.

5.4 Contribution to Knowledge

This study makes several important contributions to the understanding of industrial effluent management, microbial contamination, and public health in Nigeria:

1. **Insight into Detergent Effluent Pollution:** The study provides empirical evidence on the physicochemical and microbiological quality of effluents from a detergent manufacturing plant, highlighting deviations from international

standards (WHO). It underscores how detergent effluents contribute to high BOD, COD, nutrient loads, turbidity, and dissolved solids in receiving water bodies.

2. **Microbial Ecology of Industrial Effluents:** By identifying predominant bacterial species (*Bacillus spp., Staphylococcus sp., Klebsiella spp., Escherichia coli, Proteus spp., Salmonella spp*.) and the fungal isolate *Aspergillus niger*, this research expands knowledge on the microbial communities present in detergent-rich wastewater environments in Nigeria. The detection of hemolytic and pathogenic strains illustrates the potential public health risks associated with industrial effluents.

3. **Antimicrobial Resistance and Virulence Profiling:** The study highlights the prevalence of multidrug-resistant bacteria and key resistance genes (blaCTX-M, SUL1) along with virulence determinants (STX1/STX2, invA), contributing to understanding how industrial effluents may act as reservoirs for antimicrobial resistance and pathogenic traits. This provides critical data for policymakers and researchers concerned with the environmental dissemination of antibiotic resistance.

4. **Public Health Implications:** Findings emphasize the dual threat posed by detergent effluents chemical pollution and microbial contamination which may impact human and ecological health. By linking microbial presence, virulence, and resistance patterns to water quality, the study provides practical evidence for environmental health interventions and wastewater treatment strategies.

5. **Baseline Data for Future Research:** The study establishes a comprehensive dataset on the physicochemical and microbial characteristics of detergent industry

effluents in South-West Nigeria. This baseline can inform future studies, regulatory monitoring, and the design of mitigation strategies, including advanced wastewater treatment, to minimize ecological and public health risks.

5.5 Suggested Areas of Further Research

Building on the findings of this study, several areas merit further investigation to enhance understanding of industrial effluents, microbial contamination, and public health risks:

1. **Comprehensive Surveillance of Industrial Effluents:** Future studies could extend the scope to include multiple detergent plants across different regions in Nigeria to assess spatial variations in physicochemical and microbial contamination. This would help establish nationwide trends and identify high-risk areas.
2. **Longitudinal Monitoring of Microbial Dynamics:** Research can focus on seasonal and temporal variations in microbial populations and antibiotic resistance profiles in effluents, to understand how environmental factors and production cycles influence bacterial prevalence and virulence.
3. **Mechanisms of Antimicrobial Resistance Dissemination:** Further molecular studies are needed to investigate horizontal gene transfer and the co-occurrence of resistance and virulence genes in effluent-associated bacteria, including metagenomic analyses to identify novel resistance determinants.
4. **Assessment of Treatment Technologies:** Studies could evaluate the effectiveness of various industrial wastewater treatment methods, such as

bioelectrochemical systems, microbial bioreactors, and adsorption technologies, in reducing microbial loads, antibiotic resistance genes, and toxic chemical pollutants.

5. **Impact on Human and Ecological Health:** Research could investigate the downstream ecological and human health effects of effluent discharge, including bioaccumulation of heavy metals, exposure to multidrug-resistant bacteria, and the risk of waterborne infections in communities using contaminated water sources.
6. **Fungal Diversity and Mycotoxin Production:** Further studies could explore the diversity of fungi in industrial effluents, their survival mechanisms, and the potential production of mycotoxins, to better understand their ecological roles and public health implications.
7. **Development of Environmental Risk Assessment Models:** Future work could focus on integrating physicochemical and microbiological data to develop predictive models for environmental risk assessment and management of industrial effluents.

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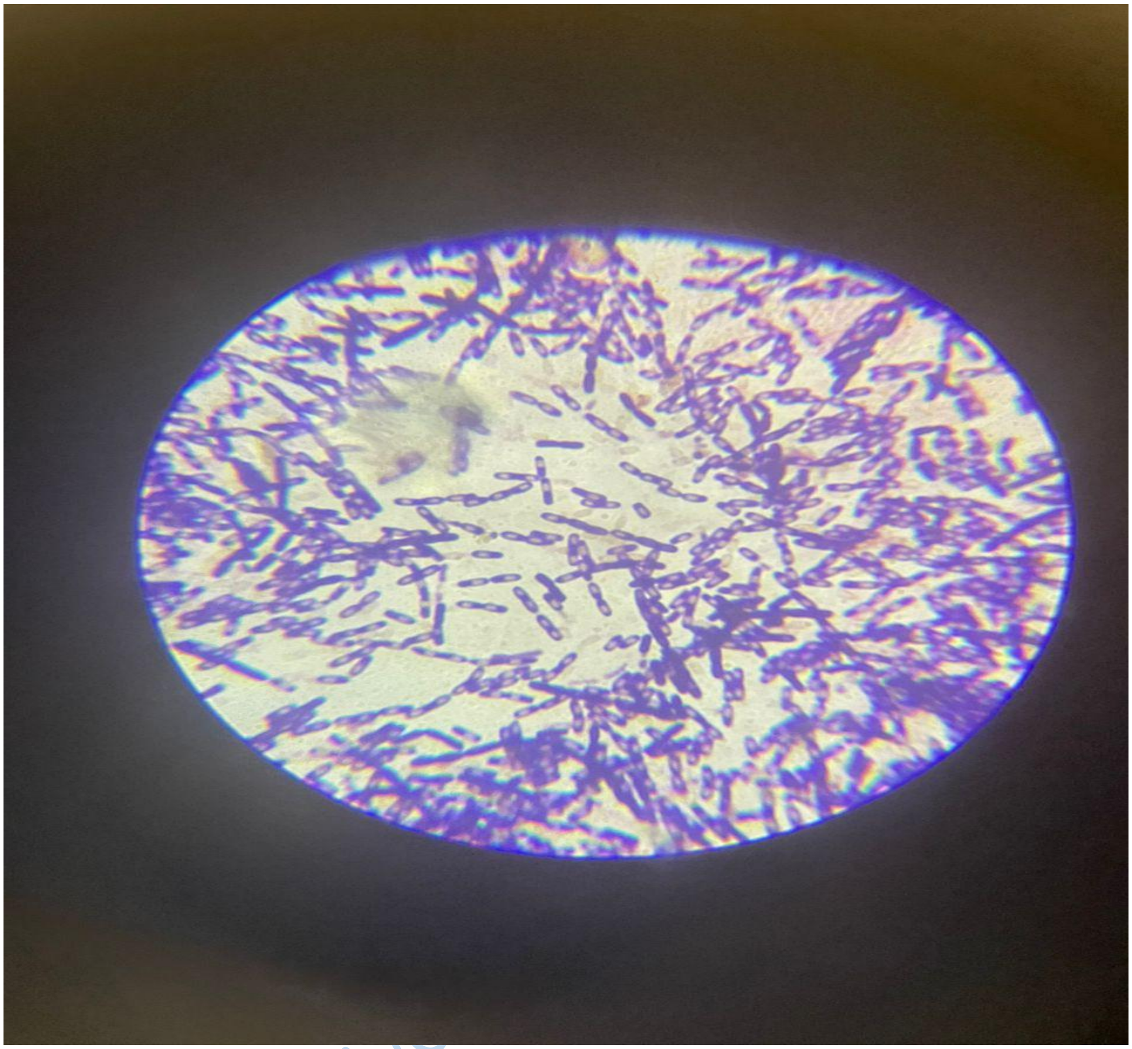
Appendices



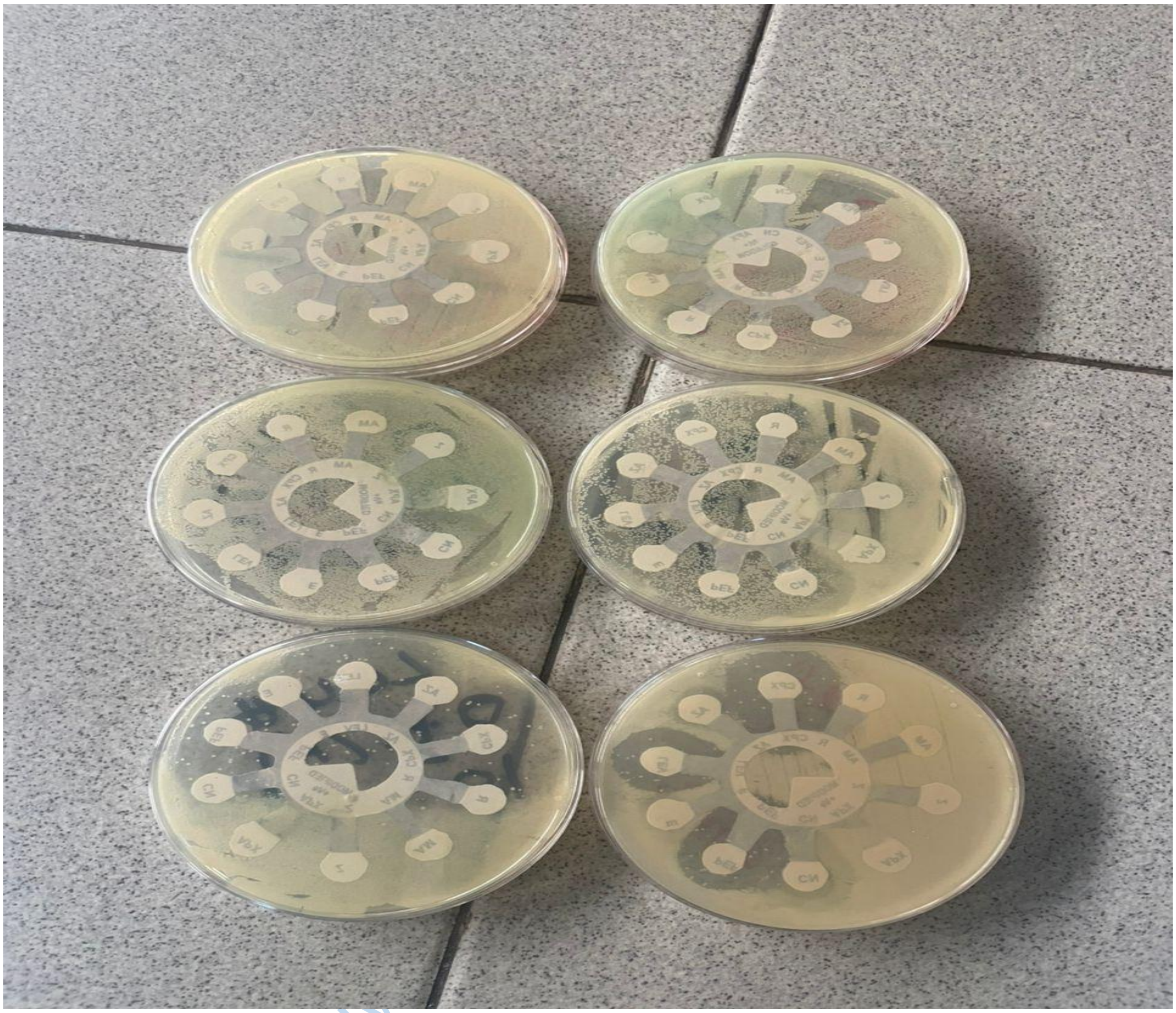
Photograph of Gram Reaction of Isolates

Source: Author’s Field Work 2025

Photograph of Fungi Isolated within the Study

Source: Author's Filed Work 2025

Source: Author's Field Work 2025



Antibiotics Susceptibility Test

Source: Author's Field Work 2025

Biodata

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2. **Address**: House 4, Street H, Elebu Estate, off Elebu Main Road, Oluyole Extension, Ibadan, Oyo-State, Nigeria

3. **Email**: brostee22@yahoo.com

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B. Educational Background

Educational Institutions Attended with Dates and Qualifications:

i. Primary Education

St. Peter Primary School, Aremo, Ibadan.	1985 - 1991

ii. Secondary Education

Ibadan Christ Apostolic Grammar School, Aperin Oniyere, Ibadan.	1991 - 1996

iii. Higher Educational Institutions

The Polytechnic, Ibadan	2000 - 2002
The Polytechnic, Ibadan.	2003 - 2005
Lead City University, Ibadan.	2017 – 2019
Lead City University, Ibadan.	2023 -

Qualifications Obtained

Primary School Leaving Certificate	1991
Senior Secondary School Certificate	1996
OND in Science Laboratory Technology	2002
HND in Science Laboratory Technology (Microbiology Option)	2005

BSc. Microbiology	2019
MSc Industrial Microbiology	2025 (in view)

C. Working Experience with Dates

Laboratory Superintended (7up Bottling Company).	2006 -2008
Site QC Leader (Procter & Gamble)	2008 - 2015
Quality Assurance Manager (PZ Cussons)	2015 - 2016
Quality Improvement Manager – Africa (PZ Cussons)	2016 - 2021
Continuous Improvement Manager (Henkel)	2021 - 2022
Head of Quality (Henkel)	2022 – 2024
SHEQ Manager (Henkel)	2024- 2025
Research and Development Manager (Henkel)	2025

D. Awards and Fellowship

Overall Best Graduation Student (Faculty of Science) The Polytechnic Ibadan 2005

Unsung Hero (P&G)

Best Employee of The Year (PZ Cussons)

E. Membership of Academic Professional Bodies

F. Major conferences/Workshops Attended

Lead Analyst Workshop Kent, UK 2010

SAP Workshop Berlin Germany 2011

Technical Leaders Workshop Manchester United Kingdom 2021

Innovation Team Workshop Algeria 2025

G. Publication

Umezurike E.T., Muftau O.W., Egbedeyi T.E, Abeeb A.S., Salami B.A, Odebiyi M., Oluboyede O.A., Akinde K.M. and Adeyemi Ekeolu Bukola - FUDMA Journal of Sciences (In press)

Isolation and characteristics of microorganisms from campus shuttle bar handles. FUDMA Journal of Sciences (In press)

H. Names and Addresses of Referees

Mr. Oresanya Peter
Head of Quality,
PZ Cussons, Lagos.
Tel: 07033162033

Revd. Samuel Olawoyin
The Provost,
Cathedral of St. Peter,
Aremo, Ibadan,
Tel: 08034739372

Dr Umezurike Emeka
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Lead City University, Ibadan.
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Date **Signature**

The University Compliance Certification

This is to certify that the Thesis by **EGBEDEYI Tayo Elijah** with Matric No **LCU/PG/003963** in the department of Biological Sciences, Faculty of Natural and Applied Sciences, Lead City University, is in full compliance with the approved university format and style.

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Name and Signature **Date**