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BACTERIOLOGICAL CONTAMINATION OF WASTEWATER, VEGETABLES, AND ASSOCIATED HEALTH RISKS IN MAIDUGURI, NIGERIA

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Abstract

This study evaluated the bacteriological quality of River Ngadda wastewater and its effects on the safety and chemical composition of vegetables irrigated with the water in Maiduguri, Nigeria. Wastewater samples were collected aseptically from three sections of the river (upper, middle, and lower courses) and analyzed for total coliforms and pathogenic bacteria using standard microbiological techniques. A controlled farm experiment was conducted in which spinach (Spinacia oleracea) and okra (Abelmoschus esculentus) were irrigated with either River Ngadda wastewater or clean borehole water. Harvested vegetables were analyzed for elemental composition using atomic absorption spectrophotometry. Results showed extremely high total coliform counts across all river sections (159 × 10^3–260 × 10^3 CFU/100 mL), exceeding World Health Organization guidelines for safe irrigation by several orders of magnitude. Pathogenic bacteria including Escherichia coli, Salmonella spp., Staphylococcus aureus, Bacillus spp., and Klebsiella spp. were detected, indicating widespread fecal contamination. Vegetables irrigated with wastewater exhibited higher microbial contamination and altered nutrient profiles compared to controls. Wastewater irrigation increased the accumulation of sodium, magnesium, chloride, and phosphate, with okra showing greater sensitivity to nutrient imbalance than spinach. Trace levels of heavy metals, including cadmium and chromium, were detected in wastewater-irrigated crops, though concentrations remained below international safety limits. The findings demonstrate that untreated River Ngadda wastewater is unsuitable for irrigating edible crops due to significant microbiological hazards and potential long-term chemical risks. The study highlights the need for wastewater treatment, improved waste management, safe irrigation practices, and continuous monitoring to protect public health and ensure food

Keywords: Wastewater Irrigation, Microbial Contamination, Foodborne Pathogens, *E. coli*, *Salmonella*, Public health, Urban Agriculture.

Introduction

Rapid urbanization, population growth, and inadequate sanitation infrastructure have intensified environmental pollution challenges in many cities across sub-Saharan Africa, including Maiduguri, northeastern Nigeria (UN-Habitat, 2018; WHO, 2022). In Maiduguri, wastewater from domestic, municipal, market, and small-scale industrial sources is often discharged untreated into open drains and natural channels, where it is subsequently reused for urban and peri-urban agriculture (Abubakar et al., 2020; Bwala & Mohammed, 2021). While wastewater reuse supports livelihoods and enhances food availability, it also poses significant risks due to the presence of pathogenic microorganisms that can contaminate vegetables and water sources used by surrounding communities (WHO, 2017; FAO, 2023).

Wastewater is known to harbor a wide range of pathogenic bacteria, including *Escherichia coli*, *Salmonella spp.*, *Shigella spp.*, *Vibrio cholerae*, and *Enterococcus* species, which originate mainly from human and animal fecal matter (Gerba & Smith, 2005; Leclerc et al., 2018). When such wastewater is used for irrigation or comes into contact with vegetables during cultivation, harvesting, washing, or transportation, these pathogens can easily adhere to plant surfaces or infiltrate edible tissues (Beuchat, 2006; Oliveira et al., 2012). Leafy vegetables such as lettuce, spinach, cabbage, and locally consumed leafy greens are particularly vulnerable due to their broad leaf surfaces and close contact with contaminated soil and water (Amoah et al., 2007; Keraita et al., 2014). Consumption of raw or poorly cooked vegetables contaminated with pathogenic bacteria significantly increases the risk of foodborne diseases (CDC, 2021; WHO, 2020).

In Maiduguri, the reliance on wastewater for vegetable farming is driven by water scarcity, especially during the long dry season, and limited access to clean irrigation water (FAO, 2019; Abubakar & Yahaya, 2020). Urban farmers often cultivate vegetables along river channels, drainage systems, and low-lying floodplains where wastewater accumulates (Bwala et al., 2021). Although this practice enhances year-round food production and income generation, it raises serious concerns about microbiological food safety and environmental health (Keraita et al., 2018). Previous studies in similar urban settings have demonstrated strong links between wastewater irrigation and elevated levels of fecal coliforms and pathogenic bacteria in vegetables, soils, and surface waters, leading to increased incidence of diarrheal diseases, typhoid fever, cholera, and other gastrointestinal infections (Hassan et al., 2014; Uyttendaele et al., 2015).

The health risks associated with bacteriological contamination are particularly severe for vulnerable populations, including children, the elderly, pregnant women, and immunocompromised individuals (WHO, 2019). In regions with limited healthcare access and weak disease surveillance systems, such infections often go underreported, contributing to persistent morbidity and mortality (Prüss-Ustün et al., 2019). In Maiduguri, where socio-economic challenges and population displacement due to insecurity have strained public health systems, exposure to contaminated water and food further exacerbates existing health burdens (UNICEF, 2021; NCDC, 2023). Street-vended vegetables and household-prepared meals using raw produce present additional pathways for pathogen transmission, especially where hygiene practices are inadequate (Mensah et al., 2012).

Despite the growing importance of wastewater reuse and urban agriculture in Maiduguri, comprehensive studies that simultaneously assess bacteriological contamination in wastewater, vegetables, and associated health risks remain limited (Bwala & Shettima, 2022). Many existing studies focus on either water quality or food contamination in isolation, without adequately linking microbial loads to exposure pathways and public health implications Understanding these interconnections is essential for developing effective risk mitigation strategies, informing policy, and protecting both consumers and farmers (WHO, 2017; FAO, 2023).

Therefore, this study focuses on assessing the bacteriological quality of wastewater used for irrigation, the level of microbial contamination in commonly consumed vegetables, and the associated health risks to residents of Maiduguri. By identifying key bacterial indicators and potential pathogenic organisms, the study aims to provide evidence-based insights into the extent of contamination and its implications for food safety and public health. The findings are expected to support the development of targeted interventions, including improved wastewater management, safer agricultural practices, public health awareness, and regulatory frameworks to reduce exposure risks (Drechsel et al., 2015; WHO, 2022). Ultimately, addressing bacteriological contamination in wastewater and vegetables is vital for ensuring sustainable urban agriculture, safeguarding public health, and improving environmental quality in Maiduguri and similar urban centers in developing countries (FAO, 2019; Prüss-Ustün et al., 2019).

Conceptual Framework and Literature Review

Concept of Food Web

The conceptual framework of this study is anchored on the food chain and food web concepts, which explain how contaminants introduced into the environment are transferred through interconnected ecological systems and ultimately affect human health. When untreated or poorly treated wastewater is used for irrigation, contaminants such as pathogens and toxic substances are introduced into the soil - plant system. These contaminants can be absorbed by vegetables during growth and subsequently transferred to humans through consumption, demonstrating a direct link between wastewater quality, food safety, and public health (Abbas et al., 2023; Khan et al., 2023).

In Maiduguri, the use of commercial and residential wastewater for vegetable irrigation is a common practice driven by water scarcity and limited access to clean irrigation sources. Vegetables cultivated with such wastewater, particularly leafy vegetables, are consumed by local populations, creating a pathway for contaminant transfer from wastewater to humans. Over time, repeated consumption of contaminated vegetables can result in bioaccumulation of harmful substances in the human body, leading to long-term health effects such as organ damage, hormonal disruption, and chronic diseases (Li et al., 2022; Iqbal et al., 2023). This highlights the relevance of the food chain concept in explaining how environmental contamination translates into human health risks.

Beyond the linear food chain, the food web concept provides a more comprehensive understanding of the interconnected trophic relationships within ecosystems. Wastewater used for irrigation often contains heavy metals, organic pollutants, and microbial pathogens that accumulate in soils and disrupt soil physicochemical properties and microbial communities (Du et al., 2022; Li et al., 2022). These disruptions affect primary producers (vegetables), which in turn influence higher trophic levels, illustrating cascading effects across the food web. Alterations in soil microbial diversity impair nutrient cycling and soil fertility, reducing crop health and productivity while increasing contaminant uptake by plants (Rasheela et al., 2025).

Crops irrigated with contaminated wastewater, especially leafy vegetables with shallow root systems and high water content, are particularly prone to accumulating contaminants. This not only affects plant growth and physiological functions but also poses serious risks to consumers. When such contaminated crops are consumed by humans or livestock, pollutants may undergo bioaccumulation and biomagnification, increasing their concentration at higher trophic levels (Li & Xiaocang, 2022; Badmus et al., 2024). Consequently, humans, positioned at the apex of the food web, are especially vulnerable to these effects (Bawa & Abdulhameed, 2025).

The framework also emphasizes human health risks**,** including gastrointestinal infections, neurological disorders, endocrine disruption, and increased cancer risk resulting from chronic exposure to contaminants through food consumption. These risks may be further amplified when pollutants leach into groundwater sources used for drinking and domestic purposes (Li & Xiaocang, 2022; Badmus et al., 2024). Additionally, consumption of contaminated crops by livestock can introduce pollutants into animal-derived foods such as meat, milk, and eggs, broadening the contamination pathway within the food web.

Overall, the conceptual framework illustrates that wastewater reuse in agriculture has far-reaching ecological and public health implications. Disruptions at one level of the ecosystem such as soil contamination can propagate through plants, animals, and humans due to the interconnected nature of food webs. This framework underscores the importance of maintaining ecosystem integrity and regulating wastewater use in agriculture to minimize contaminant transfer, protect food safety, and reduce health risks. It provides a logical basis for understanding how wastewater quality influences human health through the food chain and guides the assessment of environmental and public health impacts in Maiduguri (Li et al., 2023; Mendoza-Lera et al., 2022).

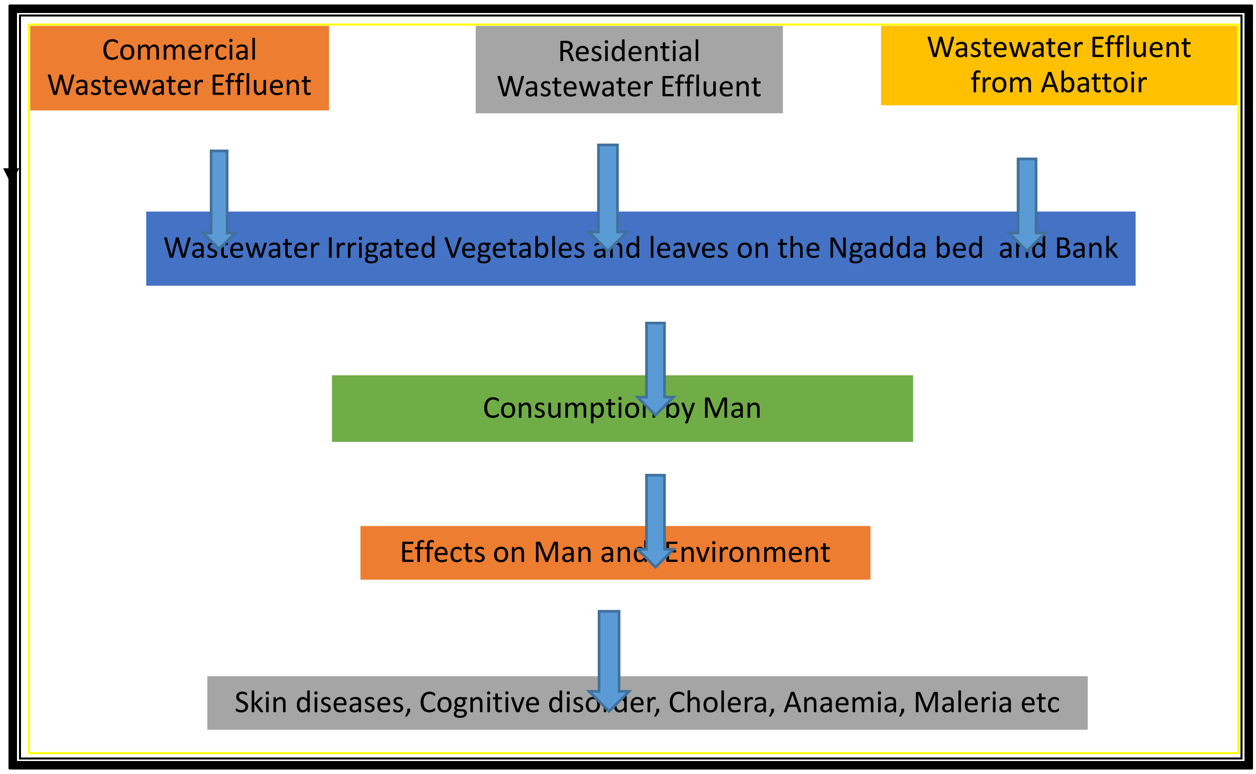

Figure 1: Flow diagram showing effects of wastewater quality on humans through food chain. (*Adapted from* Frontiers in Public Health, 2018)

Conceptual Framework and Literature Review

Wastewater use and bacteriological contamination

The reuse of wastewater in agriculture has become an increasingly common practice, particularly in water-scarce regions where conventional freshwater resources are limited, seasonal, or economically inaccessible. According to the Food and Agriculture Organization (FAO, 2021), nearly 20 million hectares of land worldwide are irrigated using wastewater, primarily in Asia, Africa, and the Middle East. Wastewater provides a readily available water source and, in many cases, contributes nutrients such as nitrogen and phosphorus, which can enhance crop growth and reduce reliance on chemical fertilizers. However, these benefits are accompanied by significant public health and environmental risks. Wastewater often contains pathogenic microorganisms including bacteria, viruses, and protozoa as well as chemical contaminants like heavy metals, organic pollutants, and pharmaceutical residues. The presence of these contaminants in irrigation water directly impacts the microbial and chemical safety of crops, creating a complex challenge for sustainable agriculture (WHO, 2022).

Studies continue to show that untreated or inadequately treated wastewater is a major source of environmental contamination. For instance, Bekele et al. (2023) investigated leafy vegetables irrigated with wastewater in Addis Ababa, Ethiopia, and found that the microbial loads on lettuce and Swiss chard were significantly higher than in crops irrigated with clean water. The study specifically identified pathogenic *Escherichia coli* strains as prevalent on these vegetables, highlighting the risk of foodborne illness for consumers and occupational exposure for farm workers. Similar patterns have been observed in other developing regions, where wastewater treatment infrastructure is insufficient and monitoring of microbial contamination is limited. These findings underscore the pressing need to assess the microbiological quality of wastewater used in agriculture and to implement interventions that reduce health risks while maintaining the benefits of wastewater reuse.

Contamination of vegetables through wastewater irrigation

Vegetables are particularly vulnerable to contamination from wastewater due to their growth habits and consumption patterns. Leafy greens such as lettuce, spinach, and cabbage have high surface areas and are often consumed raw, making them prime vehicles for microbial transfer from irrigation water. Multiple studies confirm that wastewater irrigation is strongly associated with contamination by both microbial pathogens and chemical pollutants. For example, Adu et al. (2023) conducted a field study in Ghana and found that lettuce irrigated with wastewater contained significant levels of opportunistic bacteria, including *Salmonella*, *Shigella*, and *Pseudomonas* species. These pathogens pose a direct risk to human health, particularly for children, immunocompromised individuals, and those in urban markets where washing and cooking may be inadequate.

Chemical contamination is also a major concern. Aftab et al. (2023) examined leafy vegetables irrigated with wastewater across several Asian countries and reported elevated concentrations of heavy metals, including cadmium, lead, and chromium. These metals can accumulate in edible tissues and, if ingested over time, lead to chronic health conditions such as kidney dysfunction, neurotoxicity, and impaired growth in children. The simultaneous presence of both microbial and chemical contaminants suggests that wastewater irrigation poses a compounded risk to human health, especially in informal urban farming settings where regulatory oversight is limited. Moreover, the accumulation of heavy metals in soils over time may reduce soil fertility and disrupt ecological balance, creating longer-term agricultural challenges.

Environmental factors such as irrigation methods, soil type, and crop handling practices further influence contamination levels. Drip irrigation, for example, has been shown to reduce direct contact between wastewater and edible crop surfaces compared to flood or sprinkler irrigation, thereby mitigating microbial transfer (Qadir et al., 2020). Nevertheless, in many low-resource farming communities, traditional flood irrigation remains the primary method due to simplicity and low cost, perpetuating high levels of vegetable contamination.

Health risks associated with bacteriological contamination

The public health implications of wastewater irrigation are significant and multifaceted. Consumption of raw vegetables contaminated with pathogenic bacteria, viruses, and parasites has been repeatedly linked to outbreaks of foodborne illness. Bekele et al. (2023) demonstrated that *E. coli* present in wastewater can readily transfer to leafy vegetables, posing direct health risks to consumers. In Burkina Faso, Ouattara et al. (2024) reported that enteric viruses were detected on lettuce irrigated with untreated wastewater, illustrating that reliance solely on bacterial indicators for monitoring may underestimate the full spectrum of pathogen-related risks. Foodborne pathogens transmitted via wastewater-irrigated crops can cause gastrointestinal illness, diarrhea, and, in severe cases, systemic infections. Occupational exposure is also a concern; farm workers who come into direct contact with contaminated water and soil are at elevated risk for skin infections, respiratory issues, and other bacterial illnesses.

Beyond microbial risks, chemical contaminants in wastewater-irrigated crops present serious long-term health challenges. Chronic exposure to heavy metals such as cadmium and lead can result in bioaccumulation in human tissues, particularly the kidneys, liver, and bones. Aftab et al. (2023) highlight that prolonged consumption of contaminated vegetables can disrupt endocrine function, impair neurological development in children, and increase the likelihood of cardiovascular disease and cancer. These effects are compounded in areas where populations rely heavily on locally grown produce as a dietary staple, creating cumulative exposure risks over time.

Globally, guidelines for safe wastewater reuse exist, such as those provided by the World Health Organization (WHO, 2006) and the Food and Agriculture Organization (FAO, 2017). These guidelines recommend proper wastewater treatment, monitoring of microbial and chemical contaminants, and safe irrigation practices to minimize health risks. However, real-world studies consistently show that untreated or partially treated wastewater continues to be used extensively, particularly in low- and middle-income countries, due to infrastructural, economic, and logistical constraints. This gap between recommended safety practices and actual farming practices underscores the need for integrated interventions that combine wastewater treatment, farmer education, and regulatory enforcement.

Study Area

The Maiduguri Metropolitan Area is situated in the northeastern region of Nigeria, serving as the capital of Borno State. Geographically, the city is located at approximately latitude 11.80° N and longitude 13.04° E to 13.22° E, extending beyond the core urban district into surrounding wards and adjacent local government areas such as parts of Jere and Konduga (Sanusi et al., 2025). The metropolis lies within the Sudan–Sahel semi-arid climatic zone, characterized by limited rainfall concentrated between June and September and a lengthy dry season for the remainder of the year (Sanusi et al., 2025; Britannica, 2025). The elevation of the region averages around 315–320 m above sea level, with the terrain predominantly flat, forming part of the undulating Borno Plain that slopes slightly toward the Lake Chad basin (Grokipedia, 2025; Weather Spark, 2025).

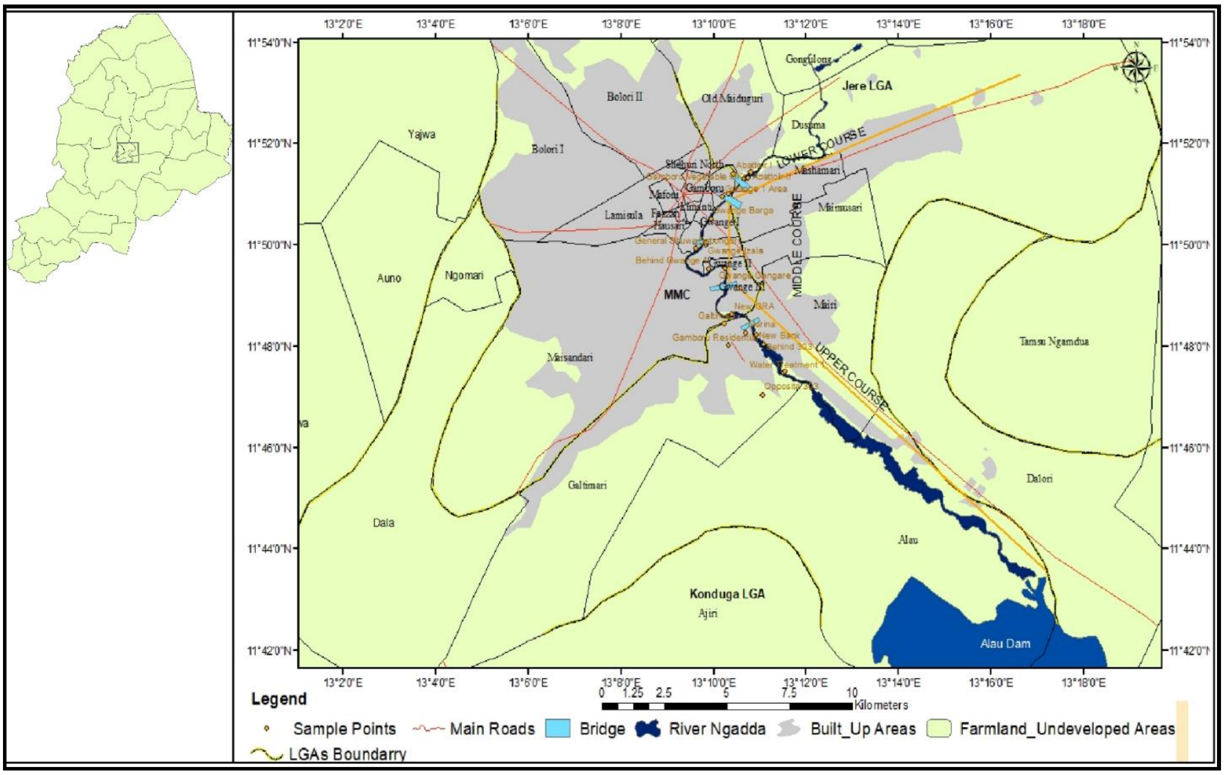

Figure 2: Study Area

Hydrologically, Maiduguri is intersected by seasonal waterways such as the Ngadda River and its tributaries, which flow mainly during the rainy months and contribute to localized flooding risks, particularly in low-lying areas (Sanusi et al., 2025; Grokipedia, 2025). The city's soil profile consists principally of sandy, alluvial, and aeolian deposits, reflecting the broader semi-arid landscape and historical sedimentation from past fluvial systems (Sanusi et al., 2025; Onlinenigeria, cited in *Urbanization and its Effects on the Environment*, 2025). Vegetation in the surrounding region remains consistent with semi-arid Sudan savannah conditions, with short grasses and scattered drought-resistant trees adapted to the limited and erratic rainfall (Sanusi et al., 2025; AZOJETE, 2025).

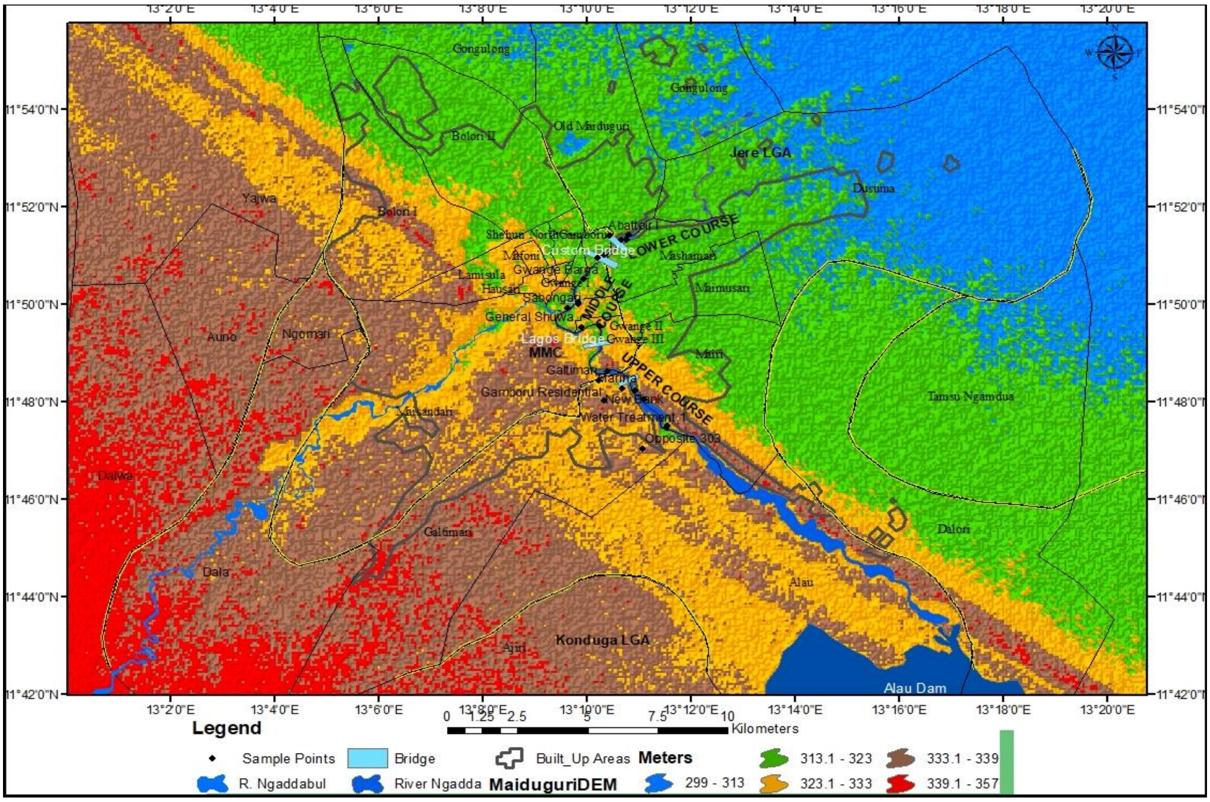

Figure 3: Relief and drainage of Maiduguri

Climatic conditions in Maiduguri are defined by a short rainy season, typically lasting from June to September, with annual rainfall averaging around 600 mm, and high rates of evapotranspiration that exceed precipitation. Seasonal temperatures range broadly, with cooler periods from October to February (about 13–25 °C) and hotter conditions from March to May (up to 45 °C) (Sanusi et al., 2025; Weather Spark, 2025). The semi-arid climate, combined with dense urban expansion, influences the city's surface hydrology and land use patterns.

Demographically, Maiduguri is a major urban center in northeastern Nigeria. While precise metropolitan population figures vary by source, estimates indicate substantial growth, with the metro area approaching approximately 791,200 people by 2022 and further increases through 2025 (Wikipedia, 2025; Macrotrends, 2025). As the administrative, commercial, and trade hub of Borno State, Maiduguri's role in regional markets and cross-border commerce significantly shapes its socio-economic dynamics and environmental landscape.

Methodology

Wastewater samples were collected aseptically from three representative points: Behind New GRA (Upper), Behind Gwange 4 (Middle), and Abattoir 1 (Lower). Samples were transported on ice and analyzed within 6 hours. For the Bacteriological Analysis, total coliform counts were done using the membrane filtration method (CFU/100ml). Isolated bacteria were identified using standard cultural, morphological, and biochemical techniques. The data analysed where Coliform counts were log-transformed and compared to WHO thresholds for restricted (<200 CFU/100ml) and unrestricted (<2.2 CFU/100ml) irrigation. Isolated pathogens were tabulated by river course. Vegetable elemental data was compared between wastewater and control plots using descriptive statistics.

Discussion of Findings

The bacteriological assessment of River Ngadda clearly demonstrates severe microbial contamination across all sampled river regimes, rendering the water unsuitable for irrigation of edible crops. Total coliform counts ranged from 159 × 10³ CFU/100 mL in the upper course to 260 × 10³ CFU/100 mL in the middle course, with the lower course recording 205 × 10³

CFU/100 mL. These values exceed the World Health Organization (WHO, 2017) guidelines for both restricted (<200 CFU/100 mL) and unrestricted irrigation (<2.2 CFU/100 mL) by two to three orders of magnitude, indicating extreme fecal pollution. Such elevated coliform levels are strong indicators of the possible presence of enteric pathogens and reflect significant public health risks associated with the use of this water for agricultural purposes.

Table 1: Total Coliform Count in the Three Regimes (CFU/100 ml)

Sample locations	River regime	Total coliform count
Behind New GRA	Upper Course	159 x 10^3 cfu
Behind Gwange 4	Middle Course	260 x 10^3 cfu
Abattoir 1	Lower Course	205 x10^3 cfu

Source: Laboratory analysis (2024)

Spatial variation and influence of anthropogenic activities

The observed spatial variation in coliform counts corresponds closely with land-use patterns and human activities along the river. The middle course, located within the densely populated core of Maiduguri, recorded the highest coliform load. This can be attributed to direct discharge of domestic sewage, hospital effluents, and poorly managed solid waste, compounded by inadequate. organic matter and fecal contaminants into the river, promoting microbial proliferation.

Although the upper course is relatively less urbanized, significant contamination was still observed. This suggests that microbial pollution is not limited to highly urbanized areas but is pervasive throughout the river system. In the upper course, contamination is likely driven by agricultural runoff, animal droppings, market waste from New Bama market, and poor sanitation practices, demonstrating that even semi-rural or peri-urban activities can substantially degrade water quality. The lower course, influenced heavily by abattoir operations and market activities at Gamboru, showed high coliform counts linked to the discharge of animal blood, entrails, and organic wastes. These inputs increase nutrient and organic loads, creating favourable conditions for the survival and multiplication of pathogenic bacteria.

Table 2: Other Isolated Micro-Organism

Upper course	Middle course	Lower course
Escherichia coli	*Bacillus Species*	*Escherichia coli*
Streptococcus faecalis	*Corynebacteria Species*	*Salmonella species*
Proteus mirabilis		*Klebsiella specie*
Salmonella specie		*Proteus mirabilis*
		Staphylococcus aureus
		Streptococcus faecalis
		Bacillus Cereus
		Bacillus Subtilis
		Corynebacteria Species

Source: Laboratory analysis (2024)

	Bacterial Limit (Faecal Coliforms)
Unrestricted irrigation	< 2.2 CFU/100ml (WHO, 2017)
Restricted irrigation	< 200 CFU/100ml (WHO, 2017)

Diversity of pathogenic microorganisms

Beyond total coliform counts, the isolation of a wide range of pathogenic and opportunistic bacteria further emphasizes the microbiological hazard posed by River Ngadda. Detected organisms included Escherichia coli, Salmonella species, Streptococcus faecalis, Staphylococcus aureus, Proteus mirabilis, Klebsiella species, Bacillus cereus, Bacillus subtilis, and Corynebacterium species. The widespread occurrence of E. coli and Salmonella species across all river regimes is particularly significant, as these organisms are definitive indicators of fecal contamination and are commonly associated with gastrointestinal infections, typhoid fever, and other enteric diseases.

Table 3: Isolated microorganisms in River Ngadda Regimes and Possible Sources of Contamination (CFU/100ml)

River Regime	Isolated Microorganisms	Possible Sources (based on terrain & anthropogenic activities)
Upper Course (Less urbanized; agricultural lands, asphalt plants, New Bama market)	*Escherichia coli*, *Streptococcus faecalis*, *Proteus mirabilis*, *Salmonella* species	Fecal contamination from agricultural runoff and market wastes; animal droppings; leachates from small-scale farming activities; improper sanitation.
Middle Course (Core of Maiduguri; highly urbanized and densely populated)	*Bacillus* species, *Corynebacterium* species, *Klebsiella* species, *Proteus mirabilis*	Domestic sewage discharge, effluents from hospitals and households, solid waste disposal, high-density population pressure, and inadequate waste management infrastructure.
Lower Course (Lowest elevation; Gamboru market, abattoir)	*Escherichia coli*, *Salmonella* species, *Staphylococcus aureus*, *Streptococcus faecalis*, *Bacillus cereus*, *Bacillus subtilis*, *Corynebacterium* species	Slaughterhouse (abattoir) waste effluents, market refuse, animal blood and entrails washed into the river, poor waste management, and intensified human activity increasing organic load.

Source: Laboratory analysis (2024)

The middle and lower courses exhibited greater microbial diversity, reflecting cumulative contamination from multiple sources such as hospitals, households, markets, and slaughterhouses. The presence of Staphylococcus aureus and Bacillus cereus, especially in the lower course, raises additional food safety concerns due to their ability to produce heat-stable toxins capable of causing food poisoning even when bacteria are no longer viable. These findings suggest not only immediate risks of acute foodborne illness but also potential long-term exposure risks for populations consuming vegetables irrigated with this water.

Implications for vegetable contamination and food safety

The vegetable contamination analysis reinforces the public health significance of the bacteriological findings. Spinach and okra irrigated with River Ngadda wastewater accumulated higher microbial and chemical contaminants compared to vegetables irrigated with clean borehole water. Leafy vegetables such as spinach are particularly vulnerable due to their large surface area, rough leaf morphology, and close contact with contaminated soil and irrigation water. Once contaminated, these vegetables can readily act as vehicles for pathogen transmission, especially when consumed raw or inadequately washed, a common practice in many urban households.

The contamination of okra further demonstrates that even non-leafy vegetables are not immune, particularly when irrigation water quality is extremely poor. The findings align with previous studies indicating that wastewater-irrigated vegetables can harbour pathogenic bacteria that persist through harvesting, transportation, and marketing stages, thereby extending contamination beyond the farm level to consumers.

Public health and environmental implications

Collectively, the results highlight a serious breakdown in the water–food–health continuum along River Ngadda. Farmers using untreated river water for irrigation are at increased occupational risk through direct contact with contaminated water and soils, while consumers are exposed through the consumption of contaminated produce. Vulnerable populations, including children, the elderly, and immunocompromised individuals, are particularly at risk of severe health outcomes. The persistence of high microbial loads across all river regimes also suggests the potential for environmental amplification, where contaminated sediments and soils serve as reservoirs for pathogens that can be re-suspended during irrigation or flooding events. Without intervention, continuous use of River Ngadda water for irrigation may sustain cycles of waterborne and foodborne disease transmission within Maiduguri.

Conclusion and Recommendations

This study concludes that River Ngadda is severely bacteriologically contaminated and unsuitable for the irrigation of edible crops. Total coliform counts across the upper, middle, and lower river courses exceeded World Health Organization (WHO) guidelines for safe irrigation by several orders of magnitude, indicating extreme fecal pollution. The widespread presence of pathogenic bacteria such as *Escherichia coli*, *Salmonella* spp., *Staphylococcus aureus*, and *Bacillus cereus* confirms significant microbiological hazards associated with the use of the river water. Spatial variations in contamination reflect differences in land use and anthropogenic activities along the river, with the highest microbial loads occurring in densely populated and highly urbanized areas, as well as zones influenced by abattoir and market activities. The contamination of spinach and okra irrigated with River Ngadda water demonstrates a direct pathway for pathogen transfer from wastewater to humans, posing serious food safety and public health risks, particularly for consumers of raw or poorly processed vegetables. Overall, the findings highlight a critical disruption of the water–food–health continuum in Maiduguri, exposing farmers and consumers to increased risks of waterborne and foodborne diseases. Without intervention, continued reliance on untreated river water for irrigation is likely to sustain environmental contamination and adverse health outcomes.

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

i. Wastewater Treatment and Control: Appropriate wastewater treatment or stabilization measures should be implemented before river water is reused for agricultural irrigation.
ii. Improved Waste Management: Proper management of domestic sewage, hospital effluents, market refuse, and abattoir wastes should be enforced to reduce direct discharge into River Ngadda.
iii. Adoption of Safer Irrigation Practices: Farmers should be encouraged to adopt safer irrigation methods, such as controlled or restricted irrigation, and to avoid cultivating high-risk crops like leafy vegetables with untreated wastewater.
iv. Regular Water Quality Monitoring: Routine bacteriological monitoring of River Ngadda should be conducted by relevant authorities to detect contamination trends and prevent disease outbreaks.
v. Public Health Education and Awareness: Farmers, vendors, and consumers should be educated on the health risks associated with wastewater irrigation and the importance of proper vegetable handling, washing, and cooking.
vi. Policy and Regulatory Enforcement**:** Government agencies should strengthen and enforce policies regulating wastewater reuse in agriculture to protect public health and promote sustainable urban farming.

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