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CHEMICAL CONTAMINATION AND NUTRIENT ACCUMULATION IN WASTEWATER-IRRIGATED VEGETABLES ALONG THE NGADDA RIVER, MAIDUGURI, NIGERIA

Ali Galadima — Division of General Studies, University of Maiduguri, Nigeria

Ikusemoran Mayomi — Department of Geography, University of Maiduguri, Nigeria

Zainab Chellube — Department of Chemistry University of Maiduguri, Nigeria

Abstract

This study examined the chemical composition and potential contamination of vegetables irrigated with wastewater along the Ngadda River in Maiduguri, northeastern Nigeria. A controlled field experiment was conducted using spinach (Spinacia oleracea) and okra (Abelmoschus esculentus) grown under two irrigation conditions: wastewater and freshwater. Four experimental plots were established, including two wastewater-irrigated plots and two freshwater control plots. At maturity, vegetable samples were harvested and analyzed for selected chemical constituents such as chloride (Cl^-), sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), phosphate (PO_4^{3-}), sulphate (SO_4^{2-}), cadmium (Cd), chromium (Cr), and phosphorus (P) using atomic absorption spectrophotometry and UV–visible spectrophotometry. The results showed notable differences in nutrient accumulation between wastewater and freshwater-irrigated vegetables. Chloride concentrations ranged from 0.005 to 0.012 mg/kg, while sodium levels varied between 0.032 to 0.106 mg/kg, with wastewater irrigation increasing sodium in okra by about 63%. Potassium concentrations ranged from 0.052 to 0.114 mg/kg, but decreased by approximately 54% in wastewater-irrigated okra. Magnesium showed the greatest variation, increasing from 0.055 mg/kg to 0.413 mg/kg in wastewater-irrigated okra. Phosphate concentrations also increased under wastewater irrigation, particularly in okra (0.004 to 0.065 mg/kg). Sulphate levels showed only slight variation. Trace heavy metals were detected at very low levels. Cadmium was found only in wastewater-irrigated okra (0.001 mg/kg), while chromium was detected at 0.001 mg/kg in spinach and wastewater-irrigated okra. These values were below international safety limits. Overall, the study indicates that wastewater irrigation can enhance nutrient availability in vegetables but may also introduce trace contaminants, highlighting the need for continuous monitoring and improved wastewater management practices.

Keywords: Wastewater Irrigation, Vegetable Contamination, Heavy Metals, Nutrient Accumulation

Introduction

Rapid urban expansion, increasing population pressure, and insufficient sanitation infrastructure have intensified environmental pollution challenges across many cities in sub-Saharan Africa, including Maiduguri in northeastern Nigeria. These factors have significantly increased the discharge of untreated wastewater into urban drainage systems and nearby surface waters (UN-Habitat, 2020; WHO, 2023). In Maiduguri, wastewater generated from domestic households, markets, municipal facilities, and small-scale industries is frequently discharged without adequate treatment into open channels and natural waterways. Such water is subsequently utilized for irrigation in urban and peri-urban agriculture (Abubakar et al., 2021; Bwala & Mohammed, 2022).

Although the reuse of wastewater supports livelihoods and contributes to food production, it presents significant environmental and public health concerns due to the presence of pathogenic microorganisms and chemical contaminants. These contaminants may be transferred to crops during irrigation, posing risks to farmers and consumers alike (WHO, 2022; FAO, 2023). Wastewater commonly contains pathogenic bacteria such as *Escherichia coli*, *Salmonella* spp., *Shigella* spp., *Vibrio cholerae*, and *Enterococcus* species, which primarily originate from human and animal fecal matter (Leclerc et al., 2018; WHO, 2023).

When contaminated wastewater is used for irrigation or comes into contact with crops during cultivation, harvesting, or post-harvest handling, pathogenic microorganisms can attach to plant surfaces or penetrate edible tissues. Such contamination pathways significantly increase the likelihood of foodborne infections (Beuchat, 2006; Oliveira et al., 2012; FAO, 2023). Leafy vegetables including lettuce, spinach, cabbage, and locally consumed greens are particularly susceptible because of their large surface areas and frequent contact with contaminated soil and irrigation water (Amoah et al., 2007; Keraita et al., 2018; Bekele et al., 2023).

The consumption of raw or minimally cooked vegetables contaminated with pathogenic microorganisms is widely recognized as a major source of foodborne illness worldwide (CDC, 2022; WHO, 2023). In Maiduguri, reliance on wastewater for irrigation is largely driven by water scarcity, particularly during the prolonged dry season when access to clean irrigation water becomes limited (FAO, 2019; Abubakar & Yahaya, 2021). Urban farmers often cultivate vegetables along riverbanks, drainage channels, and floodplain areas where wastewater accumulates, enabling year-round production (Bwala et al., 2022).

Conceptual Framework and Literature Review

Food Chain and Food Web Concepts

The conceptual framework for this study is grounded in the ecological principles of the food chain and food web, which explain how contaminants introduced into environmental systems can move through interconnected biological pathways and ultimately affect human health. When untreated or poorly treated wastewater is applied to agricultural land, contaminants including pathogens and toxic chemicals enter the soil–plant system. These substances may subsequently be absorbed by crops and transferred to humans through food consumption, illustrating the connection between environmental contamination, food safety, and public health (Abbas et al., 2023; Khan et al., 2023).

In Maiduguri, wastewater from residential and commercial activities is widely used for irrigating vegetables due to limited access to clean water. Vegetables cultivated with such wastewater particularly leafy varieties are commonly consumed by the local population. This practice creates a direct pathway for contaminant transfer from wastewater to humans. Repeated consumption of contaminated vegetables can lead to the gradual accumulation of toxic substances within the human body, potentially resulting in long-term health problems such as organ damage, endocrine disruption, and chronic disease development (Li et al., 2022; Iqbal et al., 2023).

While the food chain represents a linear transfer of contaminants, the food web concept provides a broader perspective on the complex interactions within ecosystems. Wastewater used for irrigation often contains heavy metals, organic pollutants, and microbial pathogens that accumulate in soils and alter their physicochemical properties as well as microbial communities (Du et al., 2022; Li et al., 2022). These changes affect primary producers such as vegetables, which subsequently influence organisms at higher trophic levels.

Disturbances in soil microbial diversity may impair nutrient cycling and soil fertility, thereby reducing crop productivity while simultaneously increasing contaminant uptake by plants (Rasheela et al., 2025). Vegetables irrigated with contaminated wastewater especially leafy vegetables characterized by shallow root systems and high water content are particularly prone to absorbing pollutants. Such contamination not only affects plant physiology but also presents significant risks to human consumers.

When contaminated crops are consumed by humans or livestock, pollutants may accumulate within biological tissues through processes such as bioaccumulation and biomagnification, resulting in increased concentrations at higher trophic levels (Li & Xiaocang, 2022; Badmus et al., 2024). Humans, positioned at the apex of the food web, therefore face heightened exposure to these contaminants (Bawa & Abdulhameed, 2025).

The conceptual framework further emphasizes the health risks associated with chronic exposure to environmental contaminants through food consumption. These risks include gastrointestinal infections, neurological disorders, endocrine disruption, and increased cancer risk. In addition, contaminants present in wastewater may infiltrate groundwater sources used for drinking and domestic activities, thereby expanding exposure pathways (Li & Xiaocang, 2022; Badmus et al., 2024).

Furthermore, livestock that consume contaminated crops may accumulate pollutants in their tissues, potentially introducing contaminants into animal-derived food products such as meat, milk, and eggs. This process broadens the contamination pathway within the food web and increases potential exposure among human populations.

Overall, this conceptual framework highlights that wastewater reuse in agriculture has significant ecological and public health implications. Contamination at one level of the ecosystem such as soil pollution can propagate through plants, animals, and humans due to the interconnected nature of food webs. Consequently, maintaining ecosystem integrity and regulating wastewater use in agriculture are critical for minimizing contaminant transfer, protecting food safety, and reducing public health risks. The framework therefore provides a logical basis for assessing the environmental and health impacts of wastewater irrigation in Maiduguri (Li et al., 2023; Mendoza-Lera et al., 2022).

Wastewater Irrigation and Contamination of Vegetables

Vegetables are particularly susceptible to contamination from wastewater due to their cultivation practices and patterns of consumption. Leafy vegetables such as lettuce, spinach, and cabbage possess large surface areas that facilitate microbial attachment and are frequently consumed raw, making them important vehicles for pathogen transmission.

Several studies have confirmed the relationship between wastewater irrigation and contamination of vegetables by microbial pathogens and chemical pollutants. For example, Adu et al. (2023) reported significant levels of opportunistic bacteria including *Salmonella*, *Shigella*, and *Pseudomonas* species in lettuce irrigated with wastewater in Ghana. These microorganisms pose serious health risks, particularly for children and immunocompromised individuals.

Chemical contamination also represents a major concern. Aftab et al. (2023) identified elevated concentrations of heavy metals such as cadmium, lead, and chromium in leafy vegetables irrigated with wastewater in several Asian countries. Long-term consumption of such contaminated vegetables can lead to serious health conditions including kidney damage, neurological disorders, and impaired growth among children.

Environmental factors such as irrigation methods, soil properties, and crop handling practices further influence contamination levels. For instance, drip irrigation has been shown to reduce direct contact between wastewater and edible crop surfaces compared with flood or sprinkler irrigation systems (Qadir et al., 2020). Nevertheless, traditional flood irrigation remains widely used in many low-income farming communities due to its simplicity and affordability, thereby increasing contamination risks.

Study Area

The Maiduguri Metropolitan Area is located in northeastern Nigeria and serves as the administrative capital of Borno State. Geographically, the city lies approximately between latitude 11.80°N and longitude 13.04°E to13.22°E, extending beyond the central urban district to include surrounding wards and nearby local government areas such as Jere and parts of Konduga (Sanusi et al., 2025).

Maiduguri is situated within the semi-arid climatic zone, characterized by low and highly seasonal rainfall that occurs mainly between June and September, followed by a prolonged dry season for the remainder of the year (Sanusi et al., 2025; Britannica, 2025). The region lies at an average elevation of approximately 315 to 320 meters above sea level, forming part of the gently undulating Borno Plain that slopes toward the Lake Chad Basin (Weather Spark, 2025).

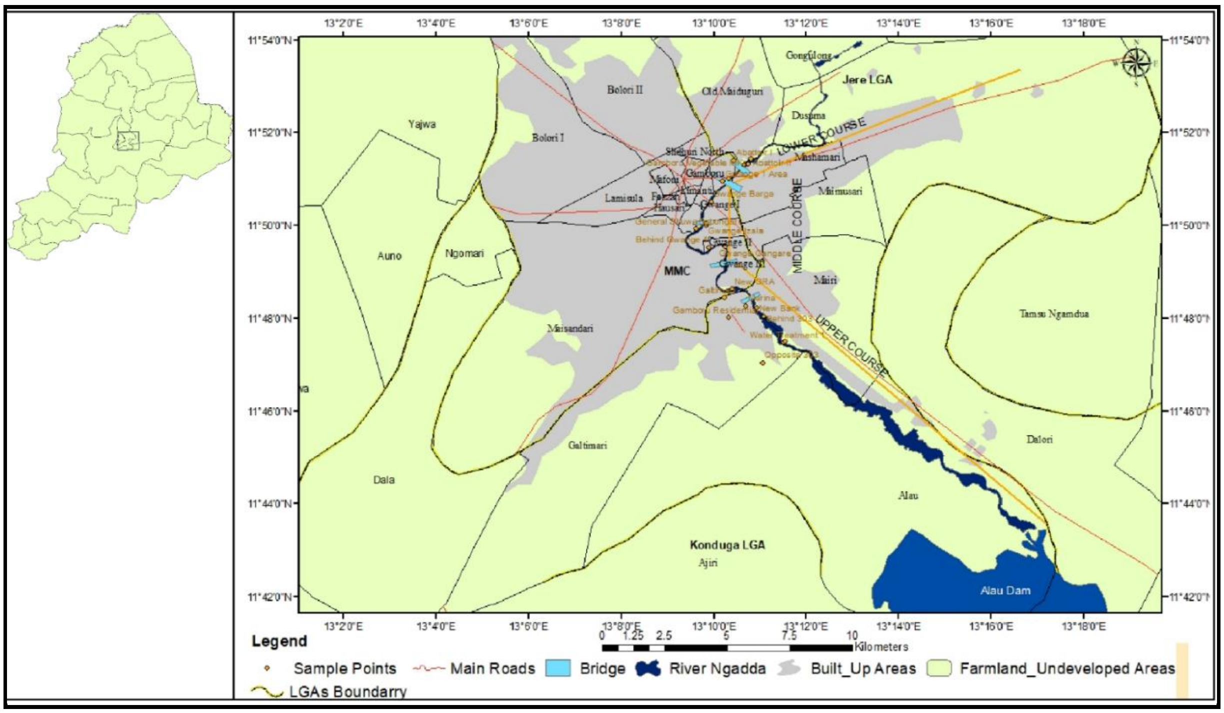

Figure 1: Study Area

Hydrologically, the city is intersected by seasonal watercourses, most notably the Ngadda River, which flows predominantly during the rainy season and contributes to occasional flooding in low-lying areas (Sanusi et al., 2025). The soils in the region are mainly sandy and alluvial, derived from aeolian and fluvial deposits typical of semi-arid environments. Vegetation in the surrounding area corresponds to the Sudan savannah ecological zone, consisting primarily of short grasses and scattered drought-resistant trees adapted to limited rainfall and high temperatures.

Climatic conditions are characterized by a short rainy season and high evapotranspiration rates. Annual rainfall averages approximately 600 mm, while temperatures range from 13–25°C during cooler months (October–February) to up to 45°C during the hottest period (March–May) (Weather Spark, 2025). Demographically, Maiduguri is a rapidly growing urban center and a key commercial hub in northeastern Nigeria. Population estimates indicate that the metropolitan area approached approximately 791,000 residents by 2022, with continued growth projected in subsequent years due to urban expansion and migration (Macrotrends, 2025). The city's economic activities, particularly agriculture and regional trade, strongly influence its environmental dynamics and land-use patterns.

Methodology

To evaluate chemical contamination resulting from wastewater irrigation, a controlled farm experiment was conducted using spinach (*Spinacia oleracea*) and okra (*Abelmoschus esculentus*). The experiment was established on farmland located on elevated terrain to prevent infiltration or runoff from external contaminated water sources. Four experimental plots were established. Two plots served as experimental treatments irrigated with wastewater, one for spinach and one for okra while two additional plots served as control treatments irrigated with clean water under similar environmental and agronomic conditions. At maturity, vegetable samples were harvested and separated into plant components including leaves, stems, and roots. The samples were subsequently dried, ashed, digested, and analyzed in the laboratory to determine the types and concentrations of chemical contaminants accumulated in plant tissues.

Prior to analysis, vegetable samples were thoroughly rinsed with distilled water to remove surface contaminants and air-dried at room temperature. The samples were then oven-dried at 60°C until constant weight was achieved. Dried samples were ground into fine powder using a mechanical grinder and passed through a 0.5 mm mesh sieve to ensure uniform particle size. Approximately 0.5 g of each ash sample was digested using a mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$) within a controlled fume hood environment. The digested samples were filtered and diluted to 50 ml with deionized water prior to chemical analysis.

Elemental concentrations including Cl^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, PO_4^{3-}, SO_4^{2-}, Cd, Cr, and P were determined using appropriate analytical instruments. Atomic Absorption Spectrophotometry (AAS) was employed for the detection of Cd, Cr, Ca, Mg, Na, and K, while UV–Visible spectrophotometry was used to determine PO_4^{3-}, SO_4^{2-}, and P concentrations. Chloride levels were measured using a chloride analyzer. Although inferential statistical analysis was not the primary focus of this study, the measured contaminant concentrations were compared with established international standards to assess potential health risks. Integrating wastewater quality data with vegetable contamination levels enabled a comprehensive evaluation of exposure pathways and associated human health implications related to wastewater reuse along the Ngadda River irrigation corridor.

Chemical Concentration in Vegetable along River Ngadda in Maiduguri

Laboratory analyses of okra and spinach irrigated with wastewater and freshwater from River Ngadda were conducted to determine the concentrations of selected chemical constituents, including Cl^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, PO_4^{3-}, SO_4^{2-}, Cd, Cr, and P. The results of these analyses are presented in Table 6.2**,** which provides a comparative assessment of the chemical composition of vegetables cultivated under the two irrigation regimes. The table highlights variations in nutrient and heavy metal uptake between wastewater-irrigated and freshwater-irrigated vegetables, offering insight into the influence of irrigation water quality on vegetable nutrition and potential food safety risks. These findings are essential for understanding the implications of wastewater reuse for vegetable production along River Ngadda.

Table 2: Concentration of Chemical in Spinach and Okra Produced in the Study Area

Elements	**Wastewater**		**Fresh water**		***WHO/FAO guidelines***	***NSDWQ***
	Spinach	Okra	Spinach	Okra		
Cl	0.012	0.005	0.010	0.006	*NS*	*NS*
Na+	0.106	0.052	0.105	0.032	*NR*	*NR*
K+	0.061	0.052	0.058	0.114	*NR*	*NR*
Ca+	0.151	0.134	0.105	0.393	*NR*	*NR*
Mg+	0.073	0.413	0.075	0.055	*NR*	*NR*
PO+	0.016	0.065	0.012	0.004	*NR*	*NR*
SO+	0.058	0.007	0.055	0.006	*NR*	*NR*
Cd	ND	0.001	ND	ND	*0.2mg/kg*	*0.1mg/kg*
Cr	0.001	0.001	0.001	ND	*0.5mg/kg*	*0.5mg/kg*
P	0.011	0.016	0.010	0.015	*NR*	*NR*

Chloride (Cl^-)

Chloride concentrations recorded in the vegetable samples were relatively low, ranging from 0.005 to 0.012 mg/kg across all treatments. Spinach irrigated with wastewater showed a slightly higher chloride concentration (0.012 mg/kg) compared with spinach irrigated with freshwater (0.010 mg/kg). In contrast, okra exhibited minimal variation between irrigation sources, with values of 0.005 mg/kg under wastewater irrigation and 0.006 mg/kg under freshwater irrigation.

These results indicate that chloride accumulation in the studied vegetables was minimal and did not pose any toxicity risk. Previous studies have shown that wastewater irrigation can introduce small quantities of chloride into agricultural soils due to dissolved salts originating from domestic effluents and urban runoff (Moussa et al., 2021; Singh & Kumar, 2021). The slightly higher concentration observed in wastewater-irrigated spinach therefore aligns with existing literature.

The negligible difference in chloride concentration in okra supports findings by Adegbola et al. (2019), who reported that fruit-bearing vegetables typically regulate chloride uptake more effectively than leafy vegetables. Chloride toxicity generally occurs only at significantly higher concentrations than those observed in the present study. Consequently, the chloride levels detected in spinach and okra along River Ngadda remain well within acceptable physiological ranges and do not represent a food safety concern.

Sodium (Na^+)

Sodium concentrations in the vegetable samples ranged between 0.032 and 0.106 mg/kg. Wastewater irrigation was associated with slightly elevated sodium levels in both crops. In spinach, sodium concentration increased marginally from 0.105 mg/kg under freshwater irrigation to 0.106 mg/kg under wastewater irrigation. However, the increase was more pronounced in okra, where sodium levels rose from 0.032 mg/kg under freshwater irrigation to 0.052 mg/kg under wastewater irrigation, representing an approximate 63% increase.

The higher sodium content observed in wastewater-irrigated vegetables is consistent with numerous studies that identify wastewater as a major source of soluble sodium salts (FAO, 2023; Singh & Kumar, 2021). Wastewater typically contains sodium derived from household detergents, industrial discharge, and domestic sewage.

The greater sodium accumulation observed in okra compared to spinach supports findings by Li et al.

(2020), who reported that fruit vegetables may exhibit weaker sodium exclusion mechanisms than leafy vegetables. Increased sodium uptake in wastewater-irrigated crops has also been associated with ionic imbalance and potential reductions in crop yield under semi-arid conditions (Adeyemi et al., 2022). Although the sodium concentrations recorded in this study remain relatively low, continuous wastewater irrigation could potentially lead to gradual salt accumulation in soils, which may affect crop productivity in the long term.

Potassium (K^+)

Potassium concentrations in the vegetables ranged from 0.052 to 0.114 mg/kg. Spinach exhibited relatively stable potassium levels between irrigation treatments, with 0.058 mg/kg recorded under freshwater irrigation and 0.061 mg/kg under wastewater irrigation. In contrast, okra showed a notable decline in potassium concentration under wastewater irrigation, decreasing from 0.114 mg/kg under freshwater irrigation to 0.052 mg/kg under wastewater irrigation.

The reduction in potassium concentration in wastewater-irrigated okra may be attributed to competitive interactions between sodium and potassium ions in the soil–plant system. Studies have demonstrated that elevated sodium levels can inhibit potassium uptake due to shared transport pathways in plant roots (Singh & Kumar, 2021). Similar patterns of potassium suppression in fruit vegetables irrigated with saline or wastewater sources have been documented in several agricultural studies (Bwala, 2021).

The higher potassium levels observed in freshwater-irrigated okra further support the conclusion that low-salinity irrigation water enhances potassium availability and uptake efficiency (FAO, 2023). The results therefore illustrate a classic sodium–potassium antagonistic relationship, which is commonly reported in soils affected by saline or wastewater irrigation.

Calcium (Ca^{2+})

Calcium concentrations ranged from 0.105 to 0.393 mg/kg across the vegetable samples. The highest calcium concentration was observed in freshwater-irrigated okra (0.393 mg/kg), whereas wastewater-irrigated okra recorded significantly lower levels (0.134 mg/kg). Spinach displayed smaller variations between treatments, with 0.105 mg/kg under freshwater irrigation and 0.151 mg/kg under wastewater irrigation.

The reduced calcium uptake observed in wastewater-irrigated okra is consistent with previous research indicating that elevated sodium concentrations in irrigation water can displace calcium from soil exchange sites, thereby limiting its availability to plants (Li et al., 2020; Chen et al., 2020). Such interactions can lead to nutrient imbalances within plant tissues.

The relatively stable calcium levels in spinach suggest that leafy vegetables may be more efficient at maintaining calcium uptake under varying soil conditions. Similar observations were reported by Adegbola et al. (2019), who found that leafy crops generally demonstrate greater resilience to nutrient imbalances compared to fruit-bearing vegetables. Overall, the results highlight the potential influence of wastewater irrigation on calcium availability and plant nutrient dynamics.

Magnesium (Mg^{2+})

Magnesium concentrations showed the most striking variation among the analyzed nutrients. Spinach maintained relatively stable magnesium levels across irrigation treatments, ranging from 0.073 to 0.075 mg/kg. In contrast, okra exhibited a dramatic increase in magnesium concentration under wastewater irrigation, rising from 0.055 mg/kg under freshwater irrigation to 0.413 mg/kg under wastewater irrigation.

The elevated magnesium levels observed in wastewater-irrigated okra are likely linked to the chemical composition of domestic wastewater, which frequently contains magnesium compounds derived from detergents and cleaning agents (Bwala, 2021; Moussa et al., 2021). The substantial increase recorded in okra also highlights the species-specific nature of nutrient uptake.

Previous studies have emphasized that excessive magnesium accumulation can interfere with the absorption of other essential nutrients such as calcium and potassium (Singh & Kumar, 2021). The nutrient imbalances observed in wastewater-irrigated okra in this study therefore support existing literature describing antagonistic relationships among major plant nutrients.

Phosphate (PO_4^{3-})

Phosphate concentrations increased in both crops under wastewater irrigation. Spinach recorded an increase from 0.012 mg/kg under freshwater irrigation to 0.016 mg/kg under wastewater irrigation. Okra exhibited a much larger increase, rising from 0.004 mg/kg under freshwater irrigation to 0.065 mg/kg under wastewater irrigation.

The substantial increase in phosphate levels under wastewater irrigation reflects the nutrient-rich nature of domestic wastewater, which often contains high concentrations of phosphorus derived from organic waste and detergents (FAO, 2023; Adeyemi et al., 2022). The pronounced phosphate accumulation in okra is consistent with findings by Ahmed et al. (2021), who reported enhanced phosphorus uptake in fruit vegetables irrigated with nutrient-rich wastewater.

While phosphorus enrichment may improve crop growth and reduce fertilizer requirements, excessive phosphate accumulation can contribute to long-term soil nutrient imbalances and environmental pollution (Kumar et al., 2022). Consequently, regular monitoring of phosphorus levels is essential in wastewater-irrigated agricultural systems.

Sulphate (SO_4^{2-})

Sulphate concentrations in the vegetable samples were relatively low and exhibited only slight variations between irrigation treatments. Spinach recorded values ranging from 0.055 to 0.058 mg/kg, while okra showed concentrations between 0.006 and 0.007 mg/kg.

These minor increases under wastewater irrigation correspond with previous studies indicating that sulphur compounds present in wastewater may slightly enhance sulphate availability in soils (Moussa et al., 2021). However, the narrow variation observed between treatments suggests that sulphate availability was not significantly influenced by irrigation water quality in the study area.

According to FAO (2023), sulphur deficiency is relatively uncommon in wastewater-irrigated agricultural systems because wastewater typically supplies adequate quantities of this nutrient. The sulphate concentrations recorded in the present study therefore do not indicate any immediate environmental or agronomic concern.

Heavy Metals: **Cadmium (Cd) and Chromium (Cr)**

Heavy metals represent a critical aspect of food safety in wastewater-irrigated agriculture due to their potential toxicity and persistence in soils. In the present study, cadmium was detected only in wastewater-irrigated okra at a concentration of 0.001 mg/kg, while it was not detected in spinach or freshwater-irrigated samples.

Although the detected cadmium concentration is significantly lower than the permissible limits established by international food safety standards, its presence indicates potential contamination pathways associated with wastewater irrigation. Studies by Chen et al. (2020) and Kumar et al. (2022) similarly identified wastewater reuse as an important source of trace heavy metals in agricultural systems.

Chromium was detected at 0.001 mg/kg in spinach under both irrigation sources and in okra only under wastewater irrigation. The presence of chromium in spinach under both treatments may reflect background levels in agricultural soils, as leafy vegetables often accumulate higher concentrations of trace metals due to their larger surface area and transpiration rates (Kumar et al., 2022).

Although the measured chromium concentrations remain well below international safety limits, previous studies have emphasized that chromium can persist in soils and accumulate gradually over time (Chen et al., 2020). Continued monitoring is therefore necessary to prevent long-term contamination.

Phosphorus (P)

Total phosphorus concentrations ranged narrowly from 0.010 to 0.016 mg/kg, with the highest value observed in wastewater-irrigated okra. These results indicate moderate phosphorus enrichment associated with wastewater irrigation.

Previous studies have shown that wastewater can act as a supplementary nutrient source, providing phosphorus that supports plant growth and reduces the need for synthetic fertilizers (FAO, 2023; Ahmed et al., 2021). However, long-term accumulation of phosphorus in soils may contribute to nutrient imbalances and environmental degradation if wastewater irrigation is not properly managed.

Comparison with Regulatory Standards

Among the elements analyzed in this study, only cadmium and chromium have established international regulatory limits for food safety. The concentrations detected in the vegetable samples were significantly lower than the permissible limits set by WHO/FAO guidelines and the Nigerian Standard for Drinking Water Quality (NSDWQ).

Other nutrients analyzed in the study including sodium, potassium, calcium, magnesium, phosphate, sulphate, chloride, and phosphorus do not have specific regulatory limits for vegetable crops. The absence of established guidelines for these elements highlights the need for expanded regulatory frameworks, particularly in regions where wastewater irrigation is widely practiced.

Overall, the results indicate that the vegetables analyzed in this study do not pose an immediate health risk based on the concentrations of heavy metals detected. However, the presence of trace metals and elevated nutrient levels underscores the importance of regular environmental monitoring to prevent long-term accumulation in soils and crops.

Conclusion

This study assessed the chemical composition and potential contamination of vegetables irrigated with wastewater and freshwater along the Ngadda River irrigation corridor in Maiduguri, Nigeria. The investigation focused on spinach (*Spinacia oleracea*) and okra (*Abelmoschus esculentus*) and analyzed the concentrations of selected chemical constituents including chloride (Cl^-), sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), phosphate (PO_4^{3-}), sulphate (SO_4^{2-}), cadmium (Cd), chromium (Cr), and phosphorus (P).

The results revealed noticeable differences in nutrient and chemical accumulation between vegetables irrigated with wastewater and those irrigated with freshwater. Wastewater irrigation generally increased the concentrations of certain elements such as sodium, magnesium, and phosphate, reflecting the nutrient-rich composition of domestic wastewater. In particular, okra irrigated with wastewater showed substantial increases in magnesium and phosphate concentrations, indicating that wastewater may serve as an additional source of plant nutrients. However, these elevated nutrient levels also suggest the possibility of long-term nutrient imbalance in soils if wastewater irrigation continues without proper management.

The study also found that sodium levels were higher in wastewater-irrigated vegetables compared with freshwater-irrigated crops, which could potentially lead to soil salinity problems and nutrient antagonism in plant uptake processes. For example, the reduction in potassium and calcium levels in wastewater-irrigated okra suggests competitive interactions among nutrients, particularly between sodium and other essential plant elements.

Heavy metals, which are major concerns in wastewater irrigation systems, were detected at very low concentrations in the vegetable samples. Cadmium was detected only in wastewater-irrigated okra at a concentration of 0.001 mg/kg, while chromium was detected at similarly low concentrations in spinach and wastewater-irrigated okra. Importantly, all measured concentrations of these heavy metals were significantly below the permissible limits established by international food safety standards such as those recommended by WHO and FAO. This indicates that the vegetables analyzed in this study do not pose an immediate health risk to consumers based on the heavy metals assessed.

Nevertheless, the presence of trace levels of cadmium and chromium highlights the potential for gradual accumulation of toxic elements in soils and crops under prolonged wastewater irrigation. Over time, such accumulation could increase the risk of contamination within the food chain and may eventually affect human health if monitoring and management measures are not implemented.

Overall, the findings demonstrate that wastewater irrigation along the Ngadda River contributes both beneficial nutrients and potential contaminants to vegetable crops. While the nutrient enrichment may support crop productivity, the associated risks of chemical accumulation and nutrient imbalance underscore the need for careful regulation and monitoring of wastewater use in agriculture. Ensuring safe wastewater reuse practices is therefore essential for protecting environmental quality, food safety, and public health in Maiduguri.

Recommendations

Based on the findings of this study, the following recommendations are proposed to promote safe and sustainable use of wastewater for agricultural irrigation along the Ngadda River and similar environments.

i. Implementation of Wastewater Treatment Measures

Municipal authorities should establish basic wastewater treatment facilities to reduce the concentration of chemical contaminants and pathogens before wastewater is used for irrigation. Even low-cost treatment systems such as stabilization ponds or constructed wetlands can significantly improve water quality and reduce health risks.

ii. Regular Monitoring of Irrigation Water and Vegetables

Environmental and public health agencies should implement routine monitoring programs to assess the chemical and microbial quality of irrigation water, soil, and vegetable crops. Continuous monitoring will help detect early signs of contaminant accumulation and prevent potential health hazards.

iii. Adoption of Safer Irrigation Techniques

Farmers should be encouraged to adopt irrigation methods that minimize direct contact between wastewater and edible plant parts. Techniques such as drip irrigation or furrow irrigation can reduce contamination compared with traditional flood irrigation practices.

iv.Farmer Education and Awareness Programs

Training programs should be organized for urban farmers to raise awareness about the potential risks associated with wastewater irrigation. Such programs should emphasize proper crop handling, hygiene practices, and safe irrigation methods to reduce contamination.

v. Development of Regulatory Frameworks

Government agencies should develop and enforce regulatory guidelines for wastewater reuse in agriculture. These regulations should specify acceptable contaminant limits for irrigation water and agricultural produce, particularly in regions where wastewater irrigation is common.

vi. Soil Quality Management
Long-term wastewater irrigation may lead to the gradual accumulation of salts and nutrients in soils. Regular soil testing and appropriate soil management practices such as crop rotation, organic amendments, and controlled irrigation schedules should be adopted to maintain soil health.

Further Research

Additional studies should be conducted to investigate microbial contamination, long-term heavy metal accumulation, and the potential health risks associated with consuming wastewater-irrigated vegetables in Maiduguri. Research should also explore effective low-cost treatment technologies suitable for local conditions.

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