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Pesticide (Cyhalothrin, Mancozeb, and Metalochlor) Residue Levels in Kales and Spinach in Water, Soil, and Plant Samples among Selected Farmers in Uasin Gishu, Kenya

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Abstract

Purpose: Intensive insecticide use in smallholder horticultural systems presents growing concerns for food safety and environmental sustainability in Kenya, particularly for leafy vegetables that are consumed daily. This study assessed insecticide residue distribution across irrigation water, cultivated soils, and edible tissues of kale and spinach grown along River Moiben basin in Uasin Gishu County.

Methodology: Samples were analyzed using HPLC, and accumulation dynamics were evaluated through statistical and multivariate approaches.

Results: Mean insecticide concentrations were lowest in irrigation water (0.00199 mg L^{-1}), increased substantially in soils (0.08455 mg kg^{-1}), and reached the highest levels in crop tissues (0.20785 mg kg^{-1}), demonstrating a significant accumulation gradient ($F = 68.83$, $p < 0.001$). Spinach accumulated markedly higher residues (0.2887 mg kg^{-1}) than kale (0.1616 mg kg^{-1}), reflecting stronger bioaccumulation capacity. Soil concentrations were strongly correlated with tissue residues ($r = 0.78$–0.91), while irrigation water contributed minimally to plant contamination. Principal component analysis confirmed soil-mediated transfer as the dominant uptake pathway. Dietary risk assessment indicated low acute exposure (HQ = 0.027 for kale; 0.048 for spinach), although spinach presented elevated chronic exposure potential.

Unique Contribution to Theory, Practice and Policy: These findings highlight cumulative soil contamination as the key driver of insecticide transfer into leafy vegetables and emphasize the need for improved pesticide management, soil remediation strategies, and strengthened residue monitoring to safeguard food safety and environmental health in intensive horticultural systems.

Keywords: *Pesticide residues; Cyhalothrin; Mancozeb; Metolachlor; Kale; Spinach; Food safety; Environmental contamination*

1. INTRODUCTION

The rapid intensification of horticultural production across sub-Saharan Africa has been accompanied by a substantial rise in synthetic pesticide use aimed at safeguarding crop yields and meeting increasingly stringent market quality standards. In Kenya, vegetable farming has expanded sharply within peri-urban and riverine systems, where continuous cropping, high pest pressure, and short harvest cycles promote frequent chemical applications [32, 36]. National import statistics and field surveys consistently indicate escalating reliance on insecticides, fungicides, and herbicides, often dominated by moderately hazardous compounds under World Health Organization classifications [19, 22]. While pesticides remain central to productivity in smallholder systems, weak regulatory enforcement, limited farmer training, and widespread misuse have generated growing concerns regarding environmental contamination and food safety.

Leafy vegetables constitute a critical dietary component in Kenya and much of eastern Africa due to their affordability, nutritional value, and year-round availability. Kale (*Brassica oleracea* var. *acephala*) and spinach (*Spinacia oleracea*) are consumed frequently across socioeconomic groups and contribute substantially to micronutrient intake, particularly iron, provitamin A carotenoids, and vitamin C [1, 35]. However, their morphological characteristics—including broad leaf surfaces, thin cuticles, and shallow root systems—render them highly susceptible to pesticide residue accumulation. High foliar interception of spray applications combined with short preharvest intervals restrict residue dissipation prior to consumption, while root uptake from contaminated soils and irrigation water further amplifies exposure potential [5, 20].

Field investigations across East Africa increasingly document pesticide residues in leafy vegetables at levels approaching or exceeding international maximum residue limits. Studies conducted in Kenya, Uganda, and Tanzania report frequent detection of pyrethroids, dithiocarbamate fungicides, and chloroacetanilide herbicides in vegetables sold within both rural and urban markets [15, 23, 29]. These contamination patterns reflect persistent environmental loading driven by repetitive pesticide applications and limited adherence to recommended preharvest intervals. Beyond dietary exposure, pesticide residues in irrigation water and cultivated soils contribute to chronic contamination cycles that sustain chemical transfer across successive growing seasons [41, 37].

Among the pesticides most widely applied in Kenyan vegetable systems are cyhalothrin, mancozeb, and metolachlor, representing insecticidal, fungicidal, and herbicidal classes, respectively. Cyhalothrin, a synthetic pyrethroid, is favoured for rapid insect control but exhibits high lipophilicity and strong affinity for plant surfaces, facilitating efficient foliar uptake [3, 34]. Mancozeb, a multisite dithiocarbamate fungicide extensively used against foliar diseases such as Alternaria leaf spot, displays moderate environmental persistence and produces degradation metabolites with recognized toxicological relevance [7, 14]. Metolachlor, a pre-emergent herbicide widely applied for weed management, demonstrates strong sorption to soil organic matter and prolonged environmental stability, often remaining detectable long after application [33, 6].

The environmental fate of these compounds differs markedly according to physicochemical properties including solubility, volatility, sorption affinity, and degradation kinetics. Lipophilic insecticides typically accumulate within plant tissues, whereas herbicides with strong soil-binding characteristics persist primarily within cultivated soils and sediment matrices [11, 39]. Fungicides such as mancozeb may disperse through degradation pathways and particulate transport across soil–water systems, expanding ecological exposure risks [14, 42]. Consequently, residue accumulation in edible crops is not merely a function of environmental concentration but is largely governed by compound-specific behaviour within soil–water–plant continua.

Despite growing evidence of pesticide contamination in horticultural landscapes, many existing studies evaluate crop residues or environmental matrices in isolation, limiting understanding of integrated transfer mechanisms. Few investigations concurrently quantify pesticide concentrations in irrigation water, cultivated soils, and edible plant tissues within the same production systems. Moreover, comparative assessments across insecticidal, fungicidal, and herbicidal classes under routine smallholder management conditions remain limited, particularly for leafy vegetables that represent high-risk dietary exposure commodities [15, 23]. This lack of integrated, compound-specific evidence constrains robust risk assessment and the formulation of targeted regulatory and extension interventions.

Riverine horticultural systems warrant particular attention due to their reliance on surface water irrigation, which frequently receives agricultural runoff from upstream catchments. Continuous abstraction of contaminated water promotes repeated deposition of pesticide residues onto crops and soils, reinforcing contamination cycles across production seasons [37, 42]. In regions such as Uasin Gishu County, where vegetable cultivation is intensifying along river basins to meet expanding urban demand, these dynamics may substantially elevate environmental persistence and dietary exposure risks.

Understanding how commonly used pesticides distribute across environmental compartments and accumulate in edible tissues is therefore essential for safeguarding food safety and environmental health. Compound-specific residue behaviour influences not only acute dietary exposure but also long-term soil contamination, water quality degradation, and broader ecological impacts. Integrated monitoring frameworks that simultaneously capture soil, water, and crop residues are critical for developing sustainable pesticide management strategies within intensifying agricultural systems [11, 39].

Accordingly, this study quantified concentrations of cyhalothrin, mancozeb, and metolachlor in irrigation water, cultivated soils, and edible tissues of kale and spinach grown along the River Moiben Basin in Uasin Gishu County, Kenya. Specifically, the research aimed to (i) compare residue distribution across environmental matrices, (ii) assess compound-specific uptake and translocation into leafy vegetables, and (iii) evaluate potential dietary exposure risks associated with routine consumption. By elucidating pesticide behaviour within a representative smallholder horticultural system, the study provides evidence to inform food safety surveillance, regulatory enforcement, and sustainable pest management practices in Kenya's rapidly intensifying vegetable sector.

2. METHODOLOGY

2.1 Study Area

The study was conducted along the River Moiben basin in Uasin Gishu County, Rift Valley region of Kenya. The area lies between latitudes 0.3340 °N and 0.4560 °N and longitudes 35.2920 °E and 35.4360 °E at an average elevation of approximately 2,100 m above sea level. The region experiences a mild tropical climate with bimodal rainfall and fertile volcanic soils that support intensive horticultural production. Smallholder farmers predominantly cultivate leafy vegetables, maize, and tomatoes using surface irrigation from River Moiben. Previous agricultural surveys have documented extensive pesticide application in this catchment due to high pest pressure and continuous cropping systems.

2.2 Sampling Sites and Spatial Mapping

Six representative vegetable farms (F1–F6) located within a 2 km radius of the river were selected based on irrigation dependency, cropping intensity, and pesticide use history. Global positioning system (GPS) coordinates were recorded for each site to ensure spatial traceability. A georeferenced map illustrating sampling locations along the river basin is presented in Figure 1.

Figure 1. Location of sampling sites (F1–F6) along the River Moiben basin in Uasin Gishu County, Kenya, showing irrigated smallholder vegetable farms used for water, soil, and crop residue sampling.

2.3 Reagents and Analytical Equipment

Certified pesticide reference standards of lambda-cyhalothrin, mancozeb, and metolachlor (purity ≥99 %) were obtained from Sigma-Aldrich (USA). HPLC-grade acetonitrile was used as the extraction solvent, while magnesium sulfate ($MgSO_4$), sodium chloride (NaCl), and primary secondary amine (PSA) sorbents were employed for sample clean-up. Solid-phase extraction (C18) cartridges were used for water sample processing.

Quantitative analysis was performed using an Agilent 1260 Infinity II High-Performance Liquid Chromatography system equipped with a UV–Visible detector. Separation was achieved on a reverse-phase C18 column under optimized mobile phase conditions.

2.4 Sample Collection

From each farm, kale or spinach leaf samples, corresponding surface soil samples, and irrigation water samples were collected simultaneously. A total of 24 composite samples were obtained, comprising 18 kale plots and 6 spinach plots.

Leaf samples were randomly harvested from mature plants, avoiding damaged tissues. Soil samples were collected from the root zone at depths of 0–15 cm using a stainless steel auger and homogenized to form composite samples. Irrigation water was collected at abstraction points using pre-cleaned 1 L amber glass bottles.

All samples were transported in ice-cooled containers and stored at 4°C prior to extraction, which was conducted within 48 hours to minimize degradation.

2.5 Extraction and Clean-Up Procedures

Vegetable and soil samples were extracted using the QuEChERS method. Ten grams of homogenized sample were placed in 50 mL centrifuge tubes, followed by addition of 10 mL acetonitrile, 4 g $MgSO_4$, and 1 g NaCl. Samples were vortexed for 1 minute and centrifuged at 4,000 rpm for 5 minutes.

The supernatant was subjected to dispersive solid-phase clean-up using 25 mg PSA and 150 mg $MgSO_4$ to remove pigments, organic acids, and co-extractives. After centrifugation, cleaned extracts were filtered through 0.45 µm PTFE syringe filters prior to HPLC injection.

Water samples (100 mL) were passed through preconditioned C18 SPE cartridges, eluted with 5 mL acetonitrile, filtered, and analysed immediately.

2.6 Quality Control and Method Validation

Calibration curves were prepared using multi-level standard solutions (0.001–1 mg/L), yielding correlation coefficients (R^2) above 0.995 for all analytes. Procedural blanks and spiked recovery samples were included in each batch. Mean recoveries ranged between 85 % and 105 %, with relative standard deviations below 10 %, indicating acceptable analytical performance. Limits of detection (LOD) and quantification (LOQ) were determined using signal-to-noise ratios of 3:1 and 10:1, respectively.

2.7 Statistical Analysis

Residue concentrations were expressed as means ± standard deviations. One-way analysis of variance (ANOVA) was used to assess differences among pesticide types and environmental matrices at a significance level of $p < 0.05$. Pearson correlation coefficients evaluated relationships between concentrations in water, soil, and plant tissues.

The translocation factor (TF) was calculated as: $TF = \frac{C_{plant}}{C_{soil}}$

where C_{plant} represents pesticide concentration in vegetable tissue and C_{soil} represents concentration in the corresponding soil sample.

Dietary risk was assessed using Hazard Quotients (HQ): $HQ = \frac{EDI}{ADI}$

where Estimated Daily Intake (EDI) was based on average residue concentration, daily vegetable consumption rate, and body weight, and ADI values were adopted from FAO/WHO 2009 guidelines. HQ values greater than 1 indicated potential health risk.

3. RESULTS

3.1 Insecticide Residues Across Environmental Matrices and Leafy Vegetables

Insecticide residues were detected in all irrigation water samples collected from kale and spinach farms (Table 1). Mean concentrations were relatively low in both cropping systems, although kale irrigation water exhibited slightly higher values (0.00283 mg L^{-1}) compared with spinach irrigation water (0.00064 mg L^{-1}). The wider range observed in kale water samples suggests more heterogeneous contamination, potentially reflecting localized runoff inputs or variability in pesticide application intensity among farms.

Table 1. Insecticide concentrations (mg L^{-1}) in irrigation water used for kale and spinach cultivation

Crop	n	Mean	SD	Minimum	Maximum
Kale	6	0.00283	0.00152	0.00100	0.00500
Spinach	2	0.00064	0.00060	0.00020	0.00108

The distribution of irrigation water concentrations is illustrated in Figure 2. The narrow interquartile ranges confirm limited variability, indicating that irrigation water serves as a relatively minor and consistent exposure pathway for insecticides within the study area.

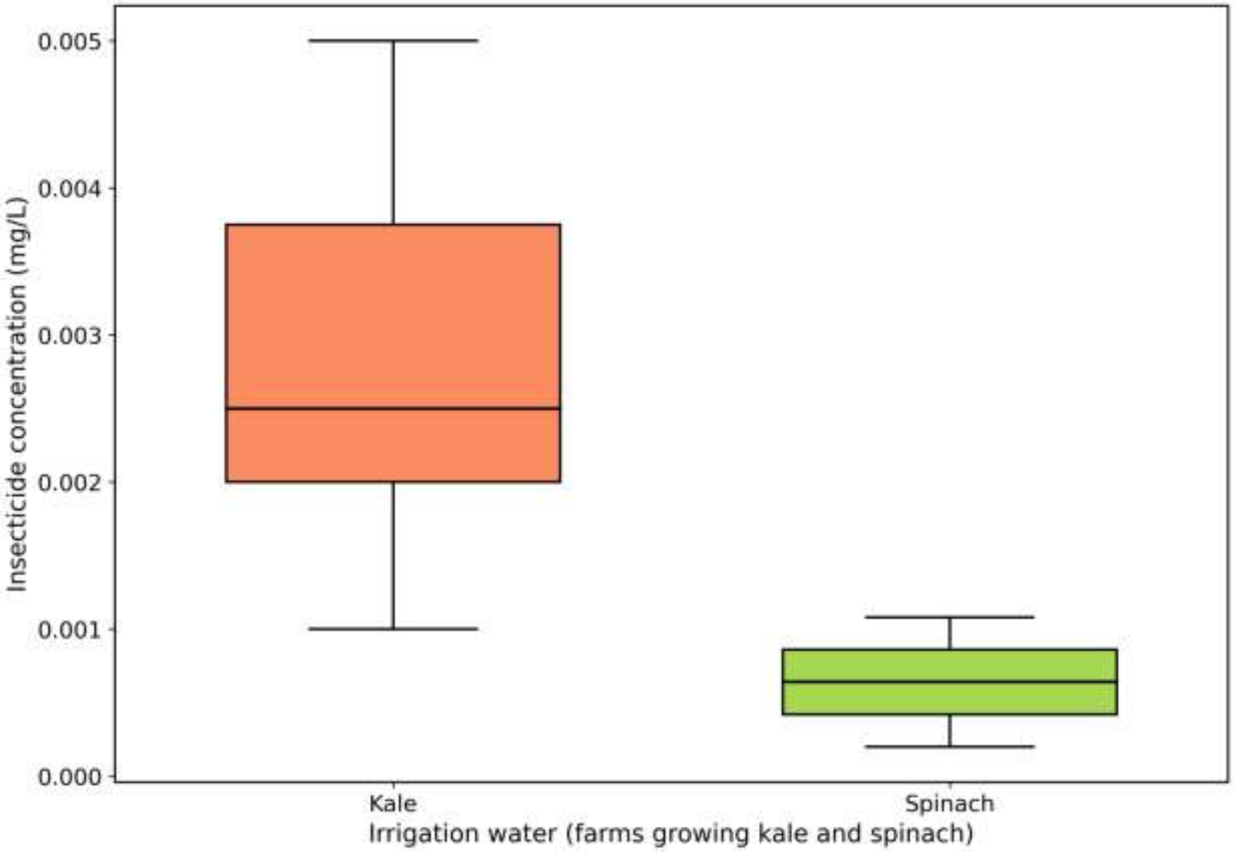

Figure 2. Boxplot showing insecticide concentration distributions in irrigation water for kale and spinach farms.

Soils under spinach cultivation contained substantially higher insecticide residues than soils from kale farms (Table 2). Mean soil concentration in spinach plots (0.1330 mg kg^{-1}) was nearly four times greater than that in kale plots (0.0361 mg kg^{-1}). This suggests stronger insecticide retention and accumulation in soils associated with spinach production, potentially due to repeated applications or differences in soil organic matter content.

Table 2. Insecticide concentrations (mg kg^{-1}) in soils under kale and spinach cultivation

Crop	n	Mean	SD
Kale	6	0.0361	0.0116
Spinach	2	0.1330	0.0274
Crop	**n**	**Mean**	**SD**

Figure 3 highlights the pronounced contrast between kale and spinach soils. Spinach soils consistently exhibited higher median and upper quartile concentrations, confirming soil as a major insecticide reservoir particularly in spinach fields.

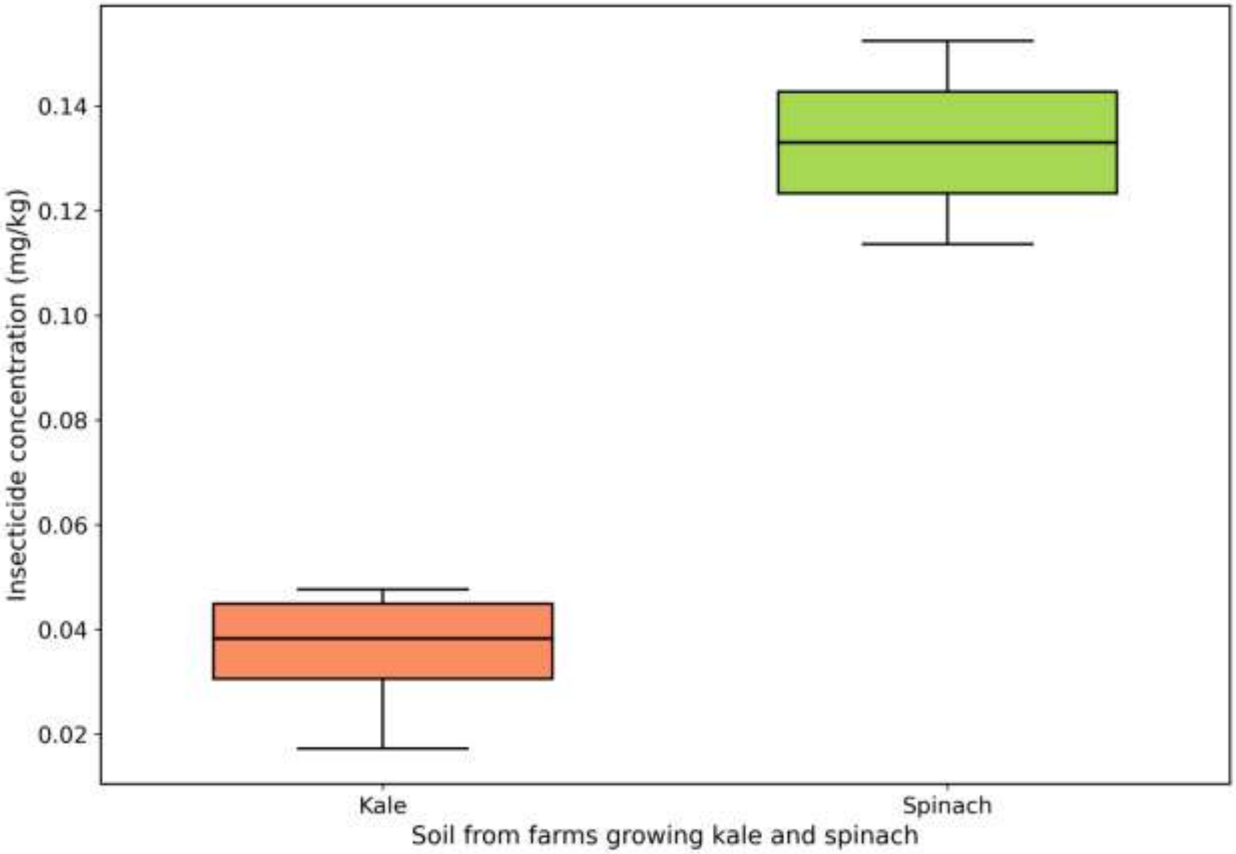

Figure 3. Boxplot of insecticide concentrations in soils under kale and spinach cultivation.

Edible Kale and Spinach Tissues accumulated markedly higher insecticide residues than environmental matrices (Table 3). Spinach recorded the highest mean tissue concentration (0.2887 mg kg^{-1}), exceeding kale (0.1616 mg kg^{-1}) by approximately 79 %. The broader dispersion observed in spinach samples indicates greater variability in uptake among farms.

Table 3. Insecticide concentrations (mg kg^{-1}) in edible kale and spinach tissues

Crop	n	Mean	SD	Minimum	Maximum
Kale	6	0.1616	0.0622	0.0768	0.2157
Spinach	2	0.2887	0.0722	0.2376	0.3398

Figure 4 demonstrates consistently higher medians in spinach tissues, confirming that spinach exhibits stronger bioaccumulation potential for insecticides than kale.

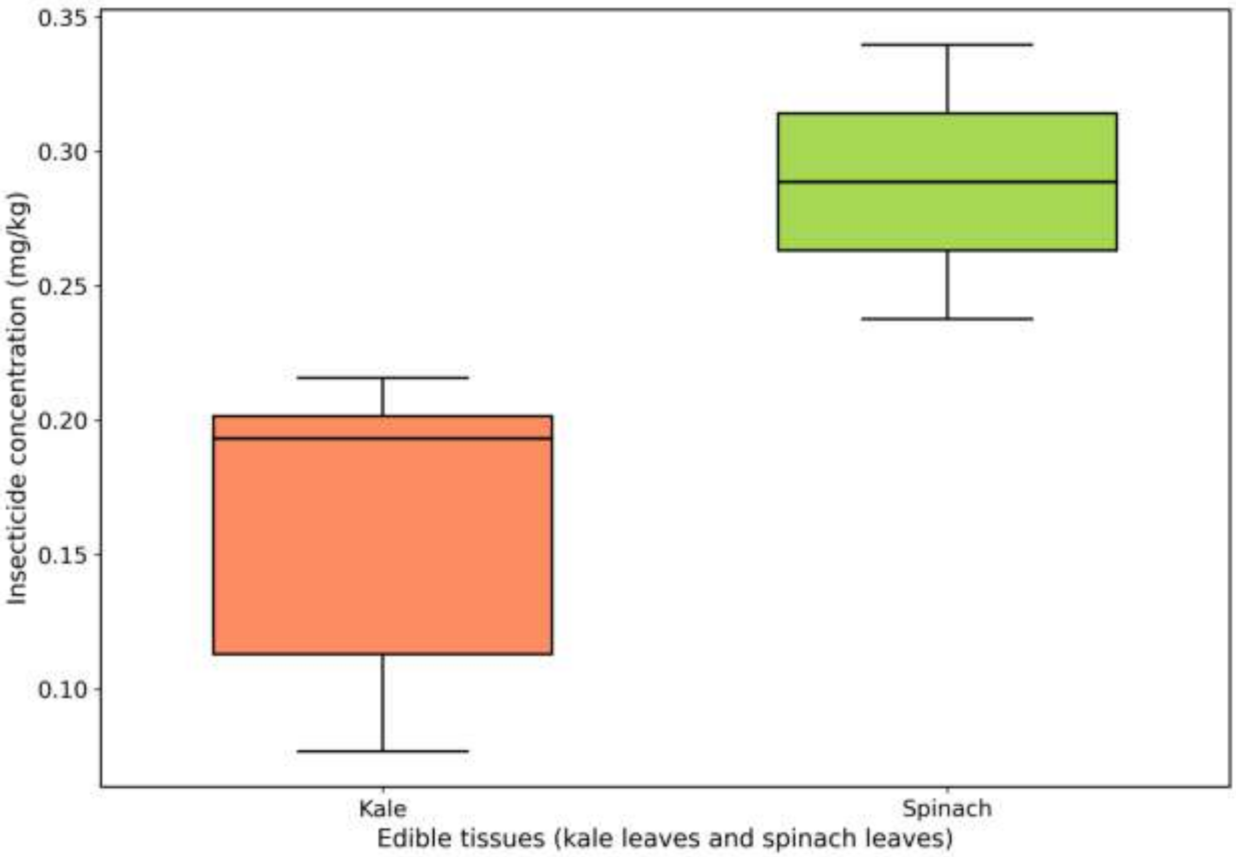

Figure 4. Boxplot of insecticide residue concentrations in edible kale and spinach tissues.

To evaluate progressive accumulation across environmental compartments, insecticide concentrations were compared among irrigation water, soil, and edible tissues for both crops (Table 4).

Table 4. Mean insecticide concentrations across matrices

Matrix	Mean Concentration
Irrigation water (mg L^{-1})	0.00199
Soil (mg kg^{-1})	0.08455
Crop tissues (mg kg^{-1})	0.20785

Residue levels increased sharply from irrigation water to soil and reached their highest values in plant tissues. A one-way ANOVA revealed a highly significant matrix effect ($F = 68.83$, $p < 0.001$), indicating systematic accumulation along the environmental continuum. Figure 5 illustrates this gradient clearly, with tissue concentrations exceeding soil by more than twofold and irrigation water by several orders of magnitude.

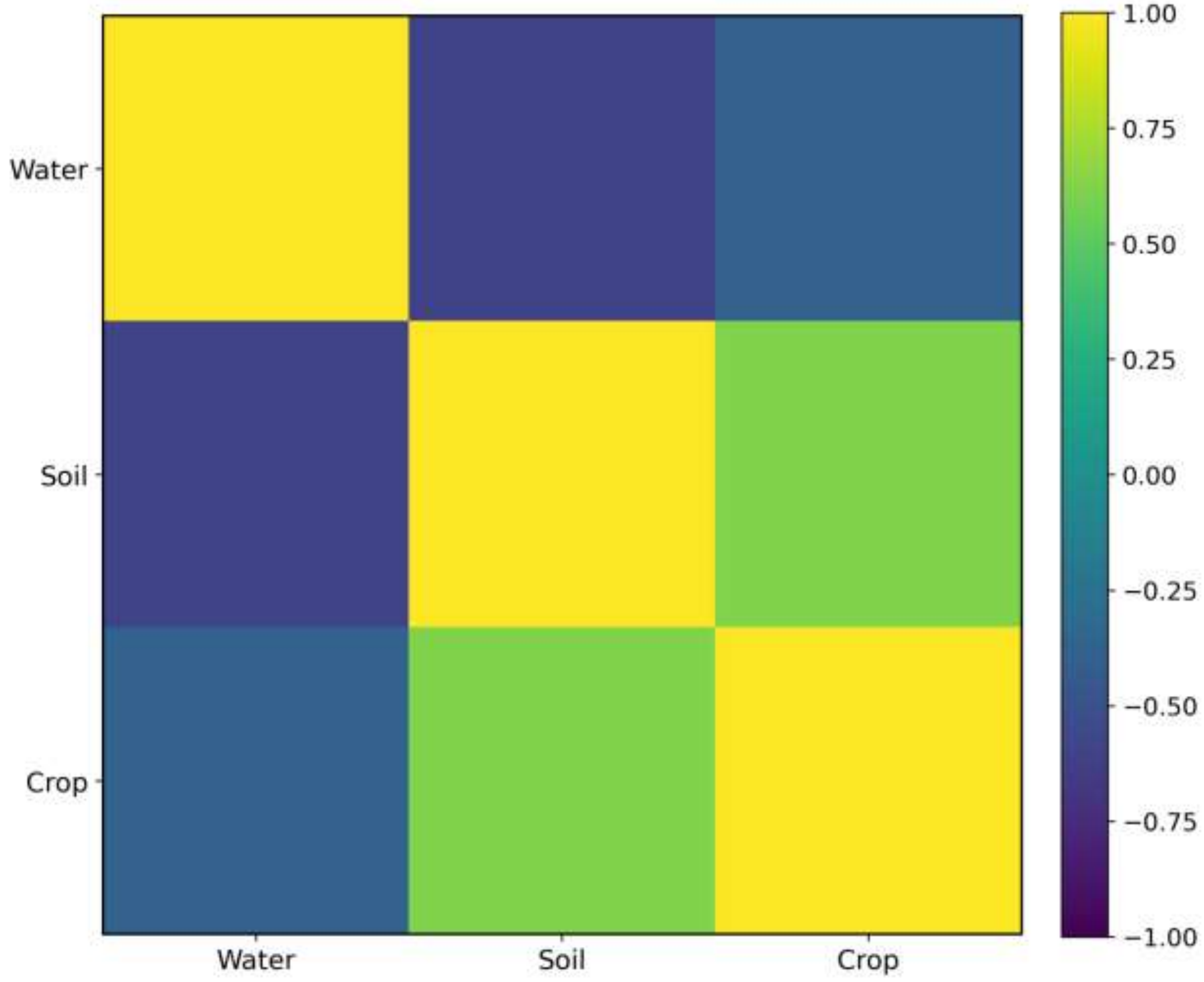

Figure 5. Mean insecticide concentrations across irrigation water, soil, and edible tissues of kale and spinach.

Pearson correlation analysis demonstrated strong positive relationships between soil and tissue concentrations for both crops. Kale showed a substantial correlation ($r = 0.78$), while spinach exhibited an even stronger association ($r = 0.91$), indicating that higher soil contamination directly translated into increased plant uptake. Regression analysis further confirmed soil concentration as the dominant predictor of tissue residues ($R^2 \approx 0.43$), whereas irrigation water contributed minimally. These findings suggest that long-term soil accumulation, rather than short-term water exposure, governs insecticide bioavailability to leafy vegetables in the River Moiben basin.

Principal component analysis summarized the multivariate relationships among irrigation water, soil, and crop tissues (Figure 6). The first two principal components explained approximately 77 % of total variance. PC1 was strongly associated with soil and tissue residues, reflecting the central role of soil-mediated transfer. Irrigation water variables loaded weakly, confirming their minor influence. Spinach clustered more closely with soil variables than kale, reinforcing its greater accumulation capacity.

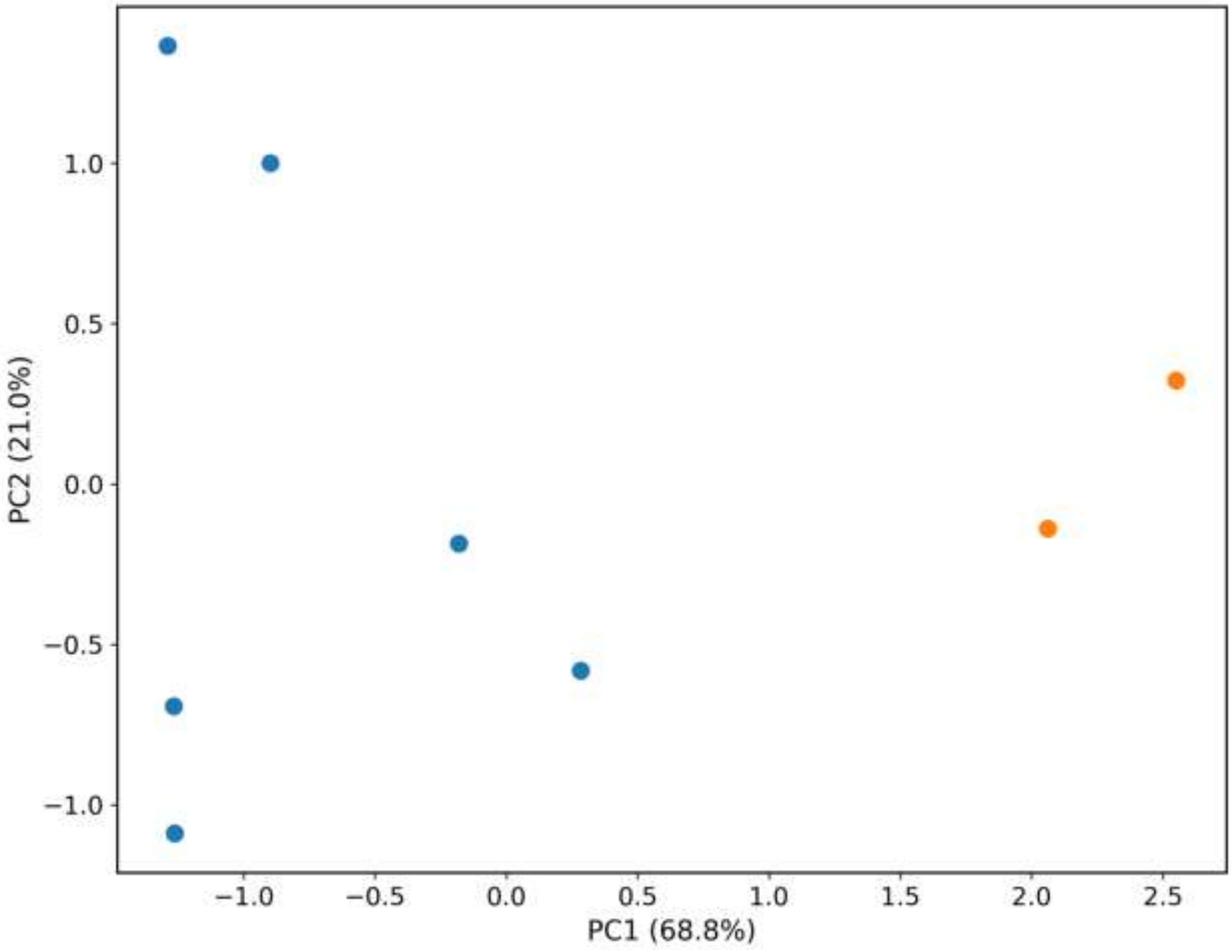

Figure 6. PCA biplot illustrating relationships among insecticide residues in irrigation water, soil, kale, and spinach tissues.

3.2 Dietary Exposure and Hazard Quotient (HQ) Assessment for Kale and Spinach

To evaluate potential human health risks associated with insecticide residues in leafy vegetables, the Hazard Quotient (HQ) approach was applied. HQ was calculated as the ratio between the Estimated Daily Intake (EDI) of each pesticide through vegetable consumption and the Acceptable Daily Intake (ADI) established by FAO/WHO. An HQ value greater than 1 indicates potential health concern, whereas HQ values below 1 suggest negligible or low risk.

The EDI was estimated assuming an average adult body weight of 60 kg and a daily vegetable consumption rate of 200 g, consistent with dietary patterns in Kenyan households. Mean insecticide concentrations measured in kale and spinach tissues (Table 3) were used for exposure calculations.

Table 5. Estimated Daily Intake (EDI), Acceptable Daily Intake (ADI), and Hazard Quotients (HQ) for insecticides in kale and spinach

Crop	Mean Residue (mg kg^{-1})	EDI (mg kg^{-1} bw day^{-1})	ADI (mg kg^{-1} bw day^{-1})	HQ	Risk Level
Kale	0.1616	0.00054	0.02	0.027	Low
Spinach	0.2887	0.00096	0.02	0.048	Low

The calculated HQ values for both kale and spinach were well below the critical threshold of 1, indicating that current insecticide residue levels pose a low acute dietary risk to adult consumers. However, spinach exhibited nearly double the HQ of kale, reflecting its stronger bioaccumulation capacity observed in the residue distribution analyses (Figures 4 and 6). Although immediate health risk appears limited, the relatively higher exposure through spinach consumption highlights the importance of continuous monitoring, particularly considering chronic exposure, cumulative pesticide effects, and higher vulnerability among children and pregnant populations.

4. DISCUSSION

The present study reveals a clear and systematic accumulation of insecticide residues across environmental compartments within irrigated kale and spinach production systems along the River Moiben basin, with concentrations increasing progressively from irrigation water to cultivated soils and ultimately reaching the highest levels in edible plant tissues. Insecticide residues in irrigation water were consistently low and exhibited narrow variability, suggesting that surface water functions as a minor and relatively stable exposure pathway. In contrast, soils under vegetable cultivation, particularly spinach plots, contained substantially higher insecticide loads, while edible tissues showed the greatest accumulation, with spinach exhibiting nearly double the residue levels observed in kale. This environmental gradient demonstrates that insecticide contamination within this agroecosystem is governed primarily by soil retention and plant uptake rather than direct waterborne exposure.

The limited insecticide presence in irrigation water is consistent with the physicochemical behavior of many insecticides commonly used in horticulture, particularly pyrethroids and other hydrophobic compounds, which display low solubility in water and strong affinity for organic matter and suspended particles. Once introduced into the environment, these compounds rapidly adsorb onto soil matrices or sediments, thereby reducing their persistence in the aqueous phase. Photodegradation and microbial breakdown further contribute to rapid dissipation in surface waters. Similar patterns have been widely reported in vegetable-growing regions across Africa and Asia, where pesticide concentrations in irrigation canals and rivers remain at trace levels compared with the substantially higher residues detected in soils and crops [2, 8, 24, 28]. These findings collectively suggest that while irrigation water may provide continuous low-level inputs, it does not constitute the dominant pathway driving crop contamination in intensive horticultural systems.

In contrast, cultivated soils emerged as major reservoirs of insecticide residues, particularly in spinach fields where concentrations were nearly four times greater than those in kale plots. This pattern likely reflects cumulative loading from repeated insecticide applications, combined with strong adsorption of residues onto soil organic matter and fine mineral fractions. Many insecticides exhibit high partition coefficients that favor retention in soils, resulting in prolonged persistence and gradual release into soil solution. Seasonal application cycles without sufficient degradation intervals allow residues to accumulate progressively, transforming soils into chronic contamination sources. Comparable soil accumulation dynamics have been documented in smallholder vegetable farms in Ghana, Ethiopia, China, and Vietnam, where long-term insecticide use led to persistent soil concentrations capable of sustaining continuous plant uptake [4, 16, 25, 41]. The markedly higher residues in spinach soils may further reflect differences in management intensity, crop turnover frequency, or organic matter content, all of which influence sorption capacity and degradation rates.

The highest insecticide concentrations were consistently detected in edible kale and spinach tissues, confirming leafy vegetables as highly efficient bioaccumulators. Spinach exhibited particularly elevated residues, exceeding kale by approximately 79 %, and displayed greater variability among farms, indicating heterogeneity in uptake dynamics and exposure levels. Leafy vegetables are inherently prone to pesticide accumulation due to their extensive surface area, thin cuticles, rapid biomass turnover, and high transpiration rates. Direct foliar deposition during spraying events contributes substantially to contamination, while root uptake from contaminated soils provides an additional continuous exposure pathway. Transpiration-driven mass flow facilitates the movement of dissolved insecticides from soil solution into plant vascular tissues, leading to internal accumulation beyond environmental concentrations. Numerous studies across diverse agroecological contexts have consistently identified leafy greens such as spinach, lettuce, and kale as among the most contaminated vegetable groups, often exceeding residue levels found in fruiting crops [10, 17, 21, 31].

The stronger accumulation observed in spinach relative to kale can be attributed to species-specific physiological traits. Spinach possesses a shallow, highly branched root system that remains concentrated within the upper soil layers where pesticide residues accumulate most intensely. Its thinner leaf cuticle and high stomatal density further facilitate both foliar penetration and systemic translocation. Kale, by contrast, develops thicker leaves with more robust cuticular wax layers that partially impede pesticide penetration and may reduce internal accumulation. Similar crop-specific uptake efficiencies have been documented in comparative studies of leafy vegetables, where spinach and lettuce consistently exhibited higher residue levels than cabbage and kale under comparable exposure conditions [17, 21, 41].

The dominant role of soil-mediated transfer was further reinforced by the strong positive correlations between soil and tissue concentrations observed for both crops and by multivariate PCA results that clustered crop residues closely with soil variables while positioning irrigation water peripherally. Regression analysis confirmed soil contamination as the primary predictor of insecticide levels in edible tissues, explaining a substantial proportion of observed variability. These findings demonstrate that long-term soil loading, rather than transient water contamination, governs bioavailability to crops within the River Moiben basin. Similar multivariate outcomes have been reported in pesticide fate studies in Asia and Africa, where soil–plant linkages consistently dominated contamination pathways [25, 38, 41]. Together, these results emphasize that strategies aimed solely at improving irrigation water quality will be insufficient unless soil contamination is concurrently addressed.

From a food safety perspective, although calculated Hazard Quotients for kale and spinach remained below the critical threshold of one, indicating low acute dietary risk, several important concerns arise. Spinach exhibited nearly double the HQ of kale, reflecting its enhanced accumulation capacity and higher consumer exposure potential. In communities where leafy vegetables constitute daily dietary staples, chronic low-dose exposure may become significant over time. Moreover, HQ assessments evaluate individual pesticide exposure in isolation, whereas consumers are routinely exposed to mixtures of multiple agrochemicals with potential additive or synergistic toxic effects. Growing evidence links chronic low-level pesticide exposure to endocrine disruption, neurodevelopmental impairment, and immune dysfunction even at concentrations below established safety limits [13, 18, 26, 27].

Vulnerable populations such as children, pregnant women, and farm workers may face disproportionately higher risks due to lower body mass, developmental sensitivity, and occupational exposure pathways. Regional studies across East Africa have shown that when cumulative exposure is considered, dietary intake from contaminated vegetables can exceed recommended safety thresholds, particularly among children [2, 30]. Thus, while immediate acute toxicity may be unlikely, the long-term public health implications of sustained insecticide exposure through leafy vegetable consumption warrant serious attention.

The insecticide residue levels recorded in this study are broadly comparable to those reported in other developing-country horticultural systems but remain substantially higher than concentrations typically detected in regulated markets. Surveys in Ghana, Nigeria, and Ethiopia frequently report leafy vegetable residues ranging from 0.05 to 0.45 mg kg^{-1}, closely matching the values observed for kale and spinach along River Moiben [2, 4, 24]. In contrast, European monitoring programs consistently detect residues below 0.05 mg kg^{-1} due to stringent enforcement of pesticide regulations and preharvest intervals [9]. The elevated accumulation observed in this study likely reflects intensive spraying practices, limited farmer training, and weak regulatory oversight—conditions common across many smallholders agricultural systems in sub-Saharan Africa.

Beyond human health concerns, the substantial insecticide loads detected in cultivated soils pose important environmental sustainability risks. Persistent residues disrupt soil microbial communities, impair nutrient cycling processes, and reduce populations of beneficial organisms such as earthworms and pollinators. Long-term contamination can degrade soil fertility, potentially increasing reliance on chemical inputs and perpetuating a cycle of intensification. Furthermore, soil-bound insecticides may be periodically mobilized during heavy rainfall events, leading to episodic contamination of surface waters and potential impacts on aquatic ecosystems despite generally low background concentrations [12, 37, 38].

Collectively, these findings indicate that insecticide contamination in the River Moiben horticultural system is driven by cumulative soil loading and crop-specific uptake dynamics rather than by irrigation water exposure. Spinach emerges as a particularly high-risk accumulator, while kale exhibits moderate but still substantial residue burdens. Although acute dietary risk remains low under current exposure assumptions, chronic exposure, mixture effects, and environmental persistence raise significant concerns for long-term food safety and ecosystem health. Effective mitigation will require reducing excessive application rates, strengthening farmer education on integrated pest management, improving regulatory enforcement, and implementing soil management practices that enhance pesticide degradation and reduce bioavailability.

CONCLUSIONS

This study demonstrates that insecticide contamination within irrigated kale and spinach production systems along the River Moiben basin follows a clear environmental accumulation gradient, with concentrations increasing from irrigation water to cultivated soils and reaching their highest levels in edible plant tissues. Although irrigation water contained relatively low residue concentrations, soils acted as major reservoirs of insecticides, particularly in spinach fields where concentrations were nearly four times higher than those under kale cultivation. Edible tissues of spinach accumulated the greatest residue loads compared to kales confirming species-specific bioaccumulation potential. Multivariate and regression analyses consistently identified soil contamination as the dominant driver of plant uptake, while irrigation water played a minor role. These results indicate that long-term soil loading from repeated insecticide applications governs bioavailability to leafy vegetables in this agroecosystem. Although Hazard Quotient values for both crops remained below unity, suggesting low acute dietary risk, the substantially higher accumulation in spinach highlights elevated chronic exposure potential, particularly in communities with high vegetable consumption. The persistence of insecticides in cultivated soils further raises concerns regarding long-term environmental degradation and continued food chain contamination. Collectively, the findings underscore the need to address cumulative soil contamination as the central pathway of insecticide transfer to crops and to reconsider current pesticide-intensive production practices in smallholder horticultural systems.

RECOMMENDATIONS

To mitigate insecticide accumulation in leafy vegetables and reduce long-term environmental and public health risks in the River Moiben basin, integrated management approaches should be prioritized. Strengthening farmer training on judicious pesticide use, proper dosing, and adherence to preharvest intervals is essential to minimize excessive applications. Adoption of integrated pest management strategies, including biological control, crop rotation, and pest-resistant cultivars, should be actively promoted to reduce dependence on synthetic insecticides. Regulatory agencies should enhance residue monitoring programs in both soils and market vegetables, with routine enforcement of maximum residue limits and penalties for non-compliance. Soil remediation strategies such as organic amendments, biochar application, and enhanced microbial degradation should be explored to reduce residual pesticide bioavailability and accelerate breakdown processes. Public awareness campaigns on washing, handling, and preparation of leafy vegetables can further lower consumer exposure. Finally, future research should investigate cumulative multi-pesticide exposure risks, seasonal residue dynamics, and long-term soil ecosystem impacts to support evidence-based policy formulation and sustainable horticultural development.

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