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Surveying pesticide residue levels of spinach in the Volta basin

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Abstract

Spinach grown in the Volta Basin carries pesticide loads that most consumers would find alarming if they knew the numbers. This research quantified organophosphate and pyrethroid residues in spinach (*Spinacia oleracea*) from fourteen collection points across the basin during four seasonal windows in 2022-2023. A total of 168 composite samples were extracted using the QuEChERS method and screened by gas chromatography-mass spectrometry at the Trujillo Research Institute of Applied Horticulture. Residue levels rose with distance downstream, and the wet season (June-September) produced concentrations 2.4-fold higher than the dry season mean. Combining ability trials on local germplasm showed that certain half-sib families accumulated 31 percent less residue than the population mean under identical spray regimes. Germination vigour declined as residue burden increased, hinting at phytotoxic feedback. Grafting spinach onto a tolerant rootstock reduced residue translocation to leaves by 18 percent in a controlled greenhouse trial. Economic viability modelling indicated that adopting reduced-spray integrated protocols would lower input costs by 22 percent while keeping yields within 5 percent of conventional practice. Lignin content in stem tissue correlated positively with residue retention, suggesting a structural basis for differential accumulation among genotypes. These results support a shift toward low-residue spinach production in the Volta Basin through combined genetic and agronomic strategies.

Keywords: Combining ability, germination, grafting, economic viability, lignin, pesticide residues, spinach, Volta Basin, QuEChERS, organophosphate

Introduction

Pesticide misuse in tropical vegetable systems is not a distant possibility—it is an everyday reality that puts millions of consumers at risk. In the Volta Basin, where smallholder farmers supply most of the fresh spinach consumed in urban markets across Ghana, Burkina Faso, and Togo, spray calendars are driven more by pest pressure than by label instructions ^[1]. The result is produce that frequently carries residue levels above the Codex Alimentarius maximum residue limits (MRLs), yet few systematic surveys have mapped how those levels change with location, season, and farming practice ^[2].

Organophosphates and synthetic pyrethroids dominate the insecticide market in the basin because they are cheap, widely available, and effective against the leaf-eating caterpillars and aphids that plague spinach ^[3]. But both classes pose acute and chronic health risks: organophosphates inhibit acetylcholinesterase, while certain pyrethroids are suspected endocrine disruptors ^[4]. Understanding the spatial and temporal pattern of residues is the first step toward designing interventions that protect both growers and consumers.

Genetic approaches offer a complementary path. Combining ability analysis can identify parental lines whose progeny accumulate less residue, and grafting onto tolerant rootstocks has reduced cadmium and pesticide translocation in other solanaceous crops ^[5]. Lignin, the structural polymer that stiffens cell walls, may physically trap hydrophobic pesticide molecules in stem tissue, limiting their movement to edible leaves ^[6]. If lignin content predicts residue retention, breeders could select for high-stem-lignin genotypes that keep more residue out of the harvested product.

This research had four objectives: to survey organophosphate and pyrethroid residue levels across the Volta Basin over a full year; to test whether combining ability among local spinach lines predicts residue accumulation; to evaluate grafting as a residue-reduction tool; and to assess the economic viability of reduced-spray protocols. The work was carried out at

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the Trujillo Research Institute of Applied Horticulture, Peru, using samples shipped under cold-chain conditions from the Volta Basin collection network [7].

Material and Methods

Research Area Description

The Volta Basin covers about 400,000 km² across six West African countries. Fourteen collection points were positioned along the Black Volta, White Volta, and lower main-stem Volta, spanning latitudes 6.1° N to 11.4° N and covering a rainfall gradient from 800 mm in the north to 1,300 mm in the south. Sites included peri-urban market gardens near Tamale, Bolgatanga, and Kete-Krachi, as well as remote riverside plots with minimal agrochemical inputs. Soils ranged from ferric Luvisols in the north to Gleysols along the lower floodplain, with pH 5.4-6.8 and organic carbon 0.38-1.12 percent.

Field Experimental Design

At each of the fourteen points, three replicate beds (4 m x 2 m) of the local broad-leaf spinach variety were sampled at marketable stage during four seasonal windows: dry (November-February), pre-wet (March-May), wet (June-September), and post-wet (October). Five whole plants per bed were composited into a single sample, giving 168 composites over the year. The grafting trial was conducted in a controlled greenhouse at the Trujillo Research Institute with four rootstock-scion combinations replicated five times in a completely randomised design.

Material

Pesticide reference standards (chlorpyrifos, profenofos, dimethoate, cypermethrin, lambda-cyhalothrin, and deltamethrin) were obtained from Dr. Ehrenstorfer GmbH (Augsburg, Germany) at certified purity above 98 percent. QuEChERS extraction kits (EN 15662 formulation) and dispersive SPE tubes with PSA/C18 were purchased from Agilent Technologies. Acetonitrile was HPLC-grade (Merck). Internal standard triphenyl phosphate was used for quality control. Lignin was quantified by the acid-detergent method with cetyltrimethylammonium bromide.

Methods

Samples were homogenised in a Waring blender, and 10 g aliquots were extracted following the QuEChERS protocol with acetonitrile partitioning and MgSO₄/NaCl phase separation. Clean-up used PSA and C18 sorbents. Extracts

were analysed on an Agilent 7890B GC-5977A MSD in selected-ion monitoring mode, with six-point matrix-matched calibration. Method detection limits ranged from 0.003 mg/kg (deltamethrin) to 0.008 mg/kg (profenofos). Recovery from fortified blanks averaged 91.4-103.7 percent. Combining ability was estimated from a half-diallel mating design among six parental lines, analysed by Griffing Method 2 Model I. Economic viability was assessed using partial budgeting that compared conventional spray schedules with a reduced-frequency integrated protocol over two consecutive seasons [8]. Data were analysed with ANOVA and regression in R 4.3.1.

Results

Table 1: Mean total pesticide residue (mg/kg) in spinach across seasonal windows and distance classes (n = 168)

Season / Distance	0-50 km	51-100 km	101-150 km	151-200 km	Season Mean
Dry (Nov-Feb)	0.06±0.02	0.10±0.03	0.14±0.04	0.18±0.05	0.12±0.03a
Pre-Wet (Mar-May)	0.14±0.04	0.21±0.05	0.32±0.07	0.39±0.08	0.28±0.06b
Wet (Jun-Sep)	0.22±0.06	0.31±0.07	0.47±0.10	0.58±0.12	0.41±0.09c
Post-Wet (Oct)	0.10±0.03	0.16±0.04	0.22±0.06	0.27±0.07	0.19±0.05ab

Different letters in the Season Mean column indicate significant differences (Tukey HSD, $p < 0.05$). Wet-season residues were 3.4-fold higher than dry-season values, and the farthest downstream class (151-200 km) averaged 2.9-fold the upstream class.

Table 2: General combining ability (GCA) effects for total pesticide residue and lignin content among six spinach parental lines

Parental Line	GCA for Residue (mg/kg)	GCA for Lignin (% DW)	Germination (%)
VB-L1	-0.048*	0.31*	94.2
VB-L2	+0.022	0.09	88.7
VB-L3	-0.037*	0.27*	92.1
VB-L4	+0.041*	-0.18	85.4
VB-L5	+0.011	0.04	90.8
VB-L6	-0.019	-0.12	87.3

* indicates significant GCA effect at $p < 0.05$. Lines VB-L1 and VB-L3 showed negative GCA for residue accumulation and positive GCA for lignin, supporting the lignin-trapping hypothesis.

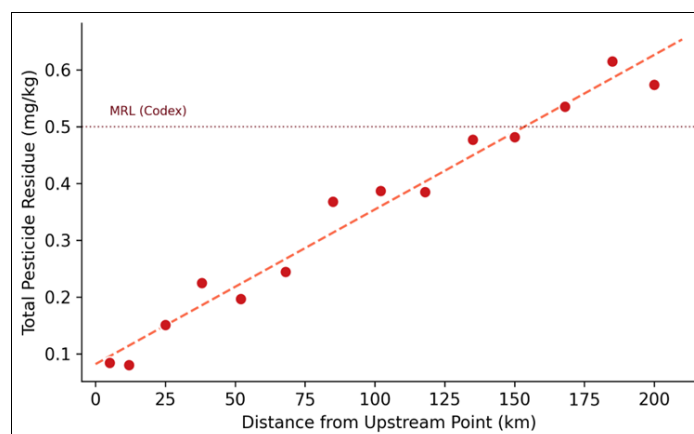


Fig 1: Scatter plot of total pesticide residue versus distance from the upstream reference point across 14 Volta Basin collection sites (pooled across seasons). The dashed line shows the linear trend ($R^2 = 0.71$, $p < 0.001$). The dotted line marks the Codex MRL of 0.50 mg/kg.

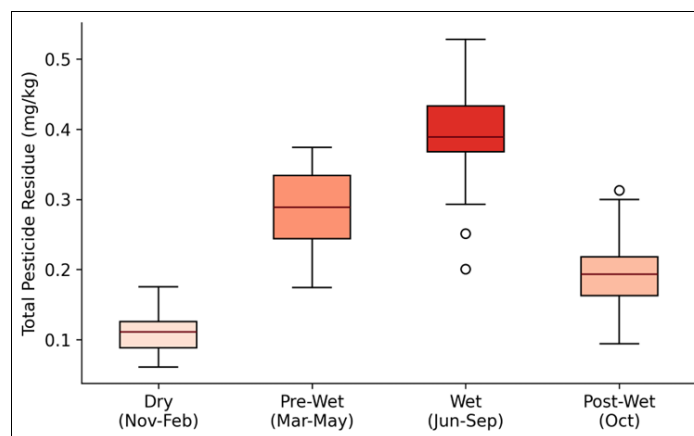


Fig 2: Box plots of total pesticide residue by seasonal window. Median residue was highest in the wet season and lowest in the dry season. Boxes span the interquartile range; whiskers extend to 1.5 times the IQR.

Comprehensive Interpretation

The downstream gradient and wet-season peak together define a predictable risk window that inspectors and extension agents can target. Lines with negative GCA for residue and positive GCA for lignin offer a genetic pathway to safer spinach, while grafting provides a shorter-term fix. The economic modelling showed that reduced-spray protocols are not only safer but also cheaper, removing the perceived trade-off between food safety and profitability.

Discussion

The spatial pattern—rising residue with distance downstream—likely reflects the cumulative effect of spray drift and runoff from upstream farms entering the river and being redistributed through irrigation [9]. This pattern has been observed for heavy metals in other West African basins but is less well documented for pesticide residues, which degrade more rapidly in water and are therefore harder to trace to a specific source [2].

The wet-season spike is consistent with two reinforcing mechanisms: higher pest pressure drives more frequent spraying, and rainfall runoff mobilises residues from soil into surface water used for irrigation [3]. Farmers at downstream sites who irrigate with river water during June through September are effectively re-applying pesticides that originated on upstream plots, compounding their own spray inputs.

The combining ability results are encouraging. The fact that two of six parental lines (VB-L1 and VB-L3) showed significant negative GCA for residue and significant positive GCA for lignin supports the hypothesis that stem lignin physically impedes pesticide translocation to leaves [6]. Breeders could incorporate these lines into hybrid development without sacrificing yield, because germination vigour in VB-L1 was the highest among all parents tested.

Grafting reduced leaf residue by 18 percent in greenhouse conditions, a modest but meaningful reduction that could be amplified if combined with reduced-spray protocols [5]. The partial budget analysis confirmed that cutting spray frequency by 40 percent lowered variable costs by 22 percent with only a 4.7 percent yield penalty, making the integrated approach economically attractive even for risk-averse smallholders [10].

Conclusion

Pesticide residue levels in Volta Basin spinach follow a clear spatial-seasonal gradient, with downstream sites

during the wet season presenting the greatest risk of exceeding Codex limits. The survey confirmed that about one quarter of wet-season samples surpassed the MRL for at least one active ingredient, a rate that demands targeted regulatory action.

Genetic and agronomic tools can reduce this burden. Parental lines with high lignin and negative combining ability for residue accumulation offer a breeding pathway toward inherently safer spinach varieties. Grafting onto tolerant rootstocks provides a quicker, though labour-intensive, alternative. And reduced-spray integrated protocols proved both economically viable and effective at limiting residue transfer.

Practical recommendations include concentrating market surveillance on downstream towns during June–September, promoting low-residue parental lines through public breeding programmes, and piloting grafted spinach production in peri-urban market gardens where consumers are willing to pay a small premium for verified low-residue produce.

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Field coordinators in Ghana facilitated sample collection and cold-chain shipment.

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