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Ishikawa Diagnosis of Pesticide Treatment Operations and FMECA Analysis of Sprayer Failures Associated with Pesticide Contamination of Three Vegetables: *Solanum lycopersicum L.*, *Lactuca sativa L.*, *Daucus carota var. sativus H.* Produced in Various Agroecological Zones of Côte d'Ivoire

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Abstract

The intensification of vegetable production in Côte d'Ivoire is accompanied by an increased and uncontrolled use of pesticides. This study evaluates the risk factors for chemical contamination of lettuce (*Lactuca sativa L.*) in Abidjan, tomato (*Solanum lycopersicum L.*) in Bouaké, and carrot (*Daucus carota var. sativus H.*) in Korhogo. A preliminary diagnosis using the Ishikawa diagram (5M) was coupled with a Failure Mode, Effects, and Criticality Analysis (FMECA) conducted on 294 knapsack sprayers. Chromatographic analyses (HPLC-DAD/UV) quantified pesticide residues in 33 harvested vegetable samples. The Ishikawa diagram reveals that the use of highly hazardous substances (75%), non-compliance with Pre-Harvest Intervals (PHIs, 50%), and equipment failures govern the contamination risk. The technical audit indicates that 85% of the sprayers are defective. The invisible widening of the nozzle orifice (Criticality, C = 40) and the lack of sealing of the tank caps (C = 48) emerge as the highest priority critical failures, causing involuntary overdosing and dermal leakage. Laboratory analyses confirm critical multi-residue contamination. Several molecules exceed Maximum Residue Limits (MRLs) in lettuce (chlorfenvinphos: 30.5 ± 0.7 µg/kg; acetamiprid: 19.6 ± 2.0 µg/kg) and tomato (chlorfenvinphos: 24.0 ± 2.8 µg/kg). Conversely, carrots were found to

be compliant with MRLs. Securing the sector requires an action plan centered on operator training and regular equipment calibration.

Keywords

Côte d'Ivoire, FMECA, Ishikawa, Pesticides, Residues, Vegetable Farming

1. Introduction

Vegetable crops make a decisive contribution to food and nutritional security by providing diets rich in micronutrients, fibers, vitamins, and antioxidants. In Côte d'Ivoire, population growth and rampant urbanization stimulate the intensification of horticultural production within the Abidjan, Bouaké, and Korhogo basins. However, this dynamic is accompanied by an increased reliance on phytosanitary inputs, characterized by poor handling, empirical dosing, chronic non-compliance with Pre-Harvest Intervals (PHIs), and the use of obsolete equipment.

Agricultural sprayers constitute the major technological interface of the treatment, and their failures (nozzle wear, lack of sealing, absence of calibration) induce environmental drift and systematic overdosing. Given the marked contrasts between the humid South of Abidjan, the transitional Center of Bouaké, and the dry North of Korhogo, operational constraints vary widely. The present work jointly mobilizes the Ishikawa diagram for the systemic analysis of contamination causes and the industrial FMECA method [1] to prioritize equipment failures and correlate these mechanical breakdown points with real pesticide residue concentrations quantified in vegetables.

2. Materials and Methods

2.1. Plant Material and Sampling

The study was conducted across 418 agricultural plots, comprising 232 lettuce (*Lactuca sativa L.*) beds in Abidjan (approximately 15 m^2 each), 106 tomato (*Solanum lycopersicum L.*) plots in Bouaké (approximately 0.5 ha each), and 80 carrot (*Daucus carota L.*) beds in Korhogo (averaging 14 m^2 each). All selected plots had received pesticide applications using the sprayers targeted for inspection. The sample size was determined using the formula proposed by Krejcie and Morgan [2], and plots were randomly selected.

Vegetable samples were randomly collected at harvest maturity from multiple plots or beds at each study site, provided that they had received at least one pesticide application using an inspected sprayer. Composite samples were prepared according to crop type, consisting of four basal and apical lettuce leaves, five tomato fruits at the breaker and red-ripe stages, or three carrot roots. Each composite sample was placed in a sterile Stomacher bag, with sample weights of 300 g for lettuce and 500 g for both tomatoes and carrots. The samples were subsequently vacuum-sealed and transported under refrigerated conditions in insulated coolers

to preserve their integrity. Overall, 33 composite vegetable samples, comprising nine lettuce, 18 tomato, and six carrot samples, were individually coded and transported to the laboratory for pesticide residue analysis.

2.2. Ishikawa Diagnosis and Sprayer Pool

The operational performance of 294 pesticide sprayers, randomly selected from vegetable growers cultivating lettuce (n = 145), tomato (n = 83), and carrot (n = 66), was assessed using an integrated approach combining the Ishikawa cause-and-effect diagram (5M framework) and Failure Mode and Effects Analysis (FMEA). Contamination causes were structured according to the 5M approach (Machine/Equipment, Manpower, Method, Milieu/Environment, Material). Concurrently, a random sample of 294 knapsack sprayers underwent direct technical monitoring (45 days in Abidjan, 60 days in Bouaké, 30 days in Korhogo).

2.3. FMECA Scoring

Global criticality was calculated using the equation: $C = G \times O \times D$. The occurrence rating (O) was determined based on defect prevalence (Pj), defined as the proportion of sprayers exhibiting a given defect at least once, and the daily occurrence rate (Oj), representing the mean number of occurrences of each defect per sprayer over the observation period. Occurrence was rated on a five-point scale, ranging from 1 (very rare; Oj < 1%) to 5 (very frequent; Oj ≥ 30%). Severity (G) was scored from 1 (negligible) to 5 (critical), according to the potential risks of pesticide overdosing and vegetable contamination. Detectability (D) was assessed through visual inspection, leak-tightness testing, nozzle calibration, and functional checks of sprayer components, and was rated from 1 (very easily detectable) to 5 (undetectable). The criticality index (C) was subsequently calculated as the product of occurrence, severity, and detectability ratings ($C = O \times G \times D$), yielding values ranging from 1 to 125. This index enabled the prioritization of failure modes according to their criticality levels (Table 1).

Table 1. Failure mode and effects analysis (FMEA) scoring scale and criticality classification thresholds.

Rating	Severity (G)	Occurrence (O)/ Daily occurrence rate (Oj)	Detectability (D)	Criticality index range (G × O × D)	Overall criticality level
1	Negligible	Very rare (Oj < 1%)	Very easily detectable	**1 - 10**	Very low
2	Minor	Rare (1% ≤ Oj < 5%)	Easily detectable	**11 - 20**	Low
3	Moderate	Occasional (5% ≤ Oj < 15%)	Moderately detectable	**21 - 35**	Moderate
4	Major	Frequent (15% ≤ Oj < 30%)	Difficult to detect	**36 - 45**	High
5	Critical	Very frequent (Oj ≥ 30%)	Undetectable	**46 - 125**	Very high

2.4. Chromatographic Analysis

Pesticide residues were analyzed using high-performance liquid chromatography

(HPLC; Shimadzu LC-20AT) equipped with a diode-array detector (DAD) or a UV-visible detector and a C18 analytical column, following a QuEChERS extraction procedure adapted to the different sample matrices [3]. Following extraction with acetonitrile, cleanup using magnesium sulfate and sodium chloride, centrifugation, filtration through a 0.45 µm membrane, and injection of a 20 µL aliquot, pesticide active ingredient concentrations were quantified by interpolation from calibration curves established over a concentration range of 0.001 - 0.050 mg/L. The principal reagents included HPLC-grade methanol and acetonitrile, ultrapure water (Milli-Q), anhydrous magnesium sulfate, and sodium chloride. The analytical performance of the methods targeting major pesticide classes, including triazines, substituted ureas, organophosphates, organochlorines, carbamates, pyrethroids, and chloroacetamides, was validated in accordance with the SANTE/11312/2021 guidelines [4], the Codex Alimentarius guidelines CAC/GL 40-1993 [5], and AOAC INTERNATIONAL recommendations [6]. Recovery rates ranged from 72% to 109%, while limits of detection (LODs) ranged from 0.001 to 0.020 mg/kg and limits of quantification (LOQs) from 0.005 to 0.050 mg/kg, except for mancozeb, which exhibited an LOD of 0.050 mg/kg and an LOQ of 0.100 mg/kg. Certified analytical reference standards with purities exceeding 98% were used to ensure reliable calibration. Depending on the physicochemical properties of the target compounds, complementary analytical techniques were employed, including HPLC coupled with diode-array or UV detection (HPLC-DAD/UV), fluorescence detection (HPLC-FLD), gas chromatography with electron capture detection (GC-ECD), gas chromatography-tandem mass spectrometry (GC-MS/MS), and liquid chromatography-tandem mass spectrometry (LC-MS/MS). Glyphosate and mancozeb were analyzed using specific analytical protocols based on the QuPPe-LC-MS/MS approach and the determination of dithiocarbamates following their conversion to carbon disulfide (CS_2), respectively.

2.5. Statistical Data Processing and Analysis

Data were statistically analyzed using SPSS, XLSTAT, and R software (version 4.5.0). Data normality and homogeneity of variances were assessed using the Shapiro-Wilk and Levene's tests, respectively. Depending on whether the assumptions for parametric analysis were satisfied, either two-way analysis of variance (ANOVA) or the nonparametric Kruskal-Wallis test was performed. Microbiological data were analyzed using one-way ANOVA, followed by Tukey's honestly significant difference (HSD) post hoc test for multiple comparisons. Statistical significance was established at a threshold of $p < 0.05$ for all analyses.

3. Results

3.1. Systemic Diagnosis via the Ishikawa Diagram

The causal analysis performed using the Ishikawa cause-and-effect diagram highlighted the predominance of human-related and technical factors affecting the food safety of vegetable crops (**Figure 1**). Within the "Materials" category, the use

of highly toxic pesticide active ingredients emerged as the leading potential source of contamination, reported among 75% of the surveyed vegetable growers. Regarding the "Manpower" category, non-compliance with recommended pre-harvest intervals (PHIs) was the predominant concern, affecting 50% of the surveyed growers, further compounded by the misinterpretation of pesticide product labels among 30% of respondents. In the "Methods" category, deliberate pesticide overdosing represented the most critical practice, accounting for 30% of the observed cases. Concerning the "Environment" category, external factors promoting pesticide spray drift, particularly unfavorable wind directions during pesticide application, were identified in 36% of spraying operations. Finally, within the "Machinery" category, a detailed technical assessment revealed multiple operational defects affecting pesticide sprayers. Failure analysis showed that blockage of the pumping lever was the most frequently reported defect (84%), followed by filter detachment into the tank (52%), carrying strap breakage (48%), defective tank-cap closure (44%), and tank cracking (42%). Additional malfunctions included loosening of nozzle holders (40%) and spray booms (39%), nozzle clogging (38%), and enlargement of nozzle orifices (26%).

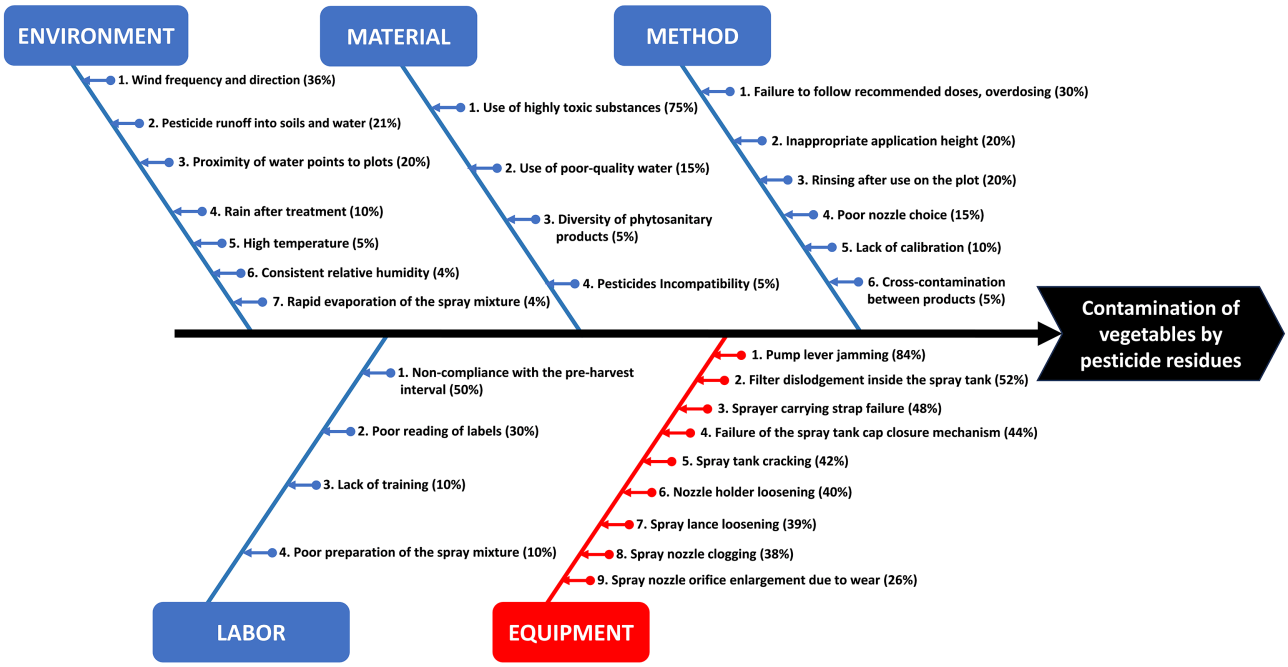

Figure 1. Modeled representation of contamination causes according to the Ishikawa diagram.

3.2. Mechanical Audit and Sprayer Failure Inventory

Inspection of the 294 pesticide sprayers revealed an overall defect prevalence of 85%, with the highest proportion recorded in Abidjan (88.3%), followed by Bouaké (85.5%) and Korhogo (77.3%) (Table 2). Among defective sprayers, the most prevalent malfunctions included pumping lever blockage (84%), filter detachment into the tank (52%), carrying strap breakage (48%), defective tank-cap closure (44%), and tank cracking (42%). Enlargement of nozzle orifices (26%) was

also identified as a notable defect, potentially compromising pesticide application accuracy and uniformity.

Table 2. Descriptive status and typology of inspected field sprayer mechanical failures by basin.

Mechanical Parameters and Structural Defects	Abidjan	Bouaké	Korhogo	Overall Total
Inspected sprayers (N)	145	83	66	294
Functional equipment (without defects)	17	12	15	44 (15%)
Defective equipment (with defects)	128	71	51	250 (85%)
◆ Jammed pumping lever	100	64	47	211 (84%)
◆ Tank internal filter dropped	51	54	24	129 (52%)
◆ Broken carrying straps	55	38	26	119 (48%)
◆ Tank cap closure impossible	47	29	35	111 (44%)
◆ Cracked chemical spray tank	45	22	38	105 (42%)
◆ Unscrewed nozzle-holder	37	30	34	101 (40%)
◆ Obstructed nozzle	41	37	18	96 (38%)
◆ Unscrewed spray boom	34	32	31	97 (39%)
◆ Widened nozzle orifice	23	25	18	66 (26%)

3.3. Industrial Criticality Analysis (FMECA)

Quantitative scoring indicates that nozzle orifice expansion positions itself as a homogeneous high-criticality risk (C = 40) due to a critical severity score (G = 5) associated with very difficult detectability to the naked eye (D = 4) (Table 3). In Bouaké and Korhogo, the inability to close the tank cap reaches the maximum criticality rating of "Very High" (C = 48), inducing risks of permanent spillage of toxic substances onto the bodies of the applicators. Statistical analysis revealed no significant overall differences in sprayer operational performance across the study sites ($p = 0.741 > 0.05$), suggesting a consistently high prevalence of equipment deterioration among the pesticide sprayers used by vegetable growers across the three study areas.

Failure Mode and Effects Analysis (FMEA) revealed that four major failure modes, with criticality indices (C) ranging from 32 to 48, may contribute through distinct mechanisms to an increased risk of pesticide residue contamination in vegetable crops. Enlarged nozzle orifices were identified as a major potential cause of undetected pesticide overapplication, whereas defective tank-cap closure represented the most critical failure mode due to spray solution leakage and increased operator exposure. Carrying strap breakage may compromise application uniformity and lead to accidental spillage, while cracks in the spray tank may result in continuous, diffuse contamination of crops, soil, and the surrounding environment. These findings highlight the need for preventive sprayer maintenance and systematic replacement of defective components prior to pesticide application.

Table 3. FMECA evaluation matrix and failure criticality index (C) ranking.

Specific Mechanical Failure Mode	Score G	Score D	C Abidjan	C Bouaké	C Korhogo	Criticality Class/Risk Level
Widened nozzle orifice	5	4	40	40	40	**High** (Involuntary Overdosing)
Tank cap closure impossible	4	4	32	48	48	**Very High** (Dermal Exposure)
Broken carrying straps	4	4	32	48	32	**Moderate to Very High**
Cracked chemical spray tank	4	4	32	32	32	**Moderate**
Unscrewed nozzle-holder	3	2	18	18	18	**Low**
Obstructed nozzle	2	3	18	18	12	**Low**
Unscrewed spray boom	5	1	15	15	15	**Low**
Tank internal filter dropped	2	2	12	12	12	**Low**
Jammed pumping lever	1	2	6	6	4	**Very Low**

3.4. Quantification of Pesticide Residue Concentrations

HPLC-DAD/UV analyses confirmed the presence of multiple pesticide residues at trace levels along the north-south geographical gradient (Table 4). Lettuce from Abidjan displays the most critical chemical loads, characterized by major MRL breaches for highly toxic compounds (aldicarb, fipronil, parathion-methyl, chlorfenvinphos) (Table 3). Tomatoes from Bouaké also present major toxicological infractions for aldicarb (15.5 ± 0.7 µg/kg) and chlorfenvinphos (24.0 ± 2.8 µg/kg). In contrast, the Korhogo basin produces chemically safe carrots, with all detected active ingredients remaining strictly below regulatory thresholds.

Table 4. Pesticide residue levels (µg/kg) quantified in vegetable samples.

Chemical class	Active ingredient	Lettuce (Abidjan)	Tomato (Bouaké)	Carrot (Korhogo)	Maximum residue limit (MRL)	Matrix recovery (%)
Triazine	Terbuthylazine	nd	nd	22.5 ± 0.7[a]	**50**	80 - 110
	Désisopropylatratzine	17.7 ± 1.2[a]	1.7 ± 0.4[b]	nd	50	80 - 110
	Désethylatrazine	nd	5.4 ± 1.4[a]	1.5 ± 0.7[a]	50	80 - 110
	Simazine	nd	23.0 ± 1.6[a]	11.5 ± 1.3[a]	50	80 - 110
	Terbutryn	21.5 ± 2.1[a]	2.5 ± 0.7[a]	nd	50	80 - 110
Triazinone	Métamitron	16.5 ± 0.7[b]	2.3 ± 0.5[b]	5.5 ± 1.1[a]	lettuce/tomato: 100; carot: 50	70 - 120
Chloroacetamide	Metazachlor	4.9 ± 0.5b	nd	nd	50	70 - 120
Organophosphoré	Chlorfenvinphos	30.5 ± 0.7[a]	24.0 ± 2.8[a]	3.8 ± 0.3[a]	**10**	82 - 95
	Methyl parathion	12.5 ± 0.7[b]	1.1 ± 0.1[a]	2.5 ± 0.7[b]	**10**	85 - 105

Continued

	Aldicarb	17.4 ± 0.6[b]	15.5 ± 0.7[b]	nd	**10**	79 - 95
Carbamate	Chlorpropham	21.5 ± 0.6[a]	15.0 ± 1.4[a]	nd	**50** (tomato)/**10** (carot)	80 - 105
	Profenos	4.4 ± 0.6a	nd	nd	50	70 - 120
Néonicotinoïde	Acétamiprid	19.6 ± 2.0[a]	nd	nd	**10**	80 - 114
Phénylpyrazole	Fipronil	10.3 ± 1.2[b]	nd	0.3 ± 0.1[b]	**10**	82 - 105
Pyréthrinoïde	Lambda-cyhalothrin	22.9 ± 2.1[a]	nd	0.6 ± 0.2[a]	**10** (tomato/carrot)	80 - 110
	Cyperméthrin	19.7 ± 5.6[a]	13.7 ± 2.4[a]	5.7 ± 1.6[a]	(lettuce/tomato): 500; Carot: 10	80 - 110
Phosphonate	Glyphosate	nd	20.4 ± 1.4[a]	0.9 ± 0.2[b]	**50**	75 - 110
	Monolinuron	30.0 ± 1.4[a]	2.7 ± 0.6[a]	4.5 ± 0.7[a]	**50**	80 - 105
Urée Dérivée	Fénuron	21.5 ± 9.2[b]	14.2 ± 1.9[b]	nd	50	80 - 105
	Méthabenzthiazuron	21.5 ± 2.1[b]	nd	nd	50	80 - 105

ND: Not detected; MRL: Maximum residue limit.

4. Discussion

The integrated Ishikawa-Failure Mode and Effects Analysis (FMEA) approach highlights the interplay between equipment failures, pesticide application practices, and crop-specific characteristics in contributing to chemical contamination of vegetables. The high prevalence of defective sprayers (85%; n = 250/294), particularly in Abidjan (88.3%), indicates widespread deterioration of pesticide application equipment. This finding reinforces the importance of equipment maintenance and calibration emphasized by Matthews [7] and is consistent with the observations of Son *i.e.* [8] and Kpan Kpan *et al.* [9] regarding technical shortcomings and inadequate phytosanitary practices in vegetable production systems. FMEA revealed a marked discrepancy between the frequency of equipment failures and their associated criticality levels. Although pumping lever blockage was the most frequently observed malfunction (211 cases), it exhibited relatively low criticality (C = 4 - 6), unlike nozzle orifice enlargement (66 cases; C = 40). This defect, characterized by limited detectability (D = 4), may increase spray discharge rates and alter droplet size distribution, thereby promoting excessive or uneven pesticide application. Baio *et al.* [10] experimentally demonstrated the influence of nozzle wear on spray characteristics. Similarly, defective tank-cap closure (C = 48), cracked spray tanks (105 cases), and broken carrying straps (119 cases) may increase the likelihood of pesticide leakage and applicator exposure. These findings are consistent with those of Tomenson and Matthews [11], who reported an association between incidents involving pesticide application equipment and health problems reported by pesticide users. The Ishikawa analysis further highlighted the importance of non-compliance with recommended pre-harvest intervals (PHIs), difficulties in interpreting pesticide product labels, and pesticide

overdosing. Son *et al.* [8] observed excessive pesticide applications in Burkina Faso, where pre-harvest intervals were frequently determined by crop phytosanitary conditions rather than recommended guidelines. Similarly, Kpan Kpan *et al.* [9] reported non-compliance with PHIs among 80.26% of vegetable growers in Port-Bouët. When combined with defective spraying equipment, such practices may contribute to pesticide residue persistence in vegetables, with dissipation patterns varying according to pesticide properties, crop characteristics, and environmental conditions [12]. Chromatographic analyses revealed several exceedances of the maximum residue limits (MRLs) adopted in this study, particularly in lettuce from Abidjan and tomatoes from Bouaké. In lettuce, chlorfenvinphos (30.5 µg/kg), acetamiprid (19.6 µg/kg), and aldicarb (17.4 µg/kg) concentrations exceeded the corresponding MRLs by factors of 3.05, 1.96, and 1.74, respectively. In tomatoes, chlorfenvinphos and aldicarb concentrations were 2.40 and 1.55 times their respective limits. These findings are consistent with those of Kpan Kpan *et al.* [6], who identified several pesticide residues exceeding regulatory limits in lettuce produced in Abidjan. Nevertheless, exceedance of regulatory residue limits does not necessarily indicate an established health risk, as the magnitude of such risk depends on dietary exposure levels and the toxicological properties of the compounds involved. Variations in pesticide residue profiles may also be partly attributed to morphological and physiological differences among vegetable crops. The extensive leaf surface area of lettuce favors the interception and retention of spray droplets, consistent with the findings of Wang *et al.* [13], who emphasized the importance of initial foliar deposition and subsequent contaminant transfer from soil. In Korhogo, the detection of terbuthylazine in carrots (22.5 µg/kg) suggests a potential indirect contamination pathway involving root uptake from contaminated soil. Collins *et al.* [14] demonstrated that the uptake and translocation of organic contaminants in plants depend on their physicochemical properties and plant-specific characteristics.

5. Conclusion

This study highlights the critical role of technical deficiencies in pesticide sprayers and inappropriate pesticide application practices as potential drivers of chemical contamination in vegetable production systems in Côte d'Ivoire. The high prevalence of defective equipment (85%) indicates widespread technological inadequacies, with nozzle wear (C = 40) and sealing defects (C up to 48) emerging as particularly critical failure modes. These deficiencies, combined with pesticide overdosing and non-compliance with recommended pre-harvest intervals (PHIs), may contribute to excessive pesticide deposition and environmental dispersion. Exceedances of maximum residue limits (MRLs) for certain pesticides in lettuce from Abidjan and tomatoes from Bouaké, together with the detection of pesticide residues in carrots from Korhogo, highlight the diversity of potential contamination pathways associated with crop-specific characteristics. The originality of this research lies in integrating the Ishikawa cause-and-effect analysis and Failure Mode and Effects Analysis (FMEA) with analytical pesticide residue characteriza-

tion, thereby providing a methodological framework for prioritizing equipment failures and identifying key intervention measures to mitigate pesticide-related risks. The findings underscore the need for an integrated preventive strategy encompassing systematic sprayer maintenance and calibration, replacement of critical defective components, improved applicator training, and strengthened pesticide residue monitoring. Future research combining quantitative spray performance parameters with measured pesticide residue concentrations would help elucidate contaminant transfer mechanisms and refine risk prevention strategies in vegetable production systems. Overall, this integrated approach provides a promising framework for promoting safer and more sustainable pesticide application practices in vegetable production systems across Côte d'Ivoire and West Africa.

Author Contributions

Conceptualization, D.P.A. and P.D.Y.A.Y.; methodology, D.P.A.; software, D.P.A.; validation, D.P.A., B.J-A.A. and P.D.Y.A.Y; formal analysis, D.P.A. and B.J-A.A.; investigation, D.P.A.; resources, D.P.A.; data curation, D.P.A. and P.D.Y.A.Y.; writing—original draft preparation, D.P.A.; writing—review and editing, B.J-A.A. and P.D.Y.A.Y.; visualization, B.J-A.A.; supervision, P.D.Y.A.Y.; project administration, D.P.A. and P.D.Y.A.Y.; funding acquisition, D.P.A. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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