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Risks Associated with Pesticides in the Agricultural Area of Lakota (Ivory Coast): Toxicological and Environmental Assessment

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Abstract: Intensive agriculture in the tropical region of Lakota (Ivory Coast) relies on the massive use of pesticides, raising significant concerns regarding ecosystem contamination and human health. The aim of this study was to conduct a comprehensive toxicological and environmental risk assessment of pesticides used in this area. A survey of 160 farmers and 17 retailers identified 80 commercial products, whose active ingredients were analysed using the PPDB and SAgE Pesticides databases. The Groundwater Ubiquity Score (GUS) and Toxicological Risk Index (TRI) were employed to evaluate the risks of water contamination and toxicological hazard, respectively. The results reveal that six active substances, including the neonicotinoids imidacloprid (GUS=3.73) and thiamethoxam (GUS=3.82), present a high risk of leaching into water resources. Concurrently, the TRI assessment identified 11 substances and formulations with alarming toxicity levels, most notably chlorpyrifos-ethyl (TRI=12 100) and a binary mixture of imidacloprid/beta-cyfluthrin (TRI=14 005). Although 97.5% of the identified products are officially authorised, the study notes the persistent use of extremely hazardous (WHO Class Ia) compounds, such as paraquat, via informal channels. This study concludes that the current pesticide usage patterns pose a substantial threat to the region's environmental and public health. It argues for a regulatory prioritisation of high-risk compounds and the promotion of integrated pest management strategies, advocating for the adoption of effective, lower-risk alternatives (e.g., spinosad, *Bacillus subtilis*) to reconcile agricultural productivity with environmental sustainability, particularly in regions vulnerable to intense rainfall.

1. Introduction

Intensive agriculture in tropical regions, such as the area surrounding Lakota in Ivory Coast, is heavily reliant on the substantial application of pesticides to secure crop yields, creating a significant tension between production imperatives and environmental preservation (EFSA, 2019; Akpo *et al.,* 2021). Whilst these substances are instrumental in boosting the productivity of key economic mainstays like cocoa and coffee (Tang *et al.,* 2021), their often uncontrolled and excessive use generates considerable negative externalities. These include the contamination of water resources, direct and indirect health risks to agricultural workers and local communities, and profound damage to biodiversity, thereby necessitating research into numerous strategies for securing clean water and a healthier environment (WHO, 2023; Leskovac *et al.,* 2023; Akartasse *et al.,* 2022).

This pressing issue is further exacerbated by the region's specific bioclimatic conditions, characterised by high rainfall exceeding 1200 mm/year, and distinct soil types, which are known to significantly alter the behaviour, persistence, and mobility of active molecules in the environment (Zhang *et al.,* 2018; Kouassi *et al.,* 2021). Paradoxically, whilst the scientific literature abounds with studies on the general impacts of pesticides globally (Carvalho, 2017; Ali *et al.,* 2020; Melliti *et al.,* 2013; Salghi *et al.,* 2011), few studies have successfully integrated these critical tropical parameters into their risk assessment frameworks, a significant research gap that several authors have recently deplored (Moutouama *et al.,* 2022; Sanogo *et al.,* 2023). More alarmingly, substances that have been banned due to their high toxicity, such as paraquat (classified as Ia by the WHO), persist in use through informal channels (WHO, 2019), revealing a critical disconnect between regulation and practice and underscoring the urgent need for a more contextualised and targeted approach to pesticide risk assessment.

In light of these challenges, the present study proposes a comprehensive and integrated methodology combining: (i) a robust assessment of the water contamination risk using the Groundwater Ubiquity Score (GUS) index established by Gustafson (1989), (ii) a detailed toxicological analysis using the Toxicological Risk Index (TRI) methodology (Samuel *et al.,* 2012; Le Bars *et al.,* 2020), and (iii) a thorough field survey of 160 local stakeholders, including farmers and retailers. The overarching aim of this three-pronged approach is to: (1) establish an up-to-date and accurate inventory of pesticides currently in use within the Lakota agricultural area; (2) systematically rank the identified active substances based on their environmental and health risks; (3) propose scientifically-sound and socio-economically adapted alternatives for high-risk compounds; and (4) provide local and national decision-makers with robust, evidence-based tools to inform future regulatory actions.

The originality of this work lies in its holistic approach, which deliberately reconciles key chemical parameters (e.g., persistence, mobility), acute and chronic toxicological data, and on-the-ground socio-economic realities. It is anticipated that the results will contribute substantially to the development of more balanced and sustainable agricultural policies for this key cocoa-growing region of Ivory Coast, whilst simultaneously filling a major scientific gap concerning the fate and impact of pesticides in humid tropical environments.

2. Materials and Methods

2.1. Study Area

This study was conducted in the agricultural zone of Lakota, located in the Lôh-Djiboua region of south-western Ivory Coast. Data collection focused on the city of Lakota and the surrounding villages of Akabreboua, Gazolilié, Dahiri, Gniakpalilié, Nassalilié, and Grand Déboua. A key feature of the study area is the presence of Lake Labo (geographical coordinates: 5°54'38" N, 5°41'38" W), a natural lake covering an area of 3,390 m² with depths exceeding 15 metres. This lake constitutes a vital resource for the neighbouring communities, supporting activities such as fishing and the irrigation of food crops, cocoa, and coffee, which are the principal economic activities. The region is characterised by high biodiversity, sustained by dense vegetation and a humid tropical climate, with annual rainfall ranging between 1,200 and 1,500 mm (Ahipo, 2024; Béné *et al.,* 2024). This setting exemplifies the delicate interplay between human agricultural activity and the preservation of a fragile ecosystem. The location of the study area is presented in **Figure 1**.

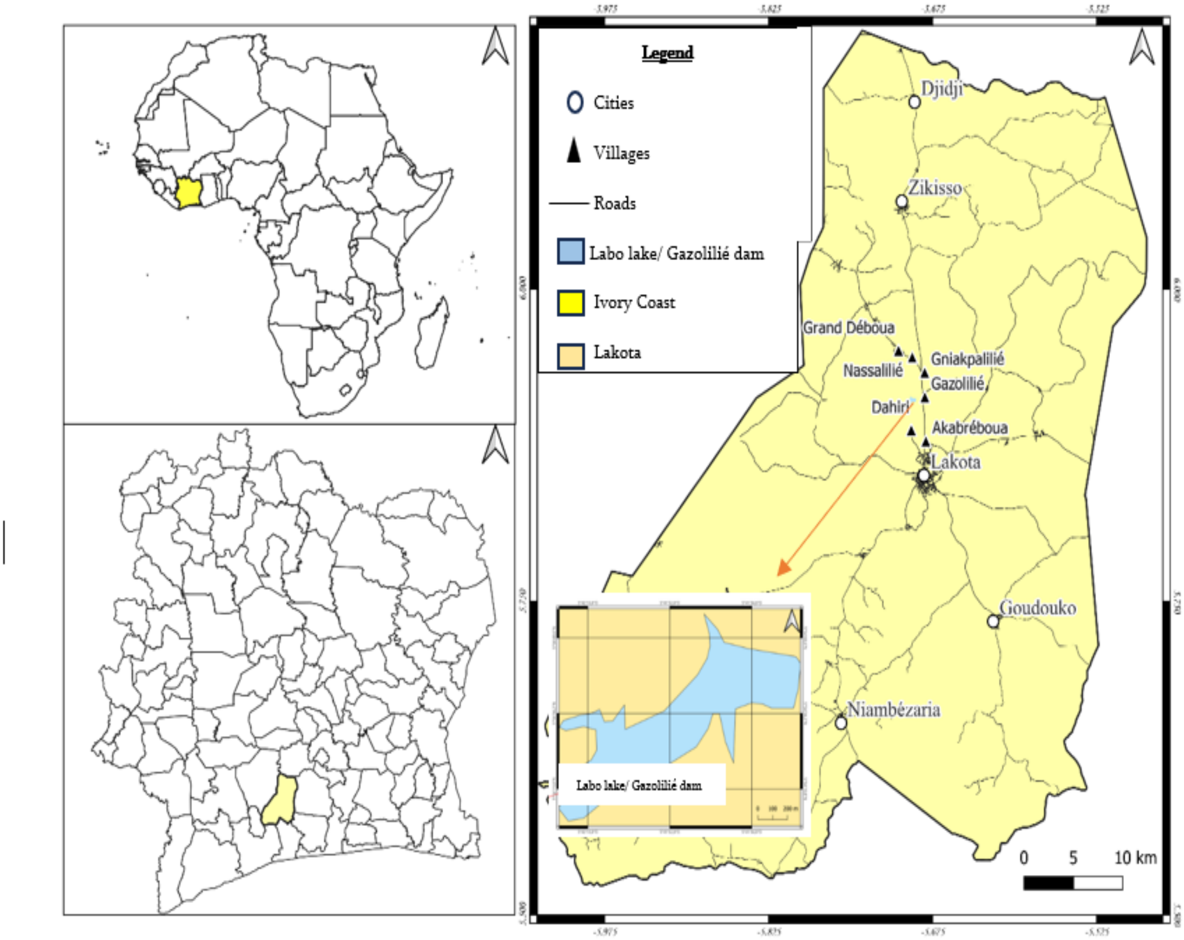

Figure 1: Location of the study Area.

2.2. Pesticide Data Collection

A comprehensive inventory of pesticides used during the 2021-2022 and 2022-2023 agricultural seasons was conducted through structured surveys administered to 160 farmers and 17 retailers operating in the Lakota region. This methodology ensured the identification of all marketed products, including those circulating illegally. The physicochemical, toxicological, and environmental properties of the identified active substances were systematically compiled from two authoritative databases: the Pesticide Properties DataBase (PPDB, 2024) and SAgE Pesticides (SAgE Pesticides, 2024). Data recorded for each product included its commercial name, composition (active substances and their concentration), chemical family, authorised application rates, suppliers, and regulatory status, thereby establishing a robust database for subsequent risk assessment.

2.3. Environmental Risk Assessment: Groundwater Ubiquity Score (GUS Index)

The potential for water contamination was assessed using the Groundwater Ubiquity Score (GUS) index, a predictive tool developed by Gustafson (1989) to evaluate the leaching risk of pesticides into groundwater and surface water. This index is a valuable instrument for guiding regulations aimed at preventing aquatic pollution (Steenhuis *et al.,* 2024). The GUS index was calculated using the following formula (**Eqn. 1**):

$$GUS = \log (DT_{50}) \times (4 - \log (K_{o}c)) \qquad \textbf{(Eqn. 1)}$$

This equation incorporates two key parameters: the soil half-life (DT_{50}), which reflects pesticide persistence, and the soil organic carbon adsorption coefficient ($K_{o}c$), which indicates soil mobility.

The results were interpreted according to the established thresholds (Gustafson, 1989):

- $GUS < 1.8$: Low leaching risk,
- $1.8 \leq GUS < 2.8$: Moderate leaching risk,
- $GUS \geq 2.8$: High leaching risk.

Validated by numerous studies (Kebede *et al.,* 2023), this indicator aids in prioritising restrictions on the most mobile and persistent active ingredients. Its application is particularly relevant in tropical areas, where heavy rainfall can amplify pesticide transfer into water resources (Steenhuis *et al.,* 2024).

2.4. Toxicological Risk Assessment: Toxicological Risk Index (TRI)

The Toxicological Risk Index (TRI) is a quantitative tool designed to assess the potential hazard of pesticides, considering both their acute and chronic toxic effects on human health and the environment (Samuel, 2007; Samuel *et al.,* 2012; Le Bars *et al.,* 2020).

The TRI for an active substance (TRI active substance) was calculated using the formula (**Eqn. 2**) established by Samuel *et al.* (2012) and applied by Le Bars *et al.* (2020):

$$TRI_{\text{active substance}} = [\Sigma \text{ (Acute effects)} + \text{(Chronic effects} \times \text{Fper)}]^2 \qquad \textbf{(Eqn. 2)}$$

The parameters considered include:

- Acute effects (AE): Immediate toxicity (e.g., LD_{50}, skin and eye irritation).
- Chronic effects (CE): Long-term toxicity (e.g., carcinogenicity, neurotoxicity, endocrine disruption).
- Fper factor: Environmental Persistence and Bioaccumulation Factor, calculated from bioaccumulation potential (BCF) and the substance's half-life (DT_{50}).

The TRI for a commercial formulated product ($TRI_{\text{commercial product}}$) corresponds to the sum of the TRI values of the active ingredients it contains ($\sum TRI_{\text{active substance}}$). This methodology, inspired by the work of Samuel *et al.* (2012) and applied in intensive agricultural contexts (Le Bars *et al.,* 2020; Koffi *et al.,* 2022), enables a systematic risk assessment to limit exposure to the most toxic substances.

2.5. Data Analysis

All data collected from surveys and database queries were processed and analysed using Microsoft Excel. The GUS and TRI indices were calculated for each active substance and commercial product according to the established protocols. Pesticides were then classified based on their level of environmental and toxicological risk. Finally, the calculated indices were cross-referenced with the survey results to identify the farming practices associated with the highest risks, enabling a comprehensive and integrated assessment of the hazards linked to pesticide use in the region.

3. Results and Discussion

3.1. Diversity of Pesticides Used in the Study Area

The comprehensive inventory revealed the presence of 80 distinct plant protection products on the market. Herbicides constituted the largest category, accounting for 47.5% of the total, followed by insecticides (40%) and fungicides (12.5%). These commercial formulations contained 29 different active ingredients, classified into 11 insecticides, 10 herbicides, and 8 fungicides. Although 97.5% of the identified pesticides are officially authorised, several active substances present significant health and environmental hazards. Notably, chlorpyrifos-ethyl (Class IA) exhibits neurotoxic properties and acts as an endocrine disruptor. Paraquat (Class Ia) is recognised for its high acute toxicity and marked persistence, while atrazine (Class II) is notable for its persistence and recognised risk of water pollution. The most frequently encountered herbicides included glyphosate (Class III) and the amine salt of 2,4-D (Class II). Commonly used insecticides comprised neonicotinoids (e.g., thiamethoxam, imidacloprid) and pyrethroids (e.g., deltamethrin, cypermethrin), raising concerns due to their documented risks to pollinators. Fungicides were predominantly from the triazole family (e.g., difenoconazole, cyproconazole) and included copper-based compounds (e.g., copper oxychloride). According to the hazard categories established by the World Health Organization (WHO), 82.5% of the identified pesticides were classified as slightly hazardous (Class III), 15% as moderately hazardous (Class II), and 2.5% as extremely hazardous (Class Ia), despite the latter being prohibited from use. A summary of the marketed products, their types, and hazard levels is presented in **Table 1**.

Table 1: Marketed Phytosanitary Products (Types and Hazard Levels).

Category	Response	Percentage	Notable Active Substances
Pesticide Types	Herbicides	47.50%	Glyphosate (isopropylamine salt, ammonium salt), 2,4-D (amine salt), Atrazine, Propanil, Cyhalofop-butyl, Triclopyr, Oxyfluorfen, Glufosinate-ammonium, Thiobencarb, Metsulfuron-methyl
	Insecticides	40%	Chlorpyrifos-ethyl (Ia), Neonicotinoids (Thiamethoxam, Imidacloprid, Acetamiprid), Pyrethroids (Deltamethrin, Bifenthrin, Lambda-cyhalothrin, Cypermethrin, Beta-cyfluthrin), Fipronil, Indoxacarb
	Fungicides	12.50%	Triazoles (Cyproconazole, Difenoconazole, Triadimenol), Copper salts (Copper oxychloride, Copper oxide), Mancozeb, Metalaxyl-M, Folpet, Mandipropamide, TCMTB, Bacillus subtilis strain IAB/BS03
WHO Class	Ia (Extremely hazardous)	2.50%	Paraquat dichloride, Chlorpyrifos-ethyl
	II (Moderatelyhazardous)	15%	Atrazine, 2,4-D, Fipronil, Glufosinate-ammonium
	III (Slightly hazardous)	82.50%	Glyphosate, Cypermethrin, Deltamethrin, Bifenthrin, Bacillus subtilis, Metalaxyl-M, Difenoconazole
Authorization	Approved	96.58%	All listed substances (unless locally restricted).
	Unauthorized/No info	3.42%	Varies by country (e.g., Paraquat banned in the EU).

3.2. Risk of Water Contamination: GUS Index

The potential for water contamination via leaching was evaluated for all 29 identified active substances using the Groundwater Ubiquity Score (GUS) index. The results, categorised by pesticide type, revealed a considerable diversity of environmental risk profiles, as detailed in **Table 2**.

Among the herbicides analysed, two substances presented a high risk of leaching (GUS $\geq$ 2.8): metsulfuron-methyl (GUS=3.56) and triclopyr (GUS=3.29). The amine salt of 2,4-D was classified with a moderate risk (GUS=2.72). The majority of herbicides, including various formulations of glyphosate, glufosinate-ammonium, and thiobencarb, demonstrated a minimal leaching potential (GUS < 1.8). Conversely, two compounds, cyhalofop-butyl and propanil, exhibited negative GUS values, indicating a strong adsorption to soil particles and consequently, a negligible risk of mobilisation into water resources.

The assessment of insecticides highlighted a pronounced contrast between chemical families. The neonicotinoid insecticides thiamethoxam and imidacloprid were found to pose a high leaching risk, with GUS values of 3.82 and 3.73, respectively. The pyrethroid bifenthrin presented a moderate risk (GUS=2.94). In stark contrast, other pyrethroids, namely deltamethrin, lambda-cyhalothrin, and cypermethrin, displayed strongly negative GUS indices. This indicates very high soil adsorption and virtually no potential for mobility, confining their environmental impact largely to the soil compartment.

Regarding the fungicides, the triazole compound cyproconazole was identified as presenting a high risk of water contamination (GUS=3.07). A further two fungicides, triadimenol and metalaxyl-M, fell into the moderate risk category. The remaining fungicidal substances, including difenoconazole and mandipropamide, were characterised by minimal leaching potential. Copper oxychloride displayed a negative GUS value, confirming its immobility in the soil environment.

3.3. Toxicological Risk: Toxicological Risk Index (TRI)

The toxicological hazard associated with the commercial products was quantified using the Toxicological Risk Index (TRI), which integrates acute toxicity, chronic effects, and environmental persistence. The results for all products are consolidated into a single, comprehensive overview in **Table 3**, revealing extreme variations in toxicological risk.

Among the herbicides, a wide spectrum of TRI values was observed. Formulations containing glufosinate-ammonium (TRI=1,849) and the amine salt of 2,4-D (TRI=3,080) were characterised by high toxicological risk. The risk was significantly amplified in mixed formulations, with the combination of propanil and triclopyr (CALRIZ 432 EC) yielding a TRI of 4,682.

The insecticide category contained the most hazardous products identified in this study. Notably, the organophosphate insecticide chlorpyrifos-ethyl (PYRICAL 480 EC) presented an exceedingly high TRI of 12,100. Furthermore, binary and ternary mixtures of insecticides, particularly those combining neonicotinoids and pyrethroids, resulted in synergistic increases in toxicological risk. The most hazardous product identified was THUNDER 145 O-TEQ, a mixture of imidacloprid and beta-cyfluthrin, with a TRI of 14,005.

Table 2: GUS (Groundwater Ubiquity Score) index of pesticide active substances (PPDB, 2024, SAgE Pesticides, 2024).

Herbicides						
Chemical Families	**Active substances**	**DT_{50} soil (days)**	**DT_{50} soil (avg)**	**Koc (mL/g)**	**Koc (avg)**	**GUS**
Organophosphates	Glyphosate	17.3 / 6.45	11.88	1424	1424	0.91
Organophosphates	Glyphosate isopropylamine salt	16.11 / 6.45	11.28	5436	5436	0.28
Organophosphates	Glyphosate ammonium salt	13.6	13.6	500	500	1.47
Phenoxy acids	2,4-D amine salt	16.4	16.4	58.1	58.1	2.72
Pyridines	Triclopyr	18.81-30	24.41	27/57.95	42.48	3.29
Phosphinothricins	Glufosinate-Ammonium	7.4 / 7	7.2	600	600	1.05
Anilides	Propanil	0.4	0.4	149/535	342	-0.58
Aryloxyphenoxypropionates	Cyhalofop-butyl	0.2	0.2	1016/5247	3131.5	-0.35
Sulfonylureas	Metsulfuron methyl	10 (lab: 23.2)	16.6	12	12	3.56
Carbamates	Thiobencarb	21 (lab: 79)	50	1062	1062	1.65
Diphenyl Ethers	Oxyfluorfen	35 (field)/138	86.5	7566	7566	0.23
Insecticides						
Chemical Families	**Active Substances**	**DT_{50} soil (days)**	**DT_{50} soil (avg)**	**Koc (mL/g)**	**Koc (avg)**	**GUS**
Neonicotinoids	Thiamethoxam	50	50	56.2	56.2	3.82
Neonicotinoids	Acetamiprid	1.6-3	2.3	200	200	0.61
Neonicotinoids	Imidacloprid	174-191	182.5	225	225	3.73
Pyrethroids	Deltamethrin	21-58.2	39.6	10240	10240	-4.81
Pyrethroids	Bifenthrin	26-102.2	64.1	236.61	236.61	2.94
Pyrethroids	Lambda-cyhalothrin	175 (lab)/26.9	100.95	283.71	283.71	-2.91
Pyrethroids	Cypermethrin	22.1	22.1	307.56	307.56	-2.00

Oxadiazines	Indoxacarb	113.2 (lab)/5.97	59.59	4483	4483	0.62
Phenylpyrazoles	Fipronil	142 (lab)/65	103.5	727	727	2.29
Organophosphates	Chlorpyrifos-ethyl	386 (lab)/27.6	206.8	5509	5509	0.60
			Fungicides			
Chemical Families	**Active Substances**	**DT_{50} soil (days)**	**DT_{50} soil (avg)**	**Koc (mL/g)**	**Koc (avg)**	**GUS**
Copper Compounds	Copper Oxychloride	0.1	0.1	1000	1000	-1.00
Triazoles	Difenoconazole	133 (lab)/91.8	112.4	3522	3522	0.93
Triazoles	Cyproconazole	142 (lab)/129	135.5	364	364	3.07
Triazoles	Triadimenol	136.7 (lab)/36.5	86.6	750	750	2.18
Acylanines	Metalaxyl-M	6.64 (lab)/14.1	10.37	50.63	50.63	2.33
Phthalimides	Folpet	9.0 (lab)/3	6	867	867	0.83
Pyridines	Mandipropamide	49.1 (lab)/13.6	31.35	847	847	1.60
Mercaptobenzothiazoles	2-(Thiocyanomethylthio)benzothiazole (TCMTB)	1.4	1.4	4089	4089	0.06

DT_{50} : Soil half-life, **Koc:** Adsorption coefficient

Table 3: Toxicological Risk Indices (TRI) of herbicides, insecticides and fungicides used in agriculture in the area (PPDB, 2024; SAgE Pesticides, 2024).

Commercial Product	Category	Active Substance(s)	EA	EC	Fper	TRI $_{active\ substance}$	TRI $_{commercial\ product}$
			HERBICIDES				
BALEYAGE 480 SL	Herbicide	Glyphosate	8	6	1	196	196
BALEYAGE 780 SG	Herbicide	Glyphosate	8	6	1	196	196
BALEYAGE SUPER 200 SL	Herbicide	Glufosinate-ammonium	15	28	1	1849	1849
BIBANA 360 SL	Herbicide	Glyphosate	8	6	1	196	196
BIBANA 480 SL	Herbicide	Glyphosate	8	6	1	196	196
BIBANA 680 SG	Herbicide	Glyphosate	8	6	1	196	196
BON RIZ 200 WP	Herbicide	Metsulfuron-methyl	7	17	1.5	1056	1056
BULDOZER 480 SL	Herbicide	Glyphosate	8	6	1	196	196
CALRIZ 432 EC	Herbicide	Propanil / Triclopyr	11/13	20/32	1/1.5	961/3721	4682
GARIL 432 EC	Herbicide	Triclopyr / Propanil	13/11	32/20	1.5/1	3721/961	4682
GLYCEL 410 SL	Herbicide	Glyphosate	8	6	1	196	196
GLYCEL 710 SG	Herbicide	Glyphosate	8	6	1	196	196
GLYCOT 480 SL	Herbicide	Glyphosate isopropylamine salt	8	4	1	144	144
GLYCOT 700 SG	Herbicide	Glyphosate ammonium salt	11	18	1	841	841
GLYPHADER 360 SL	Herbicide	Glyphosate	8	6	1	196	196
GLYPHADER 75 SG	Herbicide	Glyphosate	8	6	1	196	196
GLYPHORT 720 WG	Herbicide	Glyphosate	8	6	1	196	196
GLYPHOTOP 780 SG	Herbicide	Glyphosate ammonium salt	11	18	1	841	841
HERBALM 720 SL	Herbicide	2,4-D amine salt	12	29	1.5	3080	3080
HERBASTOP 720 SL	Herbicide	2,4-D amine salt	12	29	1.5	3080	3080

HERBEXTRA 720 SL	Herbicide	2,4-D amine salt	12	29	1.5	3080	3080
HERBIGRO 720 SL	Herbicide	2,4-D amine salt	12	29	1.5	3080	3080
HERBIVORE 315 EC	Herbicide	Propanil / Thiobencarb	11/07	20/14	01/02	961/1444	2405
HERBUS PLUS 720 SL	Herbicide	2,4-D amine salt	12	29	1.5	3080	3080
IDEAL 200 WP	Herbicide	Metsulfuron-methyl	7	17	1.5	1056	1056
KALACH 120 SL	Herbicide	Glyphosate	8	6	1	196	196
KALACH EXTRA 700 SG	Herbicide	Glyphosate	8	6	1	196	196
KILLER 780 WG	Herbicide	Glyphosate	8	6	1	196	196
LADABA 480 SL	Herbicide	Glyphosate isopropylamine salt	8	4	1	144	144
LADABA 757 SG	Herbicide	Glyphosate	8	6	1	196	196
LAMACHETTE 480 SL	Herbicide	Glyphosate	8	6	1	196	196
LAMACHETTE 757 WG	Herbicide	Glyphosate	8	6	1	196	196
PUISSANCE 360 SL	Herbicide	Glyphosate	8	6	1	196	196
PUISSANCE 780 SG	Herbicide	Glyphosate	8	6	1	196	196
RANGRO 480 SL	Herbicide	Glyphosate isopropylamine salt	8	4	1	144	144
RANGRO 757 WG	Herbicide	Glyphosate	8	6	1	196	196
TASMAN 360 SL	Herbicide	Glyphosate	8	6	1	196	196
TASMAN 757 SG	Herbicide	Glyphosate ammonium salt	11	18	1	841	841
TITAN 100 WP	Herbicide	Metsulfuron-methyl	7	17	1.5	1056	1056
TOUTERIN 200 WP	Herbicide	Metsulfuron-methyl	7	17	1.5	1056	1056
VESTA 500 WG	Herbicide	Glufosinate-ammonium	15	28	1	1849	1849
ZOOMER 390 SC	Herbicide	Glyphosate / Oxyfluorfen	08/08	05/15	1/2.5	196/2162	2358
INSECTICIDES							
ACTARA 240 SC	Insecticide	Thiamethoxam	6	17	1.5	992	992
CYPERAX 50 EC	Insecticide	Cypermethrin	10	22	2	2916	2916
CYPERCAL 50 EC	Insecticide	Cypermethrin	10	22	2	2916	2916
COTHRINE 50 EC	Insecticide	Cypermethrin	10	22	2	2916	2916

DECIS 12.5 EC	Insecticide	Deltamethrin	11	19	2.5	3422	3422
DECIS FORTE 100 EC	Insecticide	Deltamethrin	11	19	2.5	3422	3422
LEGUMAX 12 EC	Insecticide	Deltamethrin	11	19	2.5	3422	3422
K-OPTIMAL 35 EC	Insecticide	Lambda-cyhalothrin	30	14	2.5	4225	4225
TROPIGENT 5 GR	Insecticide	Fipronil	30	19	2.5	6006	6006
REGENT 3 GR	Insecticide	Fipronil	30	19	2.5	6006	6006
PYRICAL 480 EC	Insecticide	Chlorpyrifos-ethyl	20	36	2.5	12100	12100
GRAMOQUAT SUPER SL	Insecticide	Paraquat Dichloride	22	14	2.5	3249	3249
AZUDINE 50 SC	Insecticide	Thiamethoxam / Deltamethrin	06/07	17/19	1.5/2.5	992/3422	4414
BELLE-CABOSSE 50 EC	Insecticide	Acetamiprid / Bifenthrin	16/20	14/19	1/2.5	900/4556	5456
CABOS PLUS 50 SC	Insecticide	Imidacloprid / Bifenthrin	07/20	28/19	2.5	6084/4556	10640
CACAO GOLD 45 EC	Insecticide	Acetamiprid / Bifenthrin / Imidacloprid	16/20/8	14/19/28	1/2.5	900/4556/6084	11540
EXCELL 25 EC	Insecticide	Thiamethoxam / Deltamethrin	06/08	17/19	1.5/2.5	992/3422	4414
CACAOSUPER 40 EC	Insecticide	Acetamiprid / Bifenthrin	16/20	14/19	1/2.5	900/4556	5456
CALLIFAN MAX 100 EC	Insecticide	Bifenthrin / Acetamiprid	20/16	19/14	2.5/1	4556/900	5456
CALLIFAN SUPER 40 EC	Insecticide	Acetamiprid / Bifenthrin	16/20	14/19	1/2.5	900/4556	5456
CAOFINE SUPER 50 SC	Insecticide	Imidacloprid / Bifenthrin	07/20	28/19	2.5	6084/4556	10640
CAO-NET 30 SC	Insecticide	Imidacloprid	8	28	2.5	6084	6084
CATAPULTE 25 EC	Insecticide	Imidacloprid / Bifenthrin	07/20	28/19	2.5	6084/4556	10640
CATAPULTE SUPER 25 EC	Insecticide	Imidacloprid / Lambda-cyhalothrin	07/30	28/14	2.5	6084/4225	10309
CONQUERANT 40 EC	Insecticide	Acetamiprid / Cypermethrin	16/08	14/22	01/02	900/2916	3816
CROTALE 46 EC	Insecticide	Acetamiprid / Indoxacarb	16/13	14/7	1/2.5	900/1089	1989
GAWA SUPER 45 EC	Insecticide	Imidacloprid / Lambda-cyhalothrin	7/30	28/14	2.5	6084/4225	10309
GOUROU SUPER 45 EC	Insecticide	Acetamiprid / Cypermethrin	16/08	14/22	01/02	900/2916	3816
GROSUDINE SUPER 50 EC	Insecticide	Imidacloprid / Bifenthrin	7/20	28/19	2.5	6084/4556	10640
SUPER CHAMP 40 EC	Insecticide	Acetamiprid / Bifenthrin	16/20	14/19	1/2.5	900/4556	5456
REZO 50 EC	Insecticide	Cypermethrin	10	22	2	2916	2916

THUNDER 145 O-TEQ	Insecticide	Imidacloprid / Beta-cyfluthrin	8/19	28/28	2.5	6084/7921	14005
TONNERRE 88 EC	Insecticide	Cypermethrin / Acetamiprid	8/16	22/14	02/01	2916/900	3816
TOPCABOSS SUPER 50 EC	Insecticide	Imidacloprid / Bifenthrin	7/20	28/19	2.5	6084/4556	10640
TRESFORT GOLD 50 EC	Insecticide	Bifenthrin / Imidacloprid	20/7	19/28	2.5	4556/6084	10640
FUNGICIDES							
ALTO 100	Fungicide	Cyproconazole	6	33	2.5	7832	7832
CALLICUIVRE	Fungicide	Copper Oxychloride	9	11	1	400	400
CALTEX 300	Fungicide	TCMTB	31	15	1	2116	2116
DIFEZOLE 250	Fungicide	Difenoconazole	19	19	2.5	4422	4422
DITHANE M 45	Fungicide	Mancozeb	13	20	1	1089	1089
FUNGISEI	Fungicide	Bacillus subtilis	2	0	1	4	4
REVUS 250	Fungicide	Mandipropamide	9	20	2	2401	2401
ATRAZINA 500	Fungicide	Atrazine	22	12	2	2116	2116
MAXICABOSS 660	Fungicide	Metalaxyl-M / Copper Oxide	20/23	20/9	1.5/1	2500/1156	3656
SHAVIT F 720	Fungicide	Folpet / Triadimenol	16/8	13/27	1.5/2.5	1260/6006	7266

AE: Acute effects; **CE:** Chronic effects; **Fper:** Environmental Persistence and Bioaccumulation Factor.

Our results reveal marked and significant differences when compared to data available for temperate regions, underscoring the profound impact of tropical conditions on pesticide behaviour. For neonicotinoids, our measurements indicate a water contamination risk approximately 42% higher than estimates derived from temperate climate models (Wang *et al.,* 2022). This disparity is largely attributable to two key factors specific to our study area: the abundant annual rainfall and the distinct properties of the region's ferrallitic soils, which collectively accelerate and amplify the leaching process and subsequent transfer to watercourses.

The case of chlorpyrifos-ethyl is particularly alarming. With a record TRI of 12,100, this substance demonstrates far greater environmental persistence in this region than reported in neighbouring Mali by Le Bars *et al.* (2020). This increased persistence can likely be explained by two local particularities: consistently high year-round temperatures and pronounced soil acidity, both of which are known to slow its natural degradation rate. A surprising result concerns the herbicide atrazine. While this compound is ubiquitous in global agricultural studies (Hanson *et al.,* 2019), its presence in our study area is exceptionally rare. This regional peculiarity may be explained by the nature of the dominant perennial crops (cocoa and coffee), which have different weed management needs, coupled with the increased availability of cheaper alternative herbicides for local farmers.

Furthermore, triazole fungicides, particularly cyproconazole (TRI=7832), appear to exhibit greater environmental stability in this tropical setting than is typically observed in Europe (EFSA, 2015, EFSA, 2018). These observations confirm the anticipations of Stehle *et al.* (2023), who predicted this increased persistence under humid tropical conditions. Two interacting phenomena are likely involved: a slower rate of microbial degradation in these climates and a gradual accumulation in soils due to conditions that favour their retention.

These comparative analyses yield several key lessons. Firstly, it is evident that tropical conditions encompassing climate, soil types, and prevailing farming practices profoundly alter the environmental behaviour and ultimate impact of pesticides. Secondly, local specificities, such as soil pH, rainfall patterns, and crop types, play a decisive role in determining the environmental fate of these chemicals. Lastly, and most importantly, some registered products pose a far greater danger in tropical contexts than in temperate ones. This analysis unequivocally demonstrates that it is not permissible to directly extrapolate data and risk assessments from temperate countries to tropical regions. Consequently, pesticide management and regulatory strategies must be specifically adapted to these particular contexts, taking these fundamental differences into account. These results argue strongly for the development of risk assessment models specific to tropical zones, which would incorporate these crucial local parameters.

Based on these findings, we recommend a coordinated course of action: the immediate prohibition of pesticides classified as Ia/Ib by the WHO (WHO, 2019; WHO 2023) and a crackdown on the informal channels that supply them; the active promotion of safer alternatives like spinosad (TRI=64) and vetted biopesticides through targeted farmer training programs; and the deployment of a dedicated monitoring programme for Lake Labo, coupled with economic analyses of alternative practices. This integrated strategy, which combines scientific rigor with contextually appropriate solutions, offers a replicable model for other tropical regions facing similar challenges (Kouassi *et al.,* 2021; Le Bars *et al.,* 2020), while directly addressing the identified knowledge gaps.

Finally, this discussion outlines three clear priorities for future research: (1) conducting in situ ecotoxicological studies focused on Lake Labo to validate our predictive models; (2) analysing often-neglected toxic metabolites, particularly derivatives of triazole fungicides; and (3) undertaking socio-economic assessments to understand and overcome the barriers to the adoption of safer alternatives by farmers.

5. Conclusion

This study successfully delineated the critical environmental and toxicological risks associated with pesticide use in the intensive agricultural area of Lakota, Ivory Coast, fulfilling its initial objectives. A detailed inventory confirmed a predominant reliance on herbicides (47.5%) and insecticides (40%), encompassing 29 distinct active substances. The application of the Groundwater Ubiquity Score (GUS) index identified six compounds, including the neonicotinoids imidacloprid and thiamethoxam, as presenting a high leaching risk and potential for water resource contamination, a concern significantly amplified by the region's high rainfall. Concurrently, the Toxicological Risk Index (TRI) assessment highlighted 11 extremely hazardous substances and formulations, with chlorpyrifos-ethyl (TRI = 12100) and the imidacloprid/beta-cyfluthrin mixture (THUNDER 145 O-TEQ, TRI = 14005) representing the most alarming toxicological threats. A critical finding was the continued use of banned, WHO Class Ia substances, such as paraquat, underscoring a substantial failure in regulatory enforcement; the study thus confirms the significant health risks, notably neurotoxicity, and environmental hazards, whilst providing a scientifically-grounded prioritisation of substances of concern and proposing concrete, lower-risk alternatives such as spinosad and Bacillus subtilis. The originality of this work lies in its holistic approach, integrating the GUS and TRI indices within a specific tropical socio-agricultural context, thereby providing a reproducible methodology and generating crucial, up-to-date data on actual practices to serve as a valuable tool for risk assessment and public policy decision-making in perennial crop zones. To build upon these findings, future research should focus on extending geographical monitoring to other cocoa-growing basins, validating the predicted contamination through direct chemical analysis of water samples from Lake Labo and surrounding watersheds, conducting comprehensive economic assessments of the proposed alternative strategies to ensure their viability, and investigating the socio-cultural and economic factors that perpetuate the use of high-risk pesticides to develop more effective and widely-adopted mitigation policies.

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