# RISK ANALYSIS OF GROUNDWATER CONTAMINATION BY PESTICIDES USED IN OIL PALM CULTIVATION IN COLOMBIA

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## ABSTRACT

The expansion of oil palm cultivation in Colombia has increased the use of herbicides, insecticides, and fungicides with heterogeneous toxicological and environmental profiles. Given the importance of shallow aquifers in key palm-growing regions such as Meta, Santander, Casanare, and Magdalena Medio, assessing the potential for pesticide leaching into the subsurface is essential. This study evaluates the potential risk of groundwater contamination by calculating the Groundwater Ubiquity Score (GUS) and the Groundwater Screening Index (GSI) for 23 active ingredients used in Colombian oil palm production, based on physicochemical properties reported by ICA, Cenipalma, ANLA, and the PPDB. Results indicate that six compounds present a very high risk of groundwater contamination: imidacloprid, metalaxyl-M, carbendazim, atrazine, fipronil, and the azoxystrobin + cyproconazole mixture. Widely used herbicides such as glyphosate and paraquat exhibit low leaching potential according to both indices, although continued monitoring is warranted due to alternative transport pathways. These findings support the prioritization of active ingredients for monitoring in vulnerable areas and provide guidance for management strategies aimed at reducing risks to groundwater resources.

**Keywords:** Leaching; aquifers; Groundwater Ubiquity Score (GUS); Groundwater Screening Index (GSI); oil palm; Colombia.

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## INTRODUCTION

Colombia has become one of the leading global producers of oil palm (Elaeis guineensis), ranking fourth worldwide and first in the Americas, with extensive cultivated areas concentrated in the Eastern Plains, the Magdalena Medio region, and the northern Caribbean zone (FAOSTAT, 2023; FEDEPALMA, 2022). These production areas are characterized by sandy to sandy-loam soils and high annual rainfall, conditions that increase the vulnerability of shallow aquifers to contamination by highly mobile agrochemicals. Pest management in oil palm relies heavily on the application of herbicides such as glyphosate, oxyfluorfen, and diuron; insecticides including neonicotinoids, avermectins, and pyrethroids; and systemic fungicides such as triazoles, strobilurins, and acylalanines. The mobility and persistence of these active ingredients vary widely according to their physicochemical profiles, and international studies have shown that compounds such as imidacloprid, atrazine, carbendazim, and metalaxyl exhibit substantial vertical transport potential and have been detected in shallow groundwater in tropical agricultural systems (BONMATIN et al., 2015; BATTAGLIN et al., 2009; LOOS et al., 2010).

Early identification of the active ingredients with greater leaching potential requires screening tools capable of providing a preliminary assessment of vertical transport risk toward saturated zones. In this context, physicochemical-based indices such as the Groundwater Ubiquity Score (GUS), proposed by Gustafson (1989), and the Groundwater Screening Index (GSI), developed by Bishop (1986), have been widely used internationally to classify pesticides according to their likelihood of reaching groundwater, integrating parameters such as soil half-life, adsorption, solubility, and partitioning behavior. Considering the recent expansion of oil palm cultivation in Colombia and the growing concern regarding groundwater quality in production regions, the objective of this study was to evaluate the groundwater contamination risk associated with pesticides used in oil palm by calculating the GUS and GSI indices based on validated datasets from ICA, ANLA, Cenipalma, and the Pesticide Properties Database (PPDB, 2024).

## STUDY AREA

This study focused on pesticides currently registered and commonly used in oil palm (*Elaeis guineensis*) cultivation in Colombia. The country has approximately 609 thousand hectares planted

with oil palm, distributed across more than 160 municipalities in 21 departments (FEDEPALMA, 2024)., with major production zones located in the Eastern Plains, Magdalena Medio, the Caribbean region, and the Andean foothills (Figure 1).

Figure 1. General location of oil palm plantations in Colombia



The selection of active ingredients was based on the official registries of the Instituto Colombiano Agropecuario, which consolidates authorized phytosanitary products for oil palm (ICA, 2023), complemented with use reports submitted to the Autoridad Nacional de Licencias Ambientales (ANLA) and technical recommendations developed by Cenipalma. The final dataset included herbicides, insecticides, and fungicides representing the main chemical groups used in commercial oil palm production in Colombia (Table 1).

Table 1. Pesticides used in Colombian oil palm

| Class | Active ingredient | Chemical class | Toxicological class | Environmental hazard class | Typical application rate |
|---|---|---|---|---|---|
| Herbicide | Glyphosate | Substituted glycine | III | III | 2–4 L/ha |
| | Paraquat | Bipyridilium (bipyridyl) | II | I | 1.5–2.5 L/ha |
| | Atrazine | Triazine | III | II | 2–3 L/ha |
| | Diuron | Phenylurea | III | II | 1.5–3 kg/ha |
| | Oxyfluorfen | Diphenyl ether | III | II | 0.5–1 L/ha |
| | Haloxyfop-R-methyl | Aryloxyphenoxypropionate | III | III | 0.6–1.2 L/ha |
| | Flumioxazin | N-phenylphthalimide | III | II | 70–100 g/ha |
| Insecticide | Chlorpyrifos | Organophosphate | II | I | 1–2 L/ha |
| | Fipronil | Phenylpyrazole | II | I | 100–200 mL/ha |
| | Imidacloprid | Neonicotinoid | II | I | 0.2–0.5 L/ha |
| | Lambda-cyhalothrin | Pyrethroid | II | I | 50–100 mL/ha |
| | Teflubenzuron | Benzoylurea | III | II | 0.3–0.5 L/ha |
| | Lufenuron | Benzoylurea | III | II | 0.3–0.4 L/ha |
| | Diflubenzuron | Benzoylurea | III | II | 0.2–0.4 kg/ha |
| | Emamectin (Emamectin benzoate) | Avermectin | II | I | 60–120 g/ha |
| | Spinetoram | Spinosyn | III | II | 100–200 mL/ha |
| Fungicide | Azoxystrobin + Cyproconazole | Strobilurin + Azole | III | II | 0.3–0.5 L/ha |
| | Mancozeb | Dithiocarbamate | IV | II | 2–3 kg/ha |
| | Tebuconazole | Triazole | III | III | 0.5–1 L/ha |
| | Carbendazim | Benzimidazole | II | II | 0.5–1 L/ha |
| | Metalaxyl-M | Acylalanine | III | II | 0.5–1.5 kg/ha |
| Acaricide | Abamectin | Avermectin | II | I | 0.6–1 L/ha |
| | Propargite | Glycol sulfite | II | I | 1–2 L/ha |

*Toxicological classes follow the WHO classification of pesticide hazard (I–IV), where I represents highest acute toxicity and IV the lowest. Environmental hazard classes correspond to the ICA/ANLA categorization for ecological risk, where I indicates high environmental hazard and III a lower hazard level.*

## MATERIALS AND METHODS

### Data Sources

Physicochemical parameters required for the calculation of leaching indices were obtained from authoritative and publicly accessible sources. Water solubility (S), soil adsorption coefficient (Koc),

octanol–water partition coefficient (Kow), and soil half-life (t½) were retrieved primarily from the Pesticide Properties Database (PPDB, University of Hertfordshire), complemented when necessary by manufacturer technical sheets and ICA's national registry of phytosanitary products. All values used correspond to experimentally reported or regulatory-validated data.

**Groundwater Ubiquity Score (GUS)**

The potential leaching behavior of each pesticide was evaluated using the Groundwater Ubiquity Score (GUS) proposed by Gustafson (1989). The index is defined as:

$$GUS = Log_{10}(t_{1/2}) \cdot [4 - Log_{10}(K_{oc})] \quad (1)$$

where t½ represents the soil degradation half-life (days) and Koc the soil organic carbon adsorption coefficient (mL $g^{-1}$). Based on established thresholds, compounds were classified as:

Leachers (L): GUS > 2.8
Transition zone (T): 1.8 ≤ GUS ≤ 2.8
Non-leachers (NL): GUS < 1.8

This index provides a screening-level assessment of pesticide mobility and is widely used to identify substances with potential to reach groundwater.

**Groundwater Screening Index (GSI)**

To complement the GUS classification, the Groundwater Screening Index (GSI) developed by Bishop (1986) was calculated for all active ingredients. The index integrates water solubility, Kow, and degradation half-life to produce a semi-quantitative estimate of groundwater contamination potential. The final GSI values were categorized according to established interpretive thresholds:

$$GSI = LN\left(\frac{S \cdot t_{1/2}}{K_{ow}}\right) \quad (2)$$

Special Treatment (TE): GSI > 5
Probable Contaminant (PC/CP): intermediate values depending on chemical class
Low Concern (I or CI): GSI < threshold values indicative of low mobility or low persistence

This dual-index approach (GUS + GSI) provides complementary insights into mobility, persistence, and sorption–desorption behavior.

### Classification and Comparative Evaluation

Each pesticide was assigned to a risk category according to both indices. Concordance and divergence between GUS and GSI classifications were evaluated to identify compounds consistently associated with high groundwater vulnerability. The analysis emphasized compounds with (i) high solubility, (ii) low Koc, and (iii) long degradation half-life, particularly in regions where soils and climatic conditions favor vertical transport.

## RESULTS AND DISCUSSION

The analysis of the GUS and GSI indices (Table 2) showed that a specific subset of active ingredients used in oil palm exhibits a markedly elevated tendency to reach the subsurface domain. In particular, imidacloprid, metalaxyl-M, carbendazim, atrazine, and the azoxystrobin + cyproconazole mixture displayed GUS values above the leaching threshold and GSI values classified as requiring special treatment, reflecting the combination of high solubility, persistence, and low soil adsorption that characterizes these compounds. Fipronil was also included in this group due to its pronounced persistence, despite showing only moderate leaching potential according to the GUS index. Collectively, these physicochemical properties indicate that these active ingredients represent the highest potential risk to shallow aquifers in oil palm regions, particularly in areas with low-retention soils and high rainfall regimes.

Table 2. Physicochemical properties and groundwater contamination risk indices (GUS and GSI) for pesticides used in Colombian oil palm

| Active ingredient | S (mg $L^{-1}$) | Koc (mL $g^{-1}$) | ($K_{ow}$) | $t_{1/2}$ (dias) | GUS cal. | Interpretation | GSI cal. | Interpretation |
|---|---|---|---|---|---|---|---|---|
| Glyphosate | 10500 | 21699 | –3.2 | 17.3 | -0.417 | NL | I | I |
| Paraquat | 70000 | 1000000 | –4.5 | 1000 | -6.000 | NL | I | I |
| Atrazine | 33 | 300 | 2.7 | 75 | 2.855 | PL | 6.82 | TE |
| Diuron | 42 | 1800 | 2.9 | 146.6 | 1.613 | NL | 7.66 | TE |
| Oxyfluorfen | 0.2 | 12000 | 5.3 | 70 | -0.146 | NL | 0.97 | CI |
| Haloxyfop-R-methyl | 3.2 | 6000 | 4.3 | 35 | 0.343 | NL | 3.26 | CP |
| Flumioxazin | 1.79 | 5200 | 3.9 | 21.9 | 0.381 | NL | 2.31 | PC |
| Chlorpyrifos | 2 | 15000 | 4.96 | 120 | -0.366 | NL | 3.88 | CP |
| Fipronil | 3.78 | 12000 | 4.5 | 210 | -0.184 | NL | 5.17 | TE |
| Imidacloprid | 610 | 225 | 0.6 | 191 | 3.759 | PL | 12.18 | TE |
| Lambda-cyhalothrin | 0.01 | 300000 | 7 | 180 | -3.331 | NL | -1.36 | CI |
| Teflubenzuron | 0.00005 | 14000 | 5.5 | 29 | -0.214 | NL | -8.24 | CI |

| Active ingredient | S (mg $L^{-1}$) | Koc (mL $g^{-1}$) | ($K_{ow}$) | $t_{1/2}$ (dias) | GUS cal. | Interpretation | GSI cal. | Interpretation |
|---|---|---|---|---|---|---|---|---|
| Lufenuron | 0.04 | 30000 | 5.12 | 140 | -1.024 | NL | 0.09 | CI |
| Diflubenzuron | 0.08 | 25000 | 4.32 | 120 | -0.827 | NL | 0.80 | CI |
| Emamectin (Emamectin benzoate) | 0.024 | 20000 | 4.9 | 180 | -0.679 | NL | -0.13 | CI |
| Spinetoram | 0.046 | 50000 | 5 | 175 | -1.568 | NL | 0.48 | TE |
| Azoxystrobin + Cyproconazole | 10 | 500 | 3.7 | 150 | 2.831 | PL | 6.00 | TE |
| Mancozeb | 0.5 | 500 | - | 0.1 | -1.301 | NL | I | I |
| Tebuconazole | 36 | 1800 | 3.8 | 280 | 1.822 | T | 7.88 | TE |
| Carbendazim | 9.6 | 700 | 1.5 | 350 | 2.938 | PL | 7.71 | TE |
| Metalaxyl-M | 840 | 250 | 1.75 | 120 | 3.331 | PL | 10.96 | TE |
| Abamectin | 0.007 | 25000 | 4.8 | 200 | -0.916 | NL | -1.23 | CI |
| Propargite | 4 | 20000 | 4.4 | 120 | -0.626 | NL | 4.69 | CP |

*S: Water solubility; Koc: Organic carbon–water partition coefficient; log Kow: Octanol–water partition coefficient; $t_{1/2}$: Soil half-life; GUS: Groundwater Ubiquity Score; GSI: Groundwater Screening Index; NL: Non-leacher; PL: Probable leacher; T: Transitional leacher; CI: Contamination improbable; PC: Possible contamination; CP: Probable contaminant; TE: Special treatment (high risk); I: Undefined.*

The majority of the evaluated pesticides, in contrast, showed low values in both indices, indicating limited mobility within the soil profile. Compounds such as glyphosate, paraquat, oxyfluorfen, the benzoylureas, and pyrethroids exhibited high sorption, low solubility, or rapid degradation, which substantially reduces the likelihood of groundwater contamination through leaching processes. An intermediate group consisting of tebuconazole, diuron, and propargite displayed moderate persistence and contamination potential under specific soil and precipitation conditions, but did not reach the threshold values associated with the highest-risk compounds. Overall, the results clearly differentiate the active ingredients that should be prioritized in hydrological monitoring programs linked to oil palm cultivation in Colombia.

The risk patterns identified for imidacloprid, metalaxyl-M, carbendazim, and atrazine are consistent with international evidence documenting the mobility and persistence of these active ingredients in agricultural systems, where they have been detected in both surface and groundwater. For neonicotinoids, numerous studies have demonstrated their high solubility and low adsorption, conditions that enhance vertical transport and the frequent detection of these compounds in water bodies in intensively cultivated regions (BONMATIN et al., 2015). Atrazine is similarly recognized as one of the most commonly detected herbicides in hydrological monitoring due to its stability and slow degradation in soils (BATTAGLIN et al., 2009). Likewise, assessments conducted in European agricultural regions have shown that systemic fungicides such as carbendazim and highly soluble compounds such as metalaxyl can migrate through soil profiles and reach groundwater under sustained recharge conditions (LOOS et al., 2010), which supports the elevated GUS and GSI values obtained in this study. At the same time, the low mobility observed for glyphosate and paraquat aligns

with experimental evidence demonstrating their strong adsorption to mineral and organic soil fractions, which significantly reduces leaching in most agricultural scenarios (OKADA et al., 2016). Collectively, these results are consistent with the international literature and underscore the need to prioritize monitoring of systemic and persistent active ingredients in oil palm regions with vulnerable aquifers.

## CONCLUSIONS

- The GUS and GSI indices clearly identified a small subset of active ingredients (primarily imidacloprid, metalaxyl-M, carbendazim, atrazine, and the azoxystrobin + cyproconazole mixture) as presenting a high likelihood of reaching groundwater in Colombian oil palm regions. These compounds are characterized by high solubility, persistence, and limited sorption capacity, making them priority targets for monitoring programs in areas with shallow aquifers and soils of low retention capacity.
- Most of the evaluated pesticides exhibited low mobility and, consequently, a reduced leaching risk; however, several moderately persistent compounds such as diuron, tebuconazole, and propargite may pose risks under specific soil and rainfall conditions. Overall, the results highlight the need for differentiated management strategies, emphasizing the monitoring of systemic and persistent compounds to protect groundwater resources in the country's main oil palm-producing regions.

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