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ENVIRONMENTAL RISK OF HERBICIDES USED IN SOYBEAN CROPS IN MATO GROSSO

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Beatriz Aparecida Blanco Gonsales[1], Miriam Hiroko Inoue[2], Cleber Daniel de Goes Maciel[3], Ana Carolina Dias Guimarães[4], Kassio Ferreira Mendes[5], Malislene Lucas de Araujo[6] and Gabriel Casagrande Castro[7]

ABSTRACT

The intensive use of pesticides in agriculture, especially in Mato Grosso, raises concerns about environmental contamination. To minimize these impacts, evaluating how active ingredients (a.i.) interact with the environment is essential. The Environmental Risk Index (ARI) is a useful tool for quantifying these effects. Therefore, this study aimed to calculate the ARI of the herbicides most used in the state in weed management in the soy. The analysis was conducted based on the active ingredients (a.i.), using data from the Institute of Agricultural Defense of Mato Grosso. The physicochemical properties of the herbicides, essential for the calculations of the ARI, were obtained from three databases: (PPDB, PPD, and IBAMA). The parameters considered in the elaboration of the IRA included soil persistence, leaching, volatility, dose, and toxicological profile of the herbicides. The study pointed out 30 herbicides most used in soybean crops, with clethodin being the first in the ranking, with a total mass of 4,451,629kg of active ingredient (a.i.) sold in the analyzed period. The analysis showed that 20% of the herbicides present high environmental risk, especially trifluralin and acetochlor, due to their high persistence and toxicity to aquatic organisms. On the other hand, 80% have a lower impact, such as clethodim and fluazifop-p-butyl. The most commercialized herbicides were clethodim, glyphosate, and trifluralin. In addition, most had medium to high toxicity, requiring continuous monitoring. These results

[1] Master's student in Environment and Agricultural Production Systems
University of the State of Mato Grosso – UNEMAT
E-mail:biablancoo@hotmail.com
[2] PhD in Agronomy (Plant Production)
University of the State of Mato Grosso – UNEMAT
E-mail: miriam@unemat.br
[3] PhD in Agronomy (Agriculture)
State University of the Midwest (UNICENTRO)
E-mail: cmaciel@unicentro.br
[4] PhD in Plant Science
University of the State of Mato Grosso – UNEMAT
E-mail: acrdias@unemat.br
[5] PhD in Nuclear Energy Sciences in Agriculture
Center for Nuclear Energy in Agriculture – CENA/USP
E-mail: kassio_mendes_06@hotmail.com
[6] Master's student in Environment and Agricultural Production Systems
University of the State of Mato Grosso – UNEMAT
E-mail: malislene.araujo@unemat.br
[7] University of the State of Mato Grosso –
Professor Eugênio Carlos Stiler University Campus Tangará da Serra, Mato Grosso
E-mail:casagrandecdc@gmail.com

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reinforce the importance of more sustainable agricultural practices to reduce environmental impacts.

Keywords: Environmental contamination. Risk analysis. Pesticides. Glycine max.

INTRODUCTION

Brazil is considered the world's largest producer of soybeans, with an estimated production of 147.35 million tons in the 2023/24 harvest, which represents approximately 45% of all world production, which is 395.91 million tons, with a planted area of 45.98 million hectares and productivity of 3,205 kg $^{ha-1}$ (USDA/PSD, 2024; CONAB, 2024).

Mato Grosso is the main producer of soybeans in the country with production of 39.34 million tons in the 2023/24 harvest (CONAB, 2024), and is also considered the largest consumer of herbicides. Probably due to the great dependence on the use of these products for soybean cultivation added to the export-oriented agricultural production model adopted by the country, which was the main cause of the high proportions of use of these products (BELO, 2012).

Pesticides can pose a health hazard, affecting not only workers who have direct contact with these substances but also the general population. Environmental exposure is a problem that affects a large portion of society and is linked to the presence of pesticides in various environmental matrices. After application, these products are distributed among the plants, soil, water, and atmosphere. In soil, compounds can undergo processes such as evaporation, photolysis, surface runoff, adsorption, chemical or biological degradation, plant uptake, and leaching.

In this way, the soil becomes a significant contamination route for air and water. When they reach the atmosphere, pesticides are dispersed in the gaseous and particulate phases, depending on their physicochemical characteristics and environmental conditions. In the air, these pesticides can be subjected to photolysis and/or volatilization where they are carried by the wind long distances from the application site or deposited on the earth's surface through wet or dry deposition. These compounds can remain in the atmosphere for long periods, whether days, weeks or even months after their application, posing a risk to public health and the environment.

Contamination of surface and groundwater by pesticides is a globally recognized problem. These chemicals can reach water through rainfall and irrigation, which facilitate the leaching, runoff, and drainage of pesticides found in soil and crops. In addition, these substances are also present in sewage, whether treated or not, which becomes another significant route of pesticide entry into aquatic environments (MEDEROS et. al, 2021).

Monitoring pesticides in the environment is a crucial tool for assessing and controlling the environmental risks associated with the use of these products in real-world situations. In

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this sense, understanding the effects that pesticides can have on the environment through a toxicological analysis of pesticides is essential to guide decisions aimed at reducing negative impacts. The Environmental Risk Index (ARI) stands out as a way to assess the potential for harm of these substances, as it takes advantage of the information available in the literature on pesticide risk assessments on an individual basis, requiring only additional investigations to determine the impact of these molecules on the environment. Thus, the analysis of the risk associated with the use of pesticides, in the context of integrated weed management, seeks to minimize damage to the ecosystem and increase the effectiveness and durability of the production system. Pesticides have the potential to impact not only cultivated plants and those growing outdoors but also the microorganisms present in the soil (ZALLER, BRÜHL, 2019). These data are extremely valuable for the development of weed management strategies, contributing to the choice of active ingredients to be employed.

The purpose of the IRA, as presented, is to provide information on the main pesticides used in soybean crops, which should be prioritized in future research. The present work aims to determine the Environmental Risk Index of herbicides used in soybean crops to assist in decision-making in agricultural operations and to minimize the impacts caused by these products on the environment.

MATERIAL AND METHODS

PESTICIDE DATA COLLECTION

Data were collected on herbicides registered for soybean crops at the Mato Grosso Institute for Agricultural Defense (INDEA) for the years 2021, 2022, and 2023. The physicochemical properties of herbicides used on soybeans were obtained in 2024 from the Pesticide Properties Database (PPDB) of the University of Hertfordshire, England, from the Pesticide Properties Database (PPD) of the U.S. Department of Agriculture, and the IBAMA Pesticide Database (LEWIS et al., 2016; USDA, 2023; IBAMA, 2024). Each parameter is presented in the following topics.

ENVIRONMENTAL RISK INDEX (ARI)

To estimate the potential hazard of pesticides, several factors were considered, such as water solubility, soil persistence, adsorption capacity, solubility in organic solvents, and mechanical and toxicological properties. Based on the data collected from the database regarding these factors, an ecological risk assessment can be carried out for each herbicide.

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In this evaluation, a simple linear equation of the Environmental Risk Index (ARI) was used, as described by Alister and Kogan (2006). Each parameter is presented in the following topics.

Table 1. Equations used to construct the Environmental Risk Index (ARI).

Parameter	Equation	Description
Persistence (P)	**K = 0.693/DT50** (1)	**K**: Degradation rate per day. **DT50**: half-life dissipation time, persistence **0.693**: Constant of proportionality.
Leaching (L)	**LIX = e (- k. Koc)**(2)	**K**: Constant of proportionality (Equation 2) **Koc**: Sorption coefficient normalized concerning the organic carbon content of soils.
Volatilization (V)	**V = 2.9 x 10-3 P M0.5** (3)	**P**: Steam pressure **M**: pesticide molecular weight
Risk Index Environmental (IRA)	**IRA = (P+L+V+TP) D** (4)	**Q:** Persistence **L:** Leaching **V:** Volatilization **Toxicology** profile **D:** Dose
Toxicological Profile (EN)	**PT= Kow + Rfd + DL50 + TA (5)**	**Kow:** Octanol-water partition coefficient **Rfd**: Reference Dose **LD50**: Acute lethal dose for humans **TA:** Animal toxicology

Source: Adapted from Alister and Kogan (2006).

PERSISTENCE

Persistence refers to the time required, in days, for 50% of the initial pesticide to be degraded (SAMGHANI, HOSSEINFATEMI, 2016). The T50 of a soil herbicide can be influenced by several factors, such as moisture, precipitation, temperature, and internal soil properties, among others. This parameter is considered a simplified estimate due to the complexity of soil-environment-pesticide interactions. It is presented in Chart 1.

Leaching

A significant proportion of the pesticides used do not reach their target directly but are deposited in the soil, either directly or indirectly. As soon as they enter the soil, the used products begin the process of redistribution and decomposition, which can happen quickly or take months or even years. The activity of pesticides in the environment is influenced by

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transport, storage, and/or transformation processes, which interact with each other, although they are often analyzed separately. Losses due to sedimentation, drift, flooding, and surface and underground flows are examples of transport mechanisms. In these cases, although the herbicide does not lose its cytotoxic activity, it is still transferred from one substrate to another in the environment. Such transfers could lead to the accumulation of products in nearby sensitive plants, in the atmosphere, and/or in water bodies in surface and underground layers (CORREIA, 2018).

The leaching potential of a product can be classified as low (≤ 0.09), medium (0.09 ≤ 0.25), high (0.25 ≤ 0.5), and very high (≥ 0.5) as shown in Table 2.

Volatilization

Volatilization is characterized by the process in which the pesticide is directed to the desired area but ends up evaporating into the atmosphere in a gaseous state, being taken out of place.

(MUELLER, 2015). Pesticide volatility is directly related to the relative humidity of the air and soil, as well as surface temperature, and is not affected by minerals, organic matter content, and soil pH (DA COSTA et al., 2016). The vapor pressure of pesticides, their chemical properties, composition, and molecular weight determine the distribution of the constituent that will volatilize or be incorporated into the soil; however, the higher the vapor pressure, the higher the rate of evolution (PIRES et al., 2022). Pesticide volatilization can be calculated as the rate of field loss using a simple formula proposed by Alister and Kogan (2006). (Table 1).

Servings

The amount of active ingredient applied to the intended environmental target, known as dosage, plays an important role. The greater the amount used, the greater the amount of chemicals in the pesticide, increasing the risk of soil and water pollution (ALISTER, KOGAN, 2006). In addition, the volume affects the various components of the Environmental Risk Index (ARI). Even if two pesticides have the same LD50, the one with the highest dose applied will have a higher risk of absorption.

With the above, for the calculation of the Environmental Risk Index (ARI), the maximum allowed dose of the herbicide was used for weed control in soybean crops, instead

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of considering several different dosages (Table 1). This approach simplifies the analysis and ensures that the results reflect the worst possible situation in terms of environmental risk.

Table 1. Degree of severity, assigned values, and intervals proposed by Alister & Kogan (2006) for each term of the Environmental Risk Index.

Degree of severity		Sorting of intervals				
Category	Assigned values	Persistence (P) (DT50, days)	Dose (D) (kg Ia/$^{ha-1}$)	Leaching (L) LIX Index	Volatility (V) (mmHg)	Toxicological Profile (TP)
Low	1	≤ 30	≤ 1	≤ 0.09	≤ 10 $^{-6}$	≤ 8
Medium	2	30 ≤ 60	1 ≤ 2	0.09 ≤ 0.25	10-6 $^{-5}$ ≤ 10	8 ≤ 14
High	3	60 < 90	2 < 3	0.25 < 0.5	$^{10-5}$ < 10-4	14 < 20
Very high	4	≥ 90	≥ 4	≥ 0.5	≥ 10 $^{-4}$	≥ 20

Source: Adapted from Alister & Kogan. (2006).

Toxicological Profile

Toxicological profiling (PT) is an analysis of the impact that a specific pesticide can exert on a living community within an ecosystem. This analysis considers crucial factors such as the estimate of Kow, Rfd, LD50, and animal toxicology (TA). The PT values can vary between 6 and 24 and the Environmental Risk Index (ARI) has a theoretical range from 4 to 64 (ALISTER, KOGAN, 2006).

The octanol-water (Kow) partition coefficient is a measure that quantifies the affinity of a molecule for the nonpolar phase (octanol) and the polar phase (water). Octanol is a substitute for lipids found in living organisms, and polarity, functional group atoms, and the symmetry of molecules positively influence solubility in water.

The reference dose (Rfd) is a risk assessment parameter, reflecting the daily amount of exposure that a human being can tolerate without compromising health. The lethal dose (LD50) represents the amount of a chemical substance that, under controlled conditions, is sufficient to reduce by 50% the population of animals that received the pesticide administration. For each of these factors, values ranging from 1 to 4 were assigned, corresponding to levels classified as low, medium, high, and very high, respectively, as shown in Table 2.

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Table 2. Degree of pesticide severity, assigned values, and intervals for each Toxicological Profile term.

Degree of severity and values assigned		Sorting of intervals					
		Kow Log Kow	Rfd kg-1 mg-1 day-1	DL50 kg-1 mg	CL50 Ave L-1 mg	DL50 Beeμg ab-1	CL50 Fishmg L-1
Low	1	≤ 1	≥ 0.1	≥ 4000	≥ 5000	≥ 100	≥ 100
Medium	2	1 ≤ 2	0.1 ≥ 0.01	4000 ≥ 400	5000 ≥ 500	100 ≥ 50	100 ≥ 50
High	3	2 > 3	0.01 > 0.001	400 > 40	500 > 50	50 > 25	50 > 10
Very high	4	≥ 3	≤ 0.001	≤ 40	≤ 50	≤ 25	≤ 10

Source: Adapted from Alister and Kogan. (2006). The bird refers *to Anas platyrhynchor / Colinus Virginia*, the bee to *Apis* spp., fish to *Oncorhynchus mykiss / Lepomis macrochirus*.

RESULTS AND DISCUSSION

Among the herbicides used in soybean crops in the three years analyzed (2021, 2022, 2023), data were collected on 30 active ingredients, present in 15 chemical groups and 9 modes of action. It is observed that four herbicides stood out in terms of commercialization volume in this period: clethodim, glyphosate, trifluralin, and clomazone (4.4 million, 2.2 million, 2.1 million, and 1.1 million kg/a.i.), respectively, together representing approximately 87% of the total herbicides commercialized in the state of Mato Grosso in this period (INDEA, 2024).

The herbicides presented in Table 3 show that of the a.i. Used, 60% (acetochlor, alachlor, butroxydim, clomazone, cyanazine, fenoxaprop-p-ethyl, fluazifop-p-buthyl, flumetsulam, flumiclorac-penthyl, fomesafen, haloxyfop-methyl, imazamox, imazaquin, lactofen, metribuzin, pendimethalin, propaquizafop, quizalofop-p-terfuryl, sulfentrazone, trifluralin) classified as type II, considered very dangerous with high toxicity to aquatic animal algae, while 33.33% (bentazone, chlorimuron-ethyl, clethodim, chloransulam-methyl, flumioxazin, glyphosate, imazethapyr, pyroxasulfone, sethoxydim) are in class III, dangerous and highly toxic to microscopic crustaceans, fish and bees (AGROFIT, 2023). In addition, a great dependence on Glyphosate and ACCase and PROTOX inhibitors is evident, which together represent most of the volume applied.

Regarding the physicochemical properties of herbicides, the highest degradation rate (T50) is for haloxyfop-methyl, which presented 0.5 days for half of the amount initially applied to be dissolved by half in the environment. On the other hand, the lowest degradation rate was that of imazethapyr with a 50-day T4D (Table 4). According to Carvalho (2013), T50 < 30 days classifies pesticides as unstable, 30 to 100 moderate persistence, 100 to 365 days and T50> 365 days indicate very durable pesticides.

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Table 3. Herbicides used in the state of Mato Grosso in the years 2021, 2022 and 2023 to control weeds in soybean crops.

Active Ingredient (a.i.)	Mode of Action	Environmental Rating*	2021	2022	2023	Total
			Total Mass**	Total Mass**	Total Mass**	Total Mass**
			kg i.a.	kg i.a.	kg i.a.	kg i.a.
Acetochlor	Cell Division	II	1	1	1	3
Alachlor	Cell Division	II	1	1	1	3
Bentazone	FS II	III	15.201	18712.2	8302.8	15.201
Butroxydim	ACCase	II	1	1	1	3
Chlorimuron-ethyl	ALS	III	78.756	94.230	66.326	239.312
Clethodim	ACCase	III	1.273.868	1.358.024	1.819.737	4.451.629
Clomazone	Carotenoids	II	263.038	537.661	368068	1.168.767
Chloransulam-methyl	ALS	II	22.614	73.290	34.823	130.727
Cyanazine	FS II	II	14	19	19	52
Fenoxaprop-p-ethyl	ACCase	II	10.169	6.041	2.889	19.099
Fluazifop-p-buthyl	ACCase	II	2.379	554	3450	6.383
Flumetsulam	ALS	III	6.436	878	9175	16.489
Flumiclorac – penthyl	PROTOX	II	43.862	31.055	22728	97.645
Flumioxazin	PROTOX	III	155.685	189.911	262.102	607.698
Fomesafen	PROTOX	II	108.192	91.686	138.325	338.203
Glyphosate	EPSP	III	728.590	945.286	526.247	2.200.123
Haloxyfop-methyl	ACCase	I	279.901	433.570	283.930	997.401
Imazamox	ALS	III	14	14	102	130
Imazaquin	ALS	III	150	3	16	169
Imazethapyr	ALS	III	145.347	176.745	97092	419.184
Lactofen	PROTOX	II	20.429	5.922	194	26.545
Metribuzin	FS II	II	2.913	469	21375	24.757
Oryzalin	Microtubules	I	1	1	1	3
Pendimethalin	Microtubules	II	3.836	5.609	28.387	37.832
Propaquizafop	ACCase	II	1	1	1	3
Pyroxasulfone	Mitosis	III	1.179	16.346	33.720	51.245
Quizalofop-P-terfuryl	ACCase	II	24.464	24.015	17452	65.931
Sethoxydim	ACCase	III	1	1	1	3
Sulfentrazone	PROTOX	II	67.390	113.233	59702	240.325
Trifluralin	Microtubules	II	722.868	1.007.430	380257	2.110.555
Total			3.247.532	4.150.365	3.616.155	11.014.052

* Data obtained from the Institute of Agricultural Defense of Mato Grosso – INDEA. ** Environmental classification according to the registration of formulated products (Agrofit – MAPA). ACCase = inhibition of aceti – CoA carboxylase; carotenoids = inhibition of carotenoid biosynthesis; microtubules = inhibition of microtubule formation; FS I = inhibition of photosynthesis in photosyntem. FS II = inhibition of photosynthesis in photosynthema II; PROTOX = inhibition of protoporphyrinogen oxidase; lipids = inhibition of lipid synthesis; mitosis = inhibition of mitosis; ALS = inhibition of acetolactate synthase; auxins = auxin mimics; cellulose = inhibition of cellulose biosynthesis; EPSPs = glycine replaced;

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Therefore, 43.33% of the herbicides analyzed act as chronic (T50 <30 days). About 30% were considered persistent at moderate levels (T50 > 30 and < 100 days), being they chlorimuron-ethyl, fomesafem, flumetsulam, flumiclorac-penthyl, oryzalin and propaquizafop. While trifluralin, sulfentrazone, pendimethalin, imazaquin, and imazamox account for 16.67% and are classified as highly durable in soil, with a T50 greater than 100 days (Table 4). In the case of sulfentrazone and imazetapyr, it took 400 and 513 days, respectively, to reduce the concentration by half.

About the adsorption coefficient of the organic carbon content - CO (Koc) (Table 4) it represents the absorption capacity of pesticides in the soil. When this value is high, the adsorption capacity will be high, so pesticides with high Koc content are difficult to dissolve in water and can be transported by sediments out of the water (GUARDA et al., 2020). The information on herbicides was tabulated according to the Pesticide Chemical Database published by Lewis et al. (2016), in which they classified Koc < 15 as highly mobile, 15 - 75 mobile, 75 - 500 moderately mobile, 500 - 4,000 slow and > 4,000 immobile, based on their retention. Thus, 60% are of considerable movement, 20% are of slow movement and 6.7% of the herbicides were classified as dynamic immobile.

Table 4. Physicochemical properties of herbicides used in soybean crops to calculate the Environmental Risk Index - ARI.

Herbicide	*DT50 a*	Koca	Kb	Vapor Pressure^{at}	Table of Contents	Dosed	*SW*	Classification	pka	Ionization
(a.i.)	(days)	(mg $^{g-1}$)	(1 day)	(mmHg)	LIX	(kg a.i./ha)	(mg $^{L-1}$)	*SW*		
Acetochlor	14	156	0,04950	2.2 X $^{10-02}$	0,0000	3,60	282	Moderate	-	-
Alachlor	14	335	0,04950	2.9 x 101	0,0000	3,36	240	Moderate	0,62	Strong Acid
Bentazone	20	55.3	0,03465	1.7 x 10-2	0,0000	1,20	7112	Discharge	3,51	Weak Acid
Butroxydim	9	635	0,07700	1.0 x 10-3	0,0000	0,94	6,9	Low	4,36	Weak Acid
Chlorimuron-ethyl	40	106	0,01733	14.9 x 10-7	0,0024	0,2	1200	Discharge	4,2	Weak Acid
Clethodim	0,55	-	1,26000	1.33 x 10-5	-	0,11	5450	Discharge	4,47	Weak Acid
Clomazone	22,6	300	0,03066	1.92 x 10-2	0,0000	1,25	1212	Discharge	n/a	Non-ionizable
Chloransulam-methyl	15	30	0,04620	1.3 x 10-5	0,2501	0,04	184	Moderate	4,81	Weak Acid
Cyanazine	16	190	0,04331	2.13 x 10-4	0,0000	1,70	171	Moderate	12,9	Very Strong Acid
Fenoxaprop-p-ethyl	0,36	11354	1,92500	5.4 x 10-5	0,0000	0,16	0,43	Low	0,18	Very Strong

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										Acid
Fluazifop-p-buthyl	15	3000	0,04620	5.3 x 10-7	0,0000	0,19	1	Low	0,0	-
Flumetsulam	45	28	0,01540	3.70 x 10-7	0,2815	0,35	5650	Discharge	4,6	Weak Acid
Flumiclorac-penthyl	45	30	0,01540	1.6 x $^{10-14}$	0,0000	0,06	0,189	Low	-	Non-ionizable
Flumioxazin	21,9	889	0,03164	3.21 x 10-4	0,0000	0,05	0,786	Low	n/a	No Dissociation
Fomesafem	86	50	0,00806	1.33 x 10-5	0,0000	0,38	50	Moderate	2,83	Strong Acid
Glyphosate	16,11	1424	0,04302	2.45 x 10-8	0,0000	2,40	100000	Discharge	2,34	Weak Acid
Haloxifop-methyl	0,5	47	1,38600	1.7 x 10-5	0,0000	0,06	7,9	Low	n/a	No Dissociation
Imazamox	200,2	-	0,00346	6.3 x 10-8	0,0000	0,42	626000	Discharge	2,3	Strong Acid
Imazaquim	106,6	20	0,00650	1.9 x 10-5	0,8781	0,15	102000	Discharge	3,45	Weak Acid
Imazethapyr	513	52	0,00135	1.3 x 10-5	0,9322	0,4	1400	Discharge	2,1	Weak Acid
Lactofem	4	10000	0,17325	2.4 x 10-6	0,0000	0,18	0,5	Low	-	Non-ionizable
Metribuzin	7,03	60	0,09858	1.6 x 10-5	0,0027	0,72	10700	Discharge	1,3	Strong Acid
Oryzalin	44,8	949	0,01547	1.1 x 10-7	0,3490	1,54	1,13	Low	9,2	Very weak acid
Pendimethalin	182,3	17491	0,00380	1.33 x 10-5	0,0000	1,60	0,33	Low	2,8	Strong Acid
Propaquizafop	70	306	0,00990	1.0 x 10-5	0,0483	0,0075	0,63	Low	n/a	No Dissociation
Pyroxasulfone	22	223	0,03150	3.0 x 10-06	0,0009	0,15	3,49	Low	-	Non-ionizable
Quizalofop-P-terfuryl	0,4	510	1,73250	4.0 x 10-5	0,0000	0,08	0,61	Low	n/a	No Dissociation
Sethoxydim	1,2	75	0,57750	1.3 x 10-2	0,3515	0,0018	4700	Discharge	4,58	Weak Acid
Sulfentrazone	400	43	0,00173	1.07 x 10-7	0,9280	0,60	780	Discharge	6,56	Weak Acid
Trifluralin	133,7	15800	0,00518	1.47 x 10-2	0,0000	1,07	0,221	Low	n/a	Non-ionizable

Legend: [a] - Average values obtained from the *Pesticide Properties DataBase* (PPDB) of the *University of Hertfordshire* and the *Pesticide Properties Data base* of the US Department of Agriculture (ARS).b - Values calculated from the DT50 according to Equation (1) [*K = 0.693/DT50]*.c - Leaching index calculated according to Equation (2) [*LIX = e* $^{(-\ k.\ Koc)}$].d - Maximum dose used for weed control. * Solubility classification according to the *Pesticide Properties Database* (PPDB) of the University of Hertfordshire, where ≤ 50 mg *L-1* = low; 50 – 500 mg $^{L-1}$ = moderate; > 500 = high solubility.

Regarding the ionization of the herbicides analyzed, 3 herbicides were classified as very strong acid, representing 10% of the total. Most of it, 36.67%, is classified as weak acid,

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16.67% as strong acid, and only 1 herbicide (lacofem) is non-ionized. For herbicides that separate from weak acids and weak bases, especially at pH below or above pKa, the higher the pH value, the lower the absorption capacity of the herbicide in the soil, which can affect the leaching potential (OLIVEIRA JR et al. 2022).

In this sense, pKa is the pH value at which the compound is 50% ionized, expressed as the value at which the non-ionized and ionized fractions are in equilibrium. According to Oliveira Jr. (2022), acidic pesticides can be considered strong if the pKa is less than 3.0; weak if the pKa is between 3.0 and 9.0; and very weak if the pKa is higher than 9.0. For bases, the strong pKa is greater than 9.0; weak from 3.0 to 9.0 and very weak pKa below 3.0.

The daily degradation rate (K) is inversely proportional to the T50, i.e., the lower the T50, the higher the K and vice versa. Therefore, the lowest decomposition rates were associated with the most persistent herbicides in the soil, such as imazethapyr and sulfentrazone, followed by pendimetalin and trifluralin.

The vapour pressure (PV) (mmHg) of the herbicide varies by orders of magnitude from 10^{-2} (for trifluralin and clomazone) to 10^{-14} (for flumiclorac-pentyl). PV indicates the pesticide's volatility and its propensity to disperse into the atmosphere after application. Herbicides with high PV ($>10^{-2}$ mmHg) have high volatility and, therefore, a higher probability of movement in the environment (DE OLIVEIRA, 2018). According to Alves (2008), products with PV $>10^{-2}$ have high volatility; from 10^{-4} to 10^{-3}, moderate volatility; from 10^{-7} to 10^{-5}, mild volatility; and no dynamic volatility $<10^{-8}$. Of the herbicides used in the state of Mato Grosso, only 25% are classified as highly volatile or volatile, namely acetochloro, alachlor, bentazon, clomazone, sethoxydim and trifluralin.

Therefore, the lower the PV value, the less likely the pesticide will volatilize. However, at elevated temperatures (above 30°C), even pesticides with low volatility can experience some dispersion. In this situation, most of the active ingredients (a.i.) researched and used in the state have low volatility, according to data available in the literature on PV at 20°C, such as chlorimuron-ethyl, clethodim, chloransulam-methyl, fenoxaprop-p-ethyl, fluazifop-p-buthyl, flumiclorac-penthyl, fomesafem, glyphosate, haloxifop-methyl, imazamox, imazaquim, imazethapyr, lactofem, metribuzin, oryzalin, pendimethalin, propaquizafop, quizalofop-P-terfuryl, and sulfentrazone (DE PAULA et al., 2021).

Among the herbicides most used in soybean cultivation areas, those that require higher doses (D) per hectare are acetochlor (3.60), alachlor (3.36), bentazon (1.20),

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clomazone (1.25), cyanazine (1.70), glyphosate (2.4), oryzalin (1.54), pendimethalin (1.60) and trifluralin (1.07).

In addition to the physicochemical properties, herbicide toxicity parameters were also collected, including Kow, reference dose (Rfd), lethal dose (LD_{50}) and animal toxicity (TA), and the data are presented in Table 5. From this set of information, a toxicity profile (PT) was created (Table 6), which will be discussed below and used in the Environmental Risk Index (ARI).

Table 5. Ecotoxicological parameters* of herbicides used for soybean in the state of Mato Grosso in the years 2021, 2022 and 2023

				Animal Toxicology (TA)		
Active ingredient	Log*	*DL50**	*Rfd**	Avea	Beeb	Fishfish
(a.i.)	*Kow*	kg-1 mg Day-1	Dermal kg-1 mg	*DL50** kg-1 mg	*CL50** µg ab-1	*DL50** L-1 mg
Acetochlor	4,14	1929	0,0036	928	200,00	0,36
Alachlor	3.09	930	-	1536	16,00	1,80
Bentazone	-4,46	1400	0,0900	1140	200,00	100,00
Butroxydim	1,90	1635	-	2000	200,00	6,90
Chlorimuron-ethyl	0,11	2000	-	5620	12,50	8,40
Clethodim	4,14	4167	0,1600	1640	51,00	25,00
Clomazone	2,58	2000	0,1300	2224	89,50	14,40
Chloransulam-methyl	-0,36	2000	-	5620	100,00	86,00
Cyanazine	2,10	288	-	400	100,00	10,00
Fenoxaprop-p-ethyl	4,58	2000	0,1000	2000	63,00	0,19
Fluazifop-p-buthyl	4,50	2420	0,0170	17000	76,00	0,53
Flumetsulam	0,21	5000	-	2250	100,00	300,00
Flumiclorac-penthyl	4,99	2000	-	2250	100,00	1,10
Flumioxazin	2,55	2000	0,0500	2250	200,00	2,30
Fomesafem	-1,20	1000	-	5000	50,00	170,00
Glyphosate	-1,60	2000	0,5000	2000	100,00	100,00
Haloxifop-methyl	4,00	2000	0,0700	1159	100,00	0,08
Imazamox	-2,90	5000	3,0000	1846	58,00	122,00
Imazaquim	-1,09	5000	0,2500	2150	36,40	100,00
Imazethapyr	1,49	2000	-	2150	100,00	340,00
Lactofem	-	2000	0,0000	2150	100,00	0,10
Metribuzin	1,75	5000	0,0200	164	100,00	74,60
Oryzalin	3,75	5000	0,0500	427	40,80	2,86
Pendimethalin	5,40	5000	0,3000	1421	196,00	0,19
Propaquizafop	4,78	5000	0,0100	2000	200,00	0,19

Pyroxasulfone	2,39	2000	-	2250	105,00	2,20
Quizalofop-ethyl	4,61	5000	0,1000	2000	100,00	0,21
Sethoxydim	1,65	2676	-	5000	10,00	170,00
Sulfentrazone	0,99	2000	-	2250	25,10	93,80
Trifluralin	5,27	2000	0,0200	2250	100,00	0,08

*Figures were obtained from the *Pesticide Properties DataBase* (PPDB) of the University of Hertfordshire and the *Pesticide Properties Database* (PPD) of the U.S. Department of Agriculture. [a] - refers to *Colinus virginiaus / Anas platyrhynchor*; [b] - refers to *Oncorhynchus mykiss / Lepomis macrochirus*; [c] - refers to *Apis* spp.

Glyphosate (10), acetochlor (16), alachlor (18), trifluralin (15), fenoxaprop-p-ethyl (15) and haloxyfop-methyl (15) recorded the highest PT values, indicating the highest animal toxicity among the herbicides analyzed. This result is related to the high Log Kow, which indicates a high risk of bioaccumulation (4), except for flumioxazin, which exhibits moderate bioaccumulative risk (3) and high toxicity to fish, bees (4) and birds (2).

Bioaccumulation is influenced by the Log Kow of the active ingredients; thus, herbicides with low Log Kow have a high affinity for water, are hydrophilic and have greater solubility, while herbicides with high Log Kow are hydrophobic and have greater potential for bioaccumulation (MERCADO-BORRAYO et al., 2015). According to Duchowicz (2019), compounds with Log Kow values ≥ 3 tend to avoid water and are highly lipophilic, facilitating absorption by animals or accumulation in the soil.

Table 6. Toxicological profile (TP)* of herbicides used in soybean cultivation constructed from ecotoxicological parameters.

Group	Active Ingredient	Log	Rfd	DL50	Bird	Fish	Bee	EN
Chloroacetamide	Acetochlor	4	2	3	2	1	4	16
Chloroacetamide	Alachlor	4	2	2	2	4	4	18
Benzotiadiazines	Bentazone	1	2	2	2	1	1	9
Cyclohexanedione	Butroxydim	2	2	2	2	1	4	13
Sulfonylureas	Chlorimuron-ethyl	1	2	1	1	4	4	13
Cyclohexanedione	Clethodim	4	1	1	2	2	3	13
Isoxazolidinone	Clomazone	3	2	1	2	2	3	13
Triazolopirimidines	Chloransulam-methyl	1	2	1	1	1	2	8
Triazine	Cyanazine	3	3	3	3	1	4	17
Antioxyphenoxypropionic acid	Fenoxaprop-p-ethyl	4	2	1	2	2	4	15
Antioxyphenoxypropionic acid	Fluazifop-p-buthyl	4	2	1	1	2	4	14
Triazolopirimidines	Flumetsulam	1	1	2	2	1	1	8
N-phenylethanamides	Flumiclorac-penthyl	4	2	2	2	1	4	15
N-phenylethanamides	Flumioxazin	3	2	2	2	1	4	14
Diphenyl ether	Fomesafen	1	2	1	1	2	1	8
Glycine substituted	Glyphosate	1	1	4	2	1	1	10

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Antioxyphenoxypropionic acid	Haloxyfop-methyl	4	2	2	2	1	4	15
Imidazolinone	Imazamox	1	1	1	2	2	1	8
Imidazolinone	Imazaquin	1	1	1	2	3	1	9
Imidazolinone	Imazethapyr	2	2	2	2	1	1	10
Diphenylethers	Lactofen	-	2	2	2	1	4	11
Triazinone	Metribuzin	2	1	2	3	1	2	11
Dinitroaniline	Oryzalin	4	1	2	3	3	4	17
Dinitroaniline	Pendimethalin	4	1	1	2	1	4	13
Antioxyphenoxypropionic acid	Propaquizafop	4	1	2	2	1	4	14
Oxazole	Pyroxasulfone	3	-	4	2	4	4	17
Antioxyphenoxypropionic acid	Quizalofop-P-terfuryl	4	1	1	2	1	4	13
Cyclohexanedione	Sethoxydim	2	2	1	1	4	1	11
Triazolinones	Sulfentrazone	1	2	2	2	2	2	11
Dinitroaniline	Trifluralin	4	2	2	2	1	4	15

*PT - toxicological profile calculated according to the Equation: $PT = K_{OW} + Rfd + LD50 + AT$. The values were assigned according to table 1 of the degree of severity.

In the general analysis, the PT ranged from 8 to 18 points. Of the 30 herbicides analyzed, 24 were classified as highly or very highly toxic. Among them, some of the most used in the state of Mato Grosso include glyphosate (10 points), clomazone (13 points) and trifluralin (15 points).

In general, most A.I. presents low risk to the system. However, it is possible to identify the important points of each combination and compare them with each other, so that experts in the technical area can receive support for planning proposals that are less harmful to the environment, through risk-based decision-making about pesticide risk levels.

Glyphosate, widely used as a herbicide, has shown significant harmful effects on different organisms and the environment. A study conducted by Argaiz et al. (2021) in an aquatic environment revealed the extreme toxicity to amphibians, even at sublethal doses, resulting in lower survival rate, delayed development of metamorphosis, and hepatic lipidosis. Da Silva et al. (2017) also observed significant effects in fish exposed to 65 mg/L^{-1}highlighting the risk to aquatic fauna. The study by Hermansen et al. (2020) shows the sorption capacity of glyphosate to the soil, which can be leached into aquatic environments, increasing the risk of contamination.

Furthermore, studies such as those by Balbuena et al. (2015) have indicated that glyphosate affects the taste ability, learning, and behavior of bees without affecting their locomotion, while in the laboratory, Farina et al. (2019) detected subtle impacts on the cognitive and sensory abilities of bees. The analysis by Abadala et al. (2016) pointed out

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consequences on pollination, affecting their muscle tissues and bee sarcomeres, emphasizing the ecological risks associated with the use of glyphosate.

Table 7. Environmental Risk Index (ARI)* of herbicides registered for soybeans used in the state of Mato Grosso in the period 2021, 2022 and 2023.

Chemical Group	Active Ingredient	P	L	V	TP	D	ANGER
Chloroacetamide	Acetochlor	1	1	4	3	3	27
Chloroacetamide	Alachlor	1	1	4	3	3	27
Benzotiadiazines	Bentazone	1	1	4	2	2	16
Cyclohexanedione	Butroxydim	1	1	4	2	1	8
Sulfonylureas	Chlorimuron-ethyl	2	1	1	2	1	6
Cyclohexanedione	Clethodim	1	1	2	2	1	6
Isoxazolidinone	Clomazone	1	1	4	2	2	16
Triazolopirimidines	Chloransulam-methyl	1	3	2	1	1	7
Triazine	Cyanazine	1	1	3	3	2	16
Antioxyphenoxypropionic acid	Fenoxaprop-p-ethyl	1	1	4	3	1	9
Antioxyphenoxypropionic acid	Fluazifop-p-buthyl	1	1	1	2	1	5
Triazolopirimidines	Flumetsulam	2	3	1	1	1	7
N-phenylethanamides	Flumiclorac-penthyl	2	1	1	3	1	7
N-phenylethanamides	Flumioxazin	1	1	3	3	1	8
Diphenyl ether	Fomesafem	3	1	2	1	1	7
Glycine substituted	Glyphosate	1	1	1	2	3	15
Antioxyphenoxypropionic acid	Haloxifop-methyl	1	1	2	3	1	7
Imidazolinone	Imazamox	4	1	1	1	1	7
Imidazolinone	Imazaquim	4	4	2	2	1	12
Imidazolinone	Imazethapyr	4	4	2	2	1	12
Diphenylethers	Lactofem	1	1	2	2	1	6
Triazinone	Metribuzin	1	1	2	2	1	6
Dinitroaniline	Oryzalin	2	3	1	3	2	18
Dinitroaniline	Pendimethalin	4	1	2	2	2	18
Antioxyphenoxypropionic acid	Propaquizafop	3	1	2	2	1	8
Oxazole	Pyroxasulfone	1	1	1	3	1	6
Cyclohexanedione	Quizalofop-P-terfuryl	1	1	2	2	1	6
Triazolinones	Sethoxydim	1	3	4	2	1	10
Dinitroaniline	Sulfentrazone	4	4	1	2	1	11
Dinitoaniline	Trifluralin	4	1	4	3	2	24

P - Persistence; L - leaching; V - volatility; PT - toxicological profile; D - dose. *IRA - environmental risk index calculated for pesticides according to the equation: *IRA = [(P+L+V+TP) x D]*. The values were based on the properties of the pesticides (Tables 4 and 5) and the toxicological profile (Table 6).

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Trifluralin, characterized in this study by its high soil adsorption, low leaching and significant volatility, has a high toxicity profile and is among the three active ingredients with the highest environmental risk index. In addition, this herbicide remains among the best sold and used in soybean cultivation in the state.

Santos et al. (2012) highlight that trifluralin, a herbicide with low filtration capacity, has a low water solubility coefficient, according to the octanol-water partition coefficient (Kow) equal to 5.27. The edaphoclimatic conditions favor permanence in the environment, although the low direct leaching capacity (Lix) = 0.00. An important point to consider is the high natural durability; trifluralin has a 133.7-day half-life (DT_{50}), contributing to its toxicity to organisms.

Finally, the pesticide clethodim, belonging to the chemical group of cyclohexanediones, is frequently applied in Mato Grosso, totaling 4,451,629 kg. Although it has low durability, volume, and volatility, which contributes to a low environmental hazard index, Sousa et al. (2023) place clethodim as unlikely to cause significant health damage, but still being dangerous to the environment. Its LD_{50} = 4,167 mg/kg confirms the toxicity of the compound, especially to fish and bees.

The analysis of herbicides has provided significant information about their properties and environmental impacts. Glyphosate, with an Environmental Risk Index (ARI) of 15, is one of seven herbicides in the spotlight, bringing together high LD_{50} and water solubility. Although it has poor mobility in the soil due to adsorption to soil particles, which depends on some factors such as organic matter, clay type, temperature and pH, glyphosate becomes persistent in aquatic environments with relatively long escape. This durability is worrisome, because, although its permanence time in the soil is not long, moderate toxicity is observed in aquatic organisms, bees, birds and soil microorganisms.

Marques et al. (2019) indicated the potential risk of contamination of water bodies by glyphosate and other compounds, emphasizing that attention would be needed in their use and the application of measures aimed at minimizing environmental impacts.

CONCLUSION

Thus, the Environmental Risk Indexes (ARI) of herbicides are essential for the identification to avoid and prevent risks of environmental contamination, especially in regions such as Mato Grosso, where the intensive use of pesticides is a common practice in agriculture. The analysis showed that a significant portion of the herbicides sold present moderate to high environmental risk. About 20% of the herbicides evaluated present high environmental risk, especially Trifluralin and Acetochlor, due to their high persistence in the soil and toxicity to aquatic organisms. On the other hand, 80% of the herbicides showed low ARI, such as Clethodim and Fluazifop-p-buthyl, indicating lower environmental impact, with higher volatility and lower toxicity. These results highlight the importance of prioritizing the study and monitoring of herbicides with high ARI, such as Trifluralin and Acetochlor. Thus, the results obtained can contribute to the adoption of more sustainable agricultural practices and subsidize future research aimed at reducing the environmental impacts of herbicides.

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REFERENCES

1. ABDALA, F. C.; COSTA, M. J.; SAMPAIO, G.; CAMARGO, D. A.; PEDROSA, M.; NOGUEIRA, F. L. A. Effect of cadmium and glyphosate on the musculature of carpenter bees. *Science, Technology and Environment*, v. 3, n. 1, p. 66-72, 2016.

2. *AGROFIT.* Phytosanitary pesticide system. Active ingredients. Available at: http://agrofit.agricultura.gov.br/agrofit_cons/principal_agrofit_cons. Accessed on: June 15, 2023.

3. ALISTER, C.; KOGAN, M. ERI: environmental risk index a simple proposal to select agrochemicals for agricultural use. *Crop Protection*, v. 25, n. xx, p. 202–211, 2006.

4. ARGAIZ, D. V; GÓMEZ-BELTRÁN, D. A.; CANO, A. Environmental fate and ecological effects of the three most commonly used herbicides in Colombia. *CES Medicina Veterinaria y Zootecnia*, v. 16, n. 2, p. 47-75, 2021.

5. BALBUENA, M. S.; TISON, L.; HAHN, M. L.; GREGGERS, U.; MENZEL, R.; FARINA, W. M**.** Effects of sublethal doses of glyphosate on bee navigation. *The Journal of Experimental Biology*, *v. 218*, *n. 17*, p. 2799-2805, 2015.

6. BELO, M. S. DA S. P., PIGNATI, W., DORES, E. F. G. DE C., MOREIRA, J. C., & PERES, F. Use of pesticides in soybean production in the state of Mato Grosso: a preliminary study of occupational and environmental risks*. Brazilian Journal of Occupational Health*, 37, 78–88. 2012.

7. BRAZIL. Ministry of Agriculture and Supply. *Agrofit*. Brasilia. Available at: <https://agrofit.agricultura.gov.br/agrofit_cons/principal_agrofit_cons>. Accessed on: June 15, 2024.

8. CORREIA, N. M. *Behavior of herbicides in the environment.* Brasília, DF: Embrapa Hortaliças, 2018. 30 p. (Embrapa Hortaliças. Documents, 160). ISSN 1415-2312.

9. DA COSTA, D. G. et al. Volatilization of 2, 4-D Applied to the Surface of Soils at Different Times. In: *XVIII Brazilian Congress of Soil Mechanics and Geotechnical Engineering – The Sustainable Future of Brazil passes through Minas.* **Belo** Horizonte-MG. 2016.

10. DA SILVA, T. F.; BARP, E. A.; ARMILIATO, N. Evaluation of the cellular toxicity of glyphosate on the gonads of Danio rerio (Cyprinidae). *Health and environment: interdisciplinary journal*, v. 6, n. 1, p. 85-95, 2017. doi: 10.24302/sma.v6i1.1041.

11. DE CARVALHO MARQUES, J. G. et al. Comparison between leaching potential indices for pesticides used in the Natuba Sub-Basin, Vitória de Santo Antão-Pernambuco. *Águas Subterrâneas*, v. 33, n. 1, p. 58-67, 2019. doi: 10.14295/aguas.v33i1.29239.

12. DE OLIVEIRA, A. F. et al. Macroaggregation and restoration of soil organic carbon in a highly weathered Brazilian lactosol after two decades under no-tillage. *Science of the*

Revista ARACÊ
ISSN: 2358-2472

Total Environment, vol. 621, pp. 1559–1567 (2018). DOI: 10.1016/j.scitotenv.2017.11.086.

13. DE PAULA, D. F.; MENDES, K. F.; BROCHADO, M. G. DA S.; LAUBE, A. F. S.; RAVE, L. A. B. Techniques to avoid the drift and volatilization of herbicides. *Sustainable development, interdisciplinarity and Environmental Sciences*. Chapter 10, p.89-115, 2021.

14. DUCHOWICZ, P. R. QSPR studies on water solubility, octanol-water partition coefficient and pesticide vapor pressure. *SAR and QSAR in Environmental Research*, v. 31, n. 2, p. 135-148, 2020. DOI: 10.1080/1062936X.2019.1699602.

15. *EMBRAPA. Online Document No. 62 - Publications - Embrapa Wheat*. September, 2006. Passo Fundo, RS. Available at: http://www.cnpt.embrapa.br/biblio/do/p_do62_17.htm. Accessed on: 18 nov. 2023.

16. FARINA, W. M. et al. Effects of the herbicide glyphosate on the sensory and cognitive abilities of bees: individual deficiencies with implications for the hive. *Insects*, v. 10, n. 10, p. 354, 2019. DOI: 10.3390/insects10100354.

17. GASNIER, Céline et al. Glyphosate-based herbicides are toxic and endocrine disruptors in human cell lines. *Toxicology*, v. 262, n. 3, p. 184-191, 2009. DOI: 10.1016/j.tox.2009.06.017.

18. Heras-Mendaza, F. et al. Erythema multiforme-like eruption due to an irritant contact dermatitis from a glyphosate pesticide. *Contact Dermatitis*, v. 59, n. 1, p. 54-56, jul. 2008. doi: 10.1111/j.1600-0536.2007.01307.x.

19. HERMANSEN, C. et al. Predicting glyphosate uptake in New Zealand pastoral soils using basic soil properties or Vis-NIR spectroscopy. *Geoderma*, v. 360, p. 114009, 2020. DOI: 10.1016/j.geoderma.2019.114009.

20. HOKANSON, R. et al. Alteration of estrogen-regulated gene expression in human cells induced by the agricultural and horticultural herbicide glyphosate. *Human & Experimental Toxicology*, v. 26, n. 9, p. 747-752, 2007. DOI: 10.1177/0960327107083453.

21. IBAMA / Consolidation of data provided by the companies registering technical products, pesticides and the like, according to article 41 of Decree No. 4,074/2002. 2022.

22. LEWIS, K. A.; TZILIVAKIS, D. W.; GREEN. A. An international database for pesticide risk assessments and management. Human and Ecological Risk Assessment. *An International Journal,* v. 22, n. 4, p. 1050-1064. 2016. DOI: 10.1080/10807039.2016.1154182

23. MARQUES, J. G. C. et al**.** Comparison between leaching potential indices for pesticides used in the Natuba Sub-Basin, Vitória de Santo Antão-Pernambuco. *Águas Subterrâneas*, v. 33, n. 1, p. 58-67, 2019. DOI: 10.14295/ras.v33i1.29239.

24. MERCADO-BORRAYO, B. M. et al. Bioaccumulation of organophosphate and organochlorine pesticides by *Eichhornia crassipes* in irrigation channels in an urban agricultural system. *International Journal of Phytoremediation*, v. 17, n. 7, p. 701-708, 2015. DOI: 10.1080/15226514.2014.964841.

25. MUELLER, T. C. Methods for measuring the volatility of herbicides. *Ciência da Erva Daninha*, v. 63, n. esp., p. 116-120, 2015.

26. OLIVEIRA JR, R. S.; MATTE, W. D.; SILVA, V. F. V.; RICARDO, L. L. Relationship between soil chemical properties and the dynamics of ionizable and non-ionizable herbicides. MENDES, K. F.; INOUE, M. H.; TORNISIELO, V. L. *Herbicides in the environment*: behavior and fate. Viçosa, ed. UFV, p.249 – 265, 2022.

27. PERES, F; MOREIRA, J. C. *Is it poison or is it medicine? Pesticides, health and environment*. Editora Fiocruz, 2003.

28. PIRES, J. L. M. et al**.** Effect of relative humidity on herbicide volatility. *Brazilian Journal of Development*, v. 8, n. 4, p. 24943-24953, 2022. DOI: 10.34117/bjdv8n4-358.

29. POLETTA, G. L. et al. Genotoxicity of the herbicide formulation Roundup® (glyphosate) in broad-snouted caiman (*Caiman latirostris*) evidenced by the Comet assay and the Micronucleus test. *Mutation Research/Genetic Toxicology and Environmental Mutagenesis*, v. 672, n. 2, p. 95-102, 2009. DOI: 10.1016/j.mrgentox.2009.04.010.

30. SAMGHANI, K.; HOSSEINFATEMI, M. Developing a support vector machine based QSPR model for prediction of half-life of some herbicides. *Ecotoxicology and Environmental Safety*, v. 129, p. 10-15, 2016. DOI: 10.1016/j.ecoenv.2016.03.002.

31. NATIONAL UNION OF INDUSTRIES OF PRODUCTS FOR AGRICULTURAL DEFENSE. *Statistical Yearbook 2008* Brasília: Sindag, 2008.

32. *SISDEV (Plant Defense System)***.** *INDEA*. Available at: https://www.indea.mt.gov.br/-/22422747-relatorio-de-comercio-de-agrotoxicos-consolidado. Accessed on: 17 May. 2024.

33. STEPHENSON, G. R. et al. Glossary of terms relating to pesticides (IUPAC Recommendations 2006). *Pure and Applied Chemistry*, v. 78, n. 11, p. 2075–2154, 2006. DOI: 10.1351/pac200678112075.

34. USDA. *Agricultural Research Service.* The ARS pesticide properties database. Available at: https://www.ars.usda.gov/northeast-area/beltsville-md-barc/beltsville-agricultural-research-center/adaptive-cropping-systems laboratory/docs/ppd/pesticide-list/: Accessed on: 20 May. 2024.

35. VARGAS, L.; ROMAN, E. S. Weed management and control in soybean crop***.*** *Passo Fundo*: Embrapa Trigo, 2006. 23 p. Available at: http://www.cnpt.embrapa.br/biblio/do/p_do62.htm. Accessed on: 22 out. 2023.