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# Environmental assessment of pesticide use in the cerrado region of Brazil

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**Abstract:** The Cerrado in Central Brazil is composed of unique vegetation types with a large source of bioactive compounds. The 1970s and 1980s were marked by the intensive incorporation of these forested areas into pastures and cropland, which increased the consumption of pesticides like glyphosate and atrazine. Today there continues to be a constant loss of native vegetation in this biome, and the pressure from land use is causing significant losses of native vegetation, driven mainly by agricultural expansion. This article offers a mapping of the estimated average consumption of pesticide per crop as well as an understanding of the risks associated with glyphosate and atrazine contamination in the state of Goiás. Both of these areas serve as a basis for understanding the challenges and opportunities for sustainability associated with agriculture in the Brazilian Cerrado.

**Keywords:** Brazilian Cerrado; environmental history; pesticide; agricultural frontier; polymorphism.

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## 1. Introduction

The Brazilian Cerrado is the second largest biogeographic territory in Brazil, composed of unique phytophysiognomies, similar to the global neotropical savannas (DUTRA E SILVA, 2020; EITEN, 1972, p. 201-341). It is characterized by abundant biodiversity, of which the floristic composition encompasses a large source of bioactive substances (PEIXOTO *et al.*, 2019). Recently, however, the expansion of the agricultural frontier in the Cerrado, particularly that directed to the global grain and commodity market, has significantly impacted the destruction of the natural vegetation of this biome. (STRASSBURG *et al.*, 2017; DUTRA E SILVA, 2020; RAJÃO *et al.*, 2020). The pressure of land use is causing heavy losses of unique vegetation types (LE POLAIN DE WAROUX *et al.*, 2017; SONG *et al.*, 2021, ZALLES *et al.*, 2021, RAJÃO *et al.*, 2020).

From the 1970s onwards, the advance of large-scale agriculture into the Cerrado was accelerated by sustained public financing in agronomic research institutes such as the Goiás Agricultural Research Company (EMGOPA), and the Brazilian Agricultural Research Company (EMBRAPA) (NEHRING, 2016; SILVA, 2019; BOAVENTURA *et al.*, forthcoming). The 1970s and 1980s were marked by the intensive incorporation of these areas into the productive process of pastures and crops, which increased the consumption of pesticides (EGGER *et al.*, 2021; SPADOTTO, 2004). In the state of Goiás, (the core area of the Cerrado), the productive process brought marked changes to the landscape, which is dominated by pasture and monoculture (soy, corn, and sugarcane) (PIGNATI *et al.*, 2017, DA SILVA BARBALHO, 2015; SILVA, 2011). Monoculture is one of the most worrying agricultural activities in terms of soil and water contamination (surface and underground) (OLIVEIRA, 2008; DA SILVA BARBALHO, 2010), and in terms of the risks to public health from the increased amounts of pesticides found in various inhabited environments (SILVÉRIO, 2012). According to Brazilian law 7.802/1989, the term pesticide is considered a product with physical, chemical or biological processes that are destined for use in the production and storage stages in the agricultural sector.

Recent studies on potential pesticide contamination were carried out by the Health Ministry's System for Monitoring the Quality of Water for Human Consumption with data from 2014 to 2017 (SISAGUA, 2018; SPADOTTO, 2010). Their studies revealed that the concentrations of pesticides in water in the country were above the margin of safety, following criteria from the European Union. In Brazil, the pesticide industry has experienced steady growth based on increase in both agricultural supply and demand. Pesticides ensure effectiveness in agricultural processes, as they control pests that could endanger yield and post-harvest losses. Worldwide, the supply and demand of pesticides are parts of a complex chain of production, distribution, and waste disposal (EMBRAPA, 2018; DAL SOGLIO; KUBO, 2009). Agriculture is a massive economic sector that supports a thriving agrochemicals industry (GURGEL, 2017). Therefore, it is necessary to consider a range of economic and political interests when looking at agricultural supply chains. Some of these political interests are executive-related, while others concern the legislation and regulation of such matters.

There are examples of laws in countries around the world that try to impose some regulatory schemes on the processes involving agribusiness as whole, and pesticides specifically (DAL SOGLIO *et al.*, 2009). Brazil is one of the world's largest consumers of pesticides, due in large part to the export-oriented model of Brazilian agriculture, which emerged after the 1960s – it was one of the six biggest national markets for agrochemicals for many years (PELAEZ *et al.*, 2010) and is now the third largest user of pesticides in the world (FAO, 2021). Legislation favorable to the use of pesticides (mainly federal law 7.802/1989 and Decree 4.074/2002) was viewed by the government as a part of a strategy to achieve agricultural modernization in the second half of the 20th century (CARVALHO; NODARI; NODARI, 2017). The norms established under national legislation regulated the components of *research, experimentation, production, packaging, labeling, transportation, storage, commercialization, usage, importation, and exportation*, but do not establish limits for usage including toxicity.

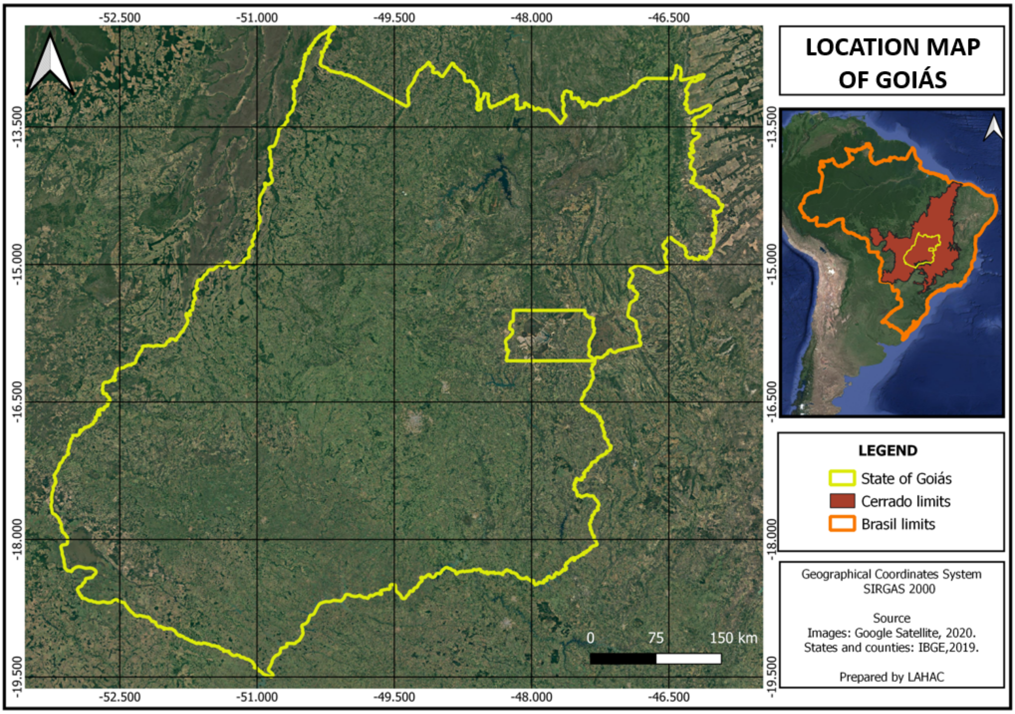
Molecular structures of pesticides generally present high reactivity, particularly the glyphosate *N-(phosphonomethyl)-glycine* and the atrazine *1-Chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine*. The herbicidal activity of both is related to their chemical structure, and any variation in structure or conformation can cause different properties (KATRITZKY, 1995; 2000; 2010). Polymorphism is the phenomenon in which solids (crystalline matter) can coexist with identical structures but different conformations, *i.e* the same molecule aggregates in different ways to form the solid- state compound (crystalline packaging) (BERNSTEIN, 2002). Brazilian legislation does not ensure a tracking process for agrochemicals; therefore, there is no control of polymorphic forms and their different physicochemical and biological properties, including greater or lesser toxicity. This work aims to investigate the risks associated with glyphosate and atrazine contamination resulting from agricultural practices as a basis to understand the challenges and opportunities for agricultural sustainability in the Brazilian Cerrado.

## 2. Geoprocessing and methods

### *2.1 Thematic mapping*

The state of Goiás is located in the Brazilian midwestern region with an area of 340,125.715 sq/km (Figure 1). The territory mostly presents a gentle rolling relief, characterized by extensive rocky regions where the sources of the Paranã, São Francisco and Tocantins-Araguaia rivers are located. Associated with this type of relief are soils in the Latosol class, which are deep, porous and well drained, and are in general very susceptible to processes of leaching (DA SILVA BARBALHO, 2010). The climate is tropical sub-humid, with two well-defined seasons: a dry season (May through September) and a rainy season (October through April). Summer provides most of the annual rainfall (DE CAMPOS *et al.*, 2001, p. 251-255). The estimated combined urban and rural population total 6,003,788 inhabitants, with a population density of 17.45 inhabitants per sq/km.

**Figure 1. Location Map of the State of Goiás**



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Agriculture is the primary economic activity in Goiás, the most common being cattle ranching and farming soy, corn and sugarcane. The urban economy is based on commercial activities and services (ARGENTI, 2015; PIGNATI *et al.*, 2014, p. 4669-4678). To evaluate the risk of environmental contamination by pesticides in Goiás, it was used Pignati's methodology, which established indicators for the average consumption of pesticides per planted area. The variables used in this work include the total area planted with crops, temporary crop areas (both in hectares) and water quality for consumption. All of the values for our variables were based on data from SISAGUA between 2014 and 2017 (SISAGUA, 2018). The results obtained were inserted into a database which then allowed to draw maps showing the usage of pesticides in agricultural fundamental crops such as soy (17.7 liters/hectares), corn (7.4 liters/hectares) and sugarcane (4.8 liters/hectares).

### *2.2 Molecular models*

To detail and understand the use of pesticides, it was analyzed the chemical structure of glyphosate and atrazine. Different chemical conformations (polymorphs) of pesticides characterize different properties, for example, a polymorph of a pesticide could present greater toxicity than another polymorph. The data (glyphosate: codes 1232531; 1232532 and 1232535; atrazine: codes 1031278, 1031279, 1031251 and 1031252) were obtained from the Cambridge Crystallographic Data Center (CCDC) (GROOM, 2016, p. 171-179), which is a database of small molecule crystalline structures (BRUNO, 2002, p. 389-397). To perform the representations, visualizations and geometric comparisons of these structures, it was used Mercury software (MACRAE, 2008, p. 466-470). It was also carried out Molecular Electrostatic Potential (MEP) calculations. The MEP map contributes to the analysis of regions of the molecule with higher and lower electron densities and thus indicates reactive regions. MEP calculations show the energy distribution of electrons on the molecular surface (SPACKMAN, 2009, p. 19-32). The MEP map glyphosate and atrazine forms were carried out using CrystalExplorer17 software (WOLFF, 2012).

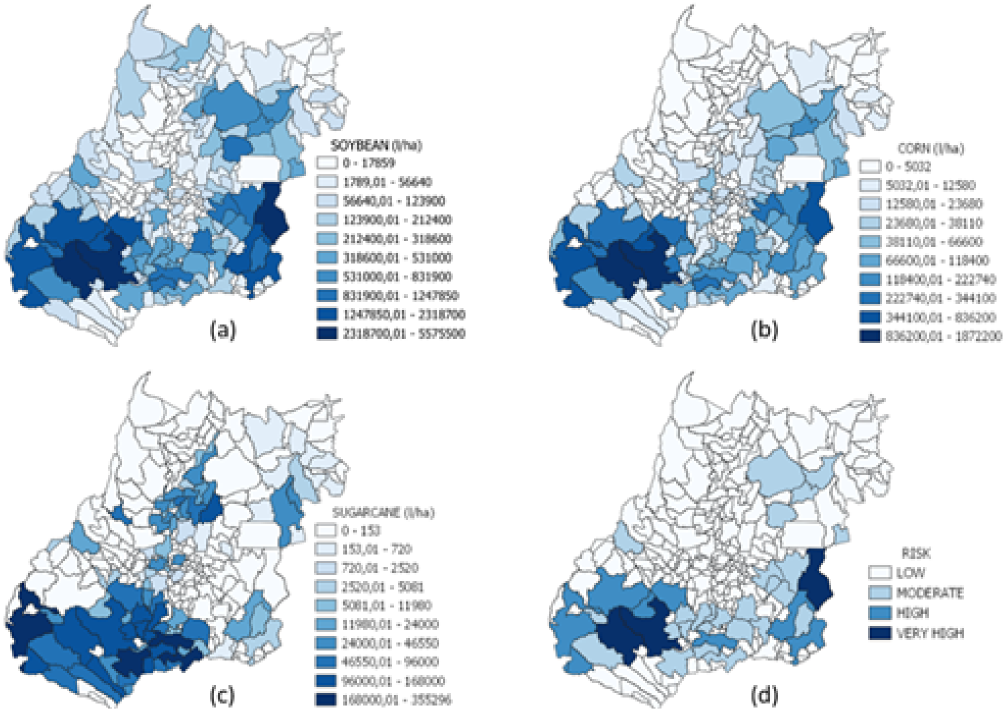
### *2.3 Pesticide regulation*

Several countries have pesticide regulations which include restrictions, registrations and control procedures for pesticide residues on food (HANDFORD, *et al.*, 2015). Therefore, understanding the legislation for each location is essential to investigate environmental challenges and sustainability transformations of societal systems. The Brazilian regulation on pesticide use was analyzed highlighting the effect on Cerrado societal system. Additionally, the lack of control procedures on polymorphic impurities, commercialization, distribution conditions and final destination are associated to environmental challenges of Brazilian regulation.

## **3. Results and discussions**

The planted area destined for the collection of the main crops (soy, corn, and sugarcane) was 5,899,992 ha, and the estimated consumption of pesticides was 75,579,060.00 liters (~80 tons), in 2017 (PIGNATI, *et al.*, 2014, p. 4669-4678). In Figure 2, the spatial data in the estimation of pesticide use in soy, corn, and sugarcane is shown by county in the state of Goiás in 2017. Also, Figure 2(a) and Figure 2(b), respectively, reveal that the cultivation of soy and corn is distributed across practically the entire territory of Goiás, predominantly in the southeastern, southwestern, southern and northern regions. The municipalities of Rio Verde and Jataí (southwestern region) and Cristalina (western region) presented the largest planted area in 2017. Sugarcane (Figure 2(c)) predominates in the southern regions (Quirinópolis, Goiatuba, Itumbiara), in the southwestern (Mineiros, Jataí, Rio Verde) and the northern region of the state of Goiás (Goianésia, Nova Glória and Vila Propício). In Figure 2(d), the most critical areas in the use of pesticides (liters/ha) are shown for the state of Goiás in 2017.

**Figure 2. (a) Estimated pesticide (l/ha) use in soybean crops by county; (b) Estimated pesticide (l/ha) use in corn crops by county; (c) Estimated pesticide (l/ha) use in sugarcane crops by county; (d) Risk class in the use of pesticides (l/ha) by county**



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In 2017, a study indicated that, among t the 246 municipalities in Goiás, pesticides were detected in 125 of them. Pesticides were not detected in 61 municipalities, and another 60 were not tested at all. The predominant crops in Goiás are soy (3,332,208.00 ha), corn (1,643,698.00 ha) and sugarcane (924,086.00 ha). The average use of pesticides in these crops is alarmingly high: 58,980,082 liters for soybean, 12,163,365 liters for corn and 4,435,612.80 liters for sugarcane.

Figure 2 reveals that the most critical areas for pesticide use are located in the southwest and western regions of the state of Goiás. In these regions, the municipalities of Jataí, Mineiros and Cristalina are classified with a very high risk of contamination. The monitoring of water in these areas is important to determine if concentrations of pesticides in the environment can affect the flora, fauna and human health. The Ministry of Health carried out research on the detection and concentration of pesticides from 2014 to 2017 with data from the System for Monitoring Water for Human Consumption (SISAGUA, 2018). The data is available from the Public Agency, Reporter BrasilPublic EyE (2018). Research by the Ministry of Health revealed that water for human consumption is contaminated by a cocktail of pesticides in practically all Brazilian municipalities. In the state of Goiás pesticides were found in the public water supply of over 50% of municipalities and some municipalities showed the presence of more than 10 types of pesticide.

A different finding, which deserves to be highlighted, involves the active principals of atrazine and glyphosate, which were detected in 118 municipalities out of the 124 that were reported to have contamination. To understand how intense the use of pesticide is in Brazil, it was have provided a demonstration of its main uses, considering the 2014 study from the Ministry of Agriculture, Livestock, and Food Supply (MAPA) as base data (2018). The selling of pesticides almost always runs into a legal disagreement, because many businesses are not regulated in line with the quantity of defensive pesticides used in production. Thus, on the one hand, there is sales monitoring but, on the other, there is not enough orientation regarding the quantities used by each group of farmers. The National Report on Health Vigilance in Populations Exposed to Pesticide (2018) (BRAZIL, 2018), demonstrates a clear connection between the market and the effects of the usage of these products in agriculture.

Amongst the most commercialized chemical pesticides in Brazil, glyphosate is the most common. It is so popular that the total amount of 2,4-D' (52889456.02 l/kg), which is the second most common, is over nine times less than the total amount of glyphosate sales (488388696,10 l/kg). Mineral Oil (alifáticos hidrocarbonets), acephate (organophosphate), methomyl (oxine methylcarbamate), chlorpyrifos (organophosphate), atrazine (triazine), paraquat dichloride (bipyridylium), carbendazim (benzimidazol) and mancozeb (dithiocarbamate), respectively, rank among the top 10 most commercialized chemical pesticides after the aforementioned ones.

Brazil set up a registry to monitor the commercialization and use of pesticides within the country. Created in 2006, decree number 5981 aimed to guarantee the registration by equivalence of pesticide (PELAEZ *et al.*, 2010). The pesticide registry in Brazil depends on the control regulations currently in place and on the time lag between legislations, which is around 13 years. Yet, federal regulations often collide with the demand to expand trade relationships and the products that businesses directly support in boosting agricultural practices for the export market.

According to Pelaez *et al.*, 2010, large businesses linked to the chemical industry are connected with the issuing of patents for technological innovations; therefore, the system which promotes patents generates a scheme of exclusive sales of the products as “these businesses take advantage of exclusiveness in the supply of products to adopt strategies of consumer fidelity to the commercial brand”. In 2015, the Brazilian Government, with the objective of amplifying and modifying decree 4.074/2002 and previous laws dealing with pesticides in Brazil (BRAZIL, 2015) launched the draft law 3200/2015. The 2015 proposal focused on altering the list of types of authorized pesticides by listing multiple products as prohibited in Brazil for research and use in agriculture (ALMEIDA, 2017).

*Structural molecular description*

The chemical structure of glyphosate is composed of 3 carbon atoms, 8 hydrogen atoms, 5 oxygen atoms, one nitrogen and one phosphorus atom, with three hydroxyl groups. For atrazine there is carbon, hydrogen, nitrogen and chlorine atom, with 3 methyl groups and a ring with 3 nitrogen molecules. For glyphosate there are 3 distinct chemical structures (polymorphs) deposited in the CCDC database, and we will call them Form **I**, Form **II** and Form **III**. Table 1 shows the parameters referring to glyphosate Forms **I**, **II** and **III,** and the parameters to atrazine Forms **I**, **II**, **III** and **IV**. Atrazine has four distinct chemical structures (polymorphs) deposited in the CCDC database, Forms **I**, **II**, **III** and **IV**. In the molecular packing, the number of glyphosate molecules in the unit cell is the same for Forms **I** and **II**, 4 molecules per unit cell; however, Form **III** has 2 molecules per unit cell. Atrazine form **II** and form **IV** have 4 molecules per unit cell, while Forms **I** and **III** have 16 and 8 molecules, respectively. glyphosate and atrazine structures pack in different ways; that is, the way they aggregate to form the solid is different.

**Table 1. Crystallography data for glyphosate Forms I, II, and III and for atrazine Forms I, II, III and IV**

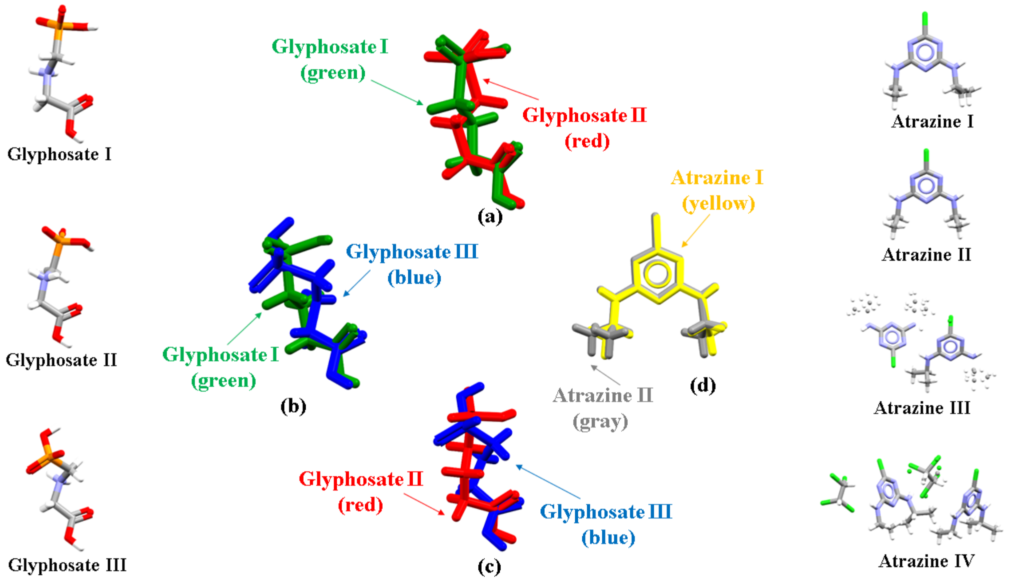
| **GLYPHOSATE** | | | | |
|---|---|---|---|---|
| **PARAMETERS** | | **FORM I** | **FORM II** | **FORM III** |
| Chemical formula | | $C_3H_8N_1O_5P_1$ | $C_3H_8N_1O_5P_1$ | $C_3H_8N_1O_5P_1$ |
| Crystal system | | Monoclinic | Monoclinic | Monoclinic |
| Space group | | $P2_{1/c}$ | $P2_{1/c}$ | $P2_1$ |
| Unit cell dimensions | | a = 8.682(5) Å<br>b = 7.973(8) Å<br>c = 9.875(5) Å<br>$\alpha = \gamma = 90°$<br>$\beta = 105.74(4)°$ | a = 8.673(2) Å<br>b = 7.977(3) Å<br>c = 9.889(3) Å<br>$\alpha = \gamma = 90°$<br>$\beta = 105.67(3)°$ | a = 7.1190(5) Å<br>b = 5.4276(10) Å<br>c = 9.1225(5) Å<br>$\alpha = \gamma = 90°$<br>$\beta = 105.043(6)°$ |
| Volume | | 657.931 Å$^3$ | 658.738 Å$^3$ | 340.406 Å$^3$ |
| Unit cell molecules | | 4 | 4 | 2 |
| **ATRAZINE** | | | | |
| | **FORM I** | **FORM II** | **FORM III** | **FORM IV** |
| Chemical formula | $C_8H_{14}N_5C_1$ | $C_7H_{12}N_5C_1$ | $2(C_8H_{14}N_5Cl)$ | $2(C_8H_{14}N_5Cl)$<br>$2(C_2H_2Cl_4)$ |
| Crystal system | Orthorhombic | Monoclinic | Orthorhombic | Monoclinic |
| Space group | Fdd2 | $P2_{1/c}$ | Pbca | $P2_{1/c}$ |

| | | | | |
|---|---|---|---|---|
| Unit cell dimensions | a = 34.2012(19) Å<br>b = 10.3247(6) Å<br>c = 12.1234(6) Å<br>α = β = γ = 90° | a = 4.4390(9) Å<br>b = 11.980(2) Å<br>c = 17.852(4) Å<br>α = γ = 90°<br>β = 94.04(3)° | a = 19.847(4) Å<br>b = 9.6160(19) Å<br>c = 23.793(5) Å<br>α = β = γ = 90° | a = 11.908(3) Å<br>b = 19.374(7) Å<br>c = 15.441(5) Å<br>α = γ = 90°<br>β = 105.86(2)° |
| Volume | 4281.0 (4) Å$^3$ | 947.0(3) Å$^3$ | 4540.9(16) Å$^3$ | 3426.7(18) |
| Unit cell molecules | 16 | 4 | 8 | 4 |

Source: xxxxxxxxx

The overlap makes it possible to compare the structures and show their conformational differences. From the coordinates and geometric data obtained experimentally by X-ray diffraction, it was possible to perform the overlap between the structures. It was performed the overlap between the three forms of glyphosate available in the database and also for two of the four available forms of atrazine. The two forms of atrazine that have not been overlapped have two molecules in the asymmetric unit, so it is not effective to perform an overlap (Figure 3). Glyphosate Form **I** was overlapped with glyphosate Form **II** (Figure 3a) and with Form **III** (Figure 3b), while Forms **II** and **III** were also overlapped (Figure 3c); for all these overlaps, the conformational structural divergences can be noted between them, because none completely overlaps. Atrazine Form **I** was overlapped with Form **II** (Figure 3d): note that these two forms are very similar, being overlapped almost completely. However, at the two extremities that have the methyl groups ($CH_3$), we note the divergence in the overlap. These overlaps for the forms of glyphosate and atrazine corroborate the polymorphic characteristic and indicate that, due to the conformational differences, each structure may have differences in its physical-chemical properties.

**Figure 3. Overlap for glyphosate and atrazine forms. Overlap between glyphosate Forms I and II (a), I and III (b), II and III (c). Overlap between atrazine Forms I and II (d)**



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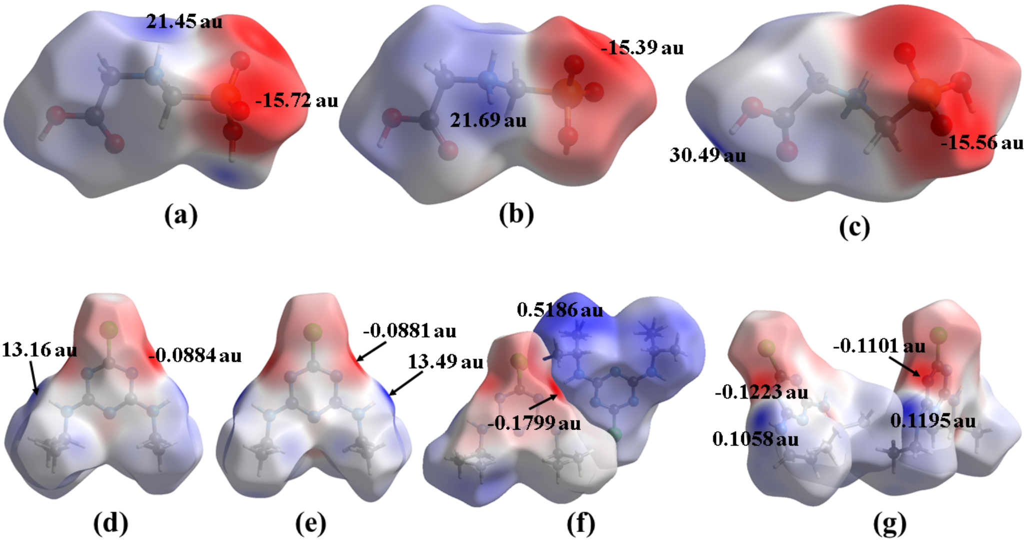
The differences between properties of molecules and some electronic features can be analyzed with the MEP, for example, electronegativity, polarity, dipole moments and chemical reactivity (SJOBERG; POLITZER, 1990, p. 3959-3961; POLITZER *et al.*, 1985, p. 191-202). The region with the greatest electrostatic potential indicates the presence of a strong positive charge and the absence of electrons, which leaves it susceptible to electrophilic attacks. The region with the lowest electrostatic potential characterizes a region with a higher concentration of electrons, which leaves it susceptible to carrying out nucleophilic reactions. In the MEP map, the red colors represent regions with negative charge density, while the blue colors indicate regions with positive charge density. Note that for glyphosate, the negative electrostatic potentials are over electronegative atoms such as oxygen, while positive potential regions are over hydrogen atoms. However, it is possible to realize that in the 3 forms of glyphosate there are different reactivity regions with different values (Figure 4a-c). For atrazine, there are more significant differences, and Forms **I** and **II** have similar values for the positive and negative regions, but the positive region appears in opposite positions (Figure 4d and 4e). Forms **III** and **IV** have 2 molecules in the unit cell, but the negative and positive regions and values are different when compared (Figure 4f and 4g). Note that the MEP map shows that for different forms of the same molecule (polymorphs) there are different regions and reactivity values.

**Figure 4.** Molecular Electrostatic Potential Map for glyphosate I (a), glyphosate II (b), glyphosate III (c), atrazine I (d), atrazine II (e), atrazine III (f) and atrazine IV (g)



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All of these structural analyzes carried out on the molecular structure of pesticides (glyphosate and atrazine) confirm that structural and conformational variations contribute to differences in its physical-chemical properties. The gap in the legislation for this polymorphism control can directly imply the environmental risks and impacts in the use of these products.

## 4. Brazilian pesticide legislation

Legislation has a direct effect on pesticide use, on the commercialization, the conditions of distribution and the final destination for pesticides. When it comes to the Cerrado's frontier, there are three major legislative issues: 1) the environment in Cerrado is protected by hierarchically lower laws, both federal (law 6938/1981) and local (laws 12280/1994, 19423/2016 and decree 4580/1995), but not by the Constitution (BRASIL, 1988); 2) there are no regulations on the amount of pesticides that can be used for different crops in Brazil, even though there is limit on the acceptable amount of residues present in post-harvest products such as grains and fruits; and 3) there are no regulations on pesticides that have polymorphic forms. The use of pesticides was, at first, established as a form to promote the "modernization" of agriculture after World War II, which resulted in the competitiveness of Brazilian agriculture on a global scale. The modernization of Brazilian agriculture entrenched rural inequality and relied heavily on chemical inputs. Powerful lobbies are staunch defenders of this agricultural model. There are studies that have shown that the quantitative and qualitative data had been manipulated to show agriculture is not harmful to the biome Cerrado (MATOS; PESSOA, 2011). Incomplete or incorrect data have also influenced the lack of pesticide regulations in the country.

In 1975, the National Program for Agricultural Pesticides (PNDA) was implemented. One of its main pillars was state support for pesticide usage in order to support the competitiveness of Brazilian agribusiness (ALMEIDA, 2017). It was only in 1989 that Law 7.802 (PELAEZ *et al.*, 2010) provided some sort of regulation on pesticide usage. Law 7.802 somewhat described the technical process involving the production, distribution, and research of pesticides, relaying the competence to regulate usage to the Sanitary Vigilance Agency (ANVISA). ANVISA is the agency responsible for sanitary regulation and administration of foods and drugs in Brazil. In 1992, ANVISA published by-law number 3 that defined terms for pesticide usage and deliberated about risks to human health caused by pesticides, their impacts on rural production, and the security of food chains. ANVISA's by-law set a precedent that was later followed by regulations from other executive federal agencies such as Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) and MAPA.

In 2002, Federal Decree 4.074 made new denominations and uses for pesticides under health and safety considerations that, among other things, considered studies, guidelines, and projects for pesticide disposal regarding the human and ecological impact of pesticides (PERES *et al.*, 2003, p. 21-41). These newly created "registration systems" were fundamental for large rural producers and regulating agencies to establish clear criteria for pesticide use. For the first time, pesticides were legally considered harmful and potentially chemically damaging for environmental and human health. However, both Law 7.802/1989 and Decree 4.074/2002 relayed the responsibility of establishing limits on pesticide usage and detection to ANVISA. In August 2021, ANVISA established limits for glyphosate detection in foods, but it does not create limits for usage in crops (ANVISA, 2021).

Brazilian legislation on pesticides is currently obsolete due to the growth of the international and national market for agricultural commodities. Even the recent Federal Decree 10.833 (October, 2021), which included the definition of the Globally Harmonized System of Classification and Labeling of Chemicals (GHS), does not limit the dosage for pesticide usage in crops. Large companies connected to the chemical industry monopolized the market by registering their patents and technological innovations, which generated a supply system exclusively for these products and created an arbitrary consumption scheme (PELAEZ *et al.*, 2010). Glyphosate (non-selective herbicide) alone represented 60% of the global market sales in the early 2000s, and, as mentioned above, it dominates the Brazilian pesticide market. Nevertheless, there are no specific regulations on the use of glyphosate in production, whether it could lead to water or soil contamination. Such open policy was ensured with the passing of resolution RDC No. 441 on December 2nd

2020, that established registration guidelines for glyphosate sales but not on its use (BRASIL, 2020). According to Amarante Junior *et al.*, (2002), glyphosate's toxicity is low, but it causes long-term chronic birth defects in animals when the dosage is beyond what are determined safe levels, which is set in 700 µg/L in potable water in the United States. In Brazil, ANVISA regulates this safety limit for human ingestion by setting each limit (in most fruits is 200 µg/L; in cereals, the range goes from 50 µg/L to 1000 µg/L). In soy, the residue limit of glyphosate is 10 mg/Kg, which is two hundred times more than the limit in European Union of 0,05 mg/Kg.

Glyphosate is a molecule that presents polymorphism and there is no regulation of polymorphic structures when used in the application of pesticides in Brazil. The national criteria for patents have failed in this instance, since it does not follow the production chain, nor does it monitor the presence or absence of polymorphism in the structures patented. The control of polymorphic structures is key to controlling results in pesticide use, considering it affects biochemical components and "the lack of control of polymorphic forms [...] opens up the possibility to indiscriminate dosage [of pesticides] that can amplify environmental impacts" (TEIXEIRA *et al.*, 2019). In 2006, Decree 5.981 (BRAZIL, 2006) ensured the registry of pesticide equivalence, not with the purpose of patent validation or controlling polymorphic structures, but for medical purposes connected to the toxicology and ecotoxicology of these products (PELAEZ *et al.*, 2010). It is hard to pinpoint which locations in Goiás deal with pesticides aligned with national legislation, and which ones do not. It is certainly important to point out that this could very well be the result of economic and political pressure from certain groups, such as agribusiness lobbies and those associated with the agricultural sector (PIGNATI *et al.*, 2017).

De Lima Tejerina (2018, p. 229-249) highlights the lack of data on pesticides in Brazil, underlining the creation of the National Health Service (SUS) and its role in the process, as well as data from the agro commerce census as evaluators of the situation. What exists are recommendations from health authorities (PIGNATI *et al.*, 2017) that outline pesticide use and its consequences. The 1988 Federal Constitution (BRAZIL, 1988) establishes general guidelines that are further regulated by both federal and state laws. If federal legislation orders that a pesticide must be used with caution, a state legislation (such as Goiás) would establish in its own regulation on pesticides widely used in within its territory. However, what could be a solution turns out to be two challenges: 1) *Brazilian states do not single out peculiarities or address issues found in the region because state level legislation is a direct copy of federal legislation*; and 2) *if states do single out location-based issues then there is no control or surveillance whatsoever to ensure that is the legislation is being followed.*

When it comes to Goiás, the state government is responsible for drafting legislation molded for its own needs. The state laws 12.280/1994 (GOIÁS, 1994), 19.423/2016 (GOIÁS, 2016) and Decree 4.580/1995 (GOIÁS, 1995) have been regulating the matter locally. They offer guidelines on the control of production and use of agrochemicals, closely aligned with Federal Legislation. This legislation would be forced to change if the Federal Constitution changes its guidelines. The current pro-pesticide trend in legislation facilitated a record production of 237,600,000 tons of pesticides that were applied to a planted area of 61,000,000 ha. Increased pesticide production contributed to the growth of Brazil's GDP via growth in agricultural exports and greater investments in grain planting, harvesting and storage. A rise in grain production follows increased pesticide use, as a direct result of the improvement in production and transformation of the sector. In other words, the growth and modernization of agriculture is reliant on agricultural inputs that improve productivity.

In order to use certain pesticides, such as glyphosate and atrazine, proper legislation would establish strict criteria in accordance with their risk. Finally, the polymorphic impurities on the pesticide (atrazine and glyphosate) that direct to different properties (such as reactivity) open up theoretical and empirical lines of control procedures on compliance with existing Brazilian legislation. The lack of control procedures highlights the environmental challenges of polymorphic impurities and sustainability transformations of Cerrado societal systems

## 5. Final remarks

The geoprocessing studies indicate a trend of increased pesticide use, and especially glyphosate, in the Cerrado, within which Goiás stands out. There is a tendency to think about the state legislation applicability in this scenario, relying on the non-compliance to the legal measures and an over-allowed use of pesticides. The chemical studies indicate that structural and conformational variations of pesticides contribute to differences in their physical-chemical properties and serve as a basis for understanding the challenges for sustainability associated with agriculture. Soy is the predominant crop grown in Goiás, occupying 78.04% of the planted area in the state, followed by corn and sugarcane. A total of 75,579,060 liters of pesticide were used on these crops in 2017. The mapping of the estimated average consumption of pesticide per crop indicates the occupation of these lands, serving as a basis to improve sustainable agricultural practices. Finally, the lack of polymorphic forms control opens the door to indiscriminate dosage use with environmental impacts (molecular structures of these pesticides show high reactivity with changes in fundamental components of biodiversity).

The transdisciplinary approach of integrating environmental history and environmental chemistry is a novel way to assess pesticide use in the Cerrado region. In particular, this approach works to bring together a range of methodologies, such as *thematic mapping,* chemical models, and legislation, to extensively comprehend the complexity of environmental consequences regarding the historical use of different kinds of pesticides in the Cerrado. This research also serves to open a broader debate on the use of other pesticides in Brazil. For example, there is currently a debate in the country on removing the ban on the pesticide called Paraquat. Paraquat is a pesticide developed in 1956 by Imperial Chemical Industries in England that plays a key role in the use of no-till farming. Although sometimes referred to as a more sustainab le agricultural practice, no-till farming relies on pesticides, such as Paraquat, to control weeds. This is especially true in the tropics where there is now winter kill (Ofstehage & Nehring, 2021). In Brazil, the use of Paraquat was banned by the ANVISA (in 2017) due to its association with incidences of cancer and Parkinson's disease. Over the past year, however, the Brazilian Association of Soy Producers (Aprosoja, Brazil) has been pressing the MAPA for the immediate release of the product for use in Brazilian agriculture.

While no decision has been made yet on the potential future legality of Paraquat in Brazil, environmental studies on the legislation, use and consequences of pesticides are essential to analyze this dynamic sector. Agriculture continues to be Brazil's most important economic sector, contributing just over a quarter of the Gross National Product (CEPEA, 2021). As it was demonstrated, pesticides are the lifeblood of agricultural industrialization in the country. That is why transdisciplinary studies on complex environmental issues, such as this one, remain crucial to assessing the ecological health and opportunities for more sustainable agriculture in the future.

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# Avaliação ambiental do uso de agrotóxicos na região do cerrado do Brasil

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***Resumo:*** O Cerrado no Brasil Central é composto por tipos de vegetação únicos com uma grande fonte de compostos bioativos. As décadas de 1970 e 1980 foram marcadas pela intensa incorporação dessas áreas com vegetação nativa a pastagens e lavouras, o que aumentou o consumo de agrotóxicos como glifosato e atrazina. Hoje continua a haver uma perda constante de vegetação natural neste bioma, e a pressão do uso da terra está causando perdas significativas de vegetação nativa, impulsionadas principalmente pela expansão agrícola. Este artigo oferece um mapeamento do consumo médio estimado de agrotóxicos por safra, bem como uma compreensão dos riscos associados à contaminação por glifosato e atrazina no estado de Goiás. Ambas as áreas servem de base para entender os desafios e oportunidades de sustentabilidade associados à agricultura no Cerrado brasileiro.

***Palavras-chave:*** Cerrado brasileiro; história ambiental; pesticida; fronteira agrícola; polimorfismo.

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# Evaluación ambiental del uso de plaguicidas en la región del cerrado de Brasil

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***Resumen:*** El Cerrado en el centro de Brasil está compuesto por tipos de vegetación únicos con una gran fuente de compuestos bioactivos. Las décadas de 1970 y 1980 estuvieron marcadas por la intensa incorporación de estas áreas nativas a pastos y cultivos, lo que incrementó el consumo de plaguicidas como el glifosato y la atrazina. Hoy en día, continúa habiendo una pérdida constante de vegetación natural en este bioma, y la presión del uso de la tierra está causando pérdidas significativas de vegetación nativa, impulsadas principalmente por la expansión agrícola. Este artículo proporciona un mapeo del consumo promedio estimado de pesticidas por cultivo, así como una comprensión de los riesgos asociados con la contaminación por glifosato y atrazina en el estado de Goiás. Ambas áreas sirven como base para comprender los desafíos y oportunidades de sostenibilidad asociados con agricultura en el estado de Goiás Cerrado brasileño.

***Palabras-clave*:** Cerrado brasileño; historia ambiental; pesticida; frontera agrícola; polimorfismo.