UNIVERSIDADE FEDERAL DOS VALES DO JEQUITINHONHA E MUCURI
Programa de Pós-Graduação em Produção Vegetal

GABRIELA MADUREIRA BARROSO

PESTICIDE RESIDUE MANAGEMENT IN BRAZIL AND PROPOSAL FOR MITIGATION

2024

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Tese apresentada à Universidade Federal dos Vales do Jequitinhonha e Mucuri como parte das exigências do Programa de Pós-Graduação em Produção Vegetal para obtenção do título de "Doutor".

Orientador: Prof. Dr. José Barbosa dos Santos

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I OFFER

To the women who do science and persevere amid the challenges faced in the scientific world. To the women who came before me and made room for me to reach this point. To all those who wanted to study but were unable to.

DEDICATION

To my sisters, from whom I have learned valuable lessons about life and love: Ariane, who teaches me every day about strength and determination; Viviane, who shows me how to be more patient and loving; and Amanda, whose companionship and friendship guide me and remind me every day of who I really am.

I dedicate.

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First, I thank God for the gift of life and for guiding and strengthening me through all the difficult times, giving me the faith and hope to persevere.

To my family, my haven, I express my deepest gratitude. My parents, for their example of integrity and dedication and for always believing in me. I especially thank my mother and sisters for their unconditional love and collaboration, brightening my days. To my nephews, who, with their laughter and joy, brought the lighter moments. To my grandmothers for being models of strength and resilience. To all my family members, I thank them for their constant support and affection, especially Aunt Tuca, for her care and dedication.

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“Alone, we can do so little; together, we can do so much.”

ABSTRACT

GABRIELA MADUREIRA BARROSO. **PESTICIDE RESIDUE MANAGEMENT IN BRAZIL AND PROPOSAL FOR MITIGATION.** 2024**.** 131p. Thesis (PhD in Vegetable Production) – Federal University of the Jequitinhonha and Mucuri Valley, Diamantina, 2024.

The increase in the use of pesticides on crops accompanied the expansion of agricultural areas and increased debates about the possible adverse effects of using these products. Although they are essential in managing pests, diseases, and weeds, even when used correctly, they can cause harm to human health, the environment, and other non-target organisms. Brazil is one of the largest consumers of pesticides, and the legislation that regulates its use has evolved. However, issues related to pesticide waste management have not followed this evolution. Therefore, it is essential that improvements be made to the management of this waste and that sustainable tools be proposed to mitigate possible negative impacts. A viable and low-cost tool is phytoremediation. This thesis aims to address the main aspects of Brazilian environmental legislation and its implications for managing pesticide residues, analyze the management of these residues in Brazil's food, water, and soil, and explore phytoremediation as a green technology for environmental decontamination. Brazilian legislation, although advanced, still faces challenges in effective implementation and supervision, but it is essential for environmental protection and public health. Creating an interinstitutional steering committee and a unified digital platform to facilitate information sharing can facilitate pesticide waste management in Brazil. As a mitigation proposal, herbicide phytoremediation proved efficient for decontaminating areas with herbicide residues and protecting water courses.

Keywords: Environmental contamination; phytoremediation; environmental legislation; waste management.

RESUMO

GABRIELA MADUREIRA BARROSO. **GESTÃO DE RESÍDUOS DE AGROTÓXICOS NO BRASIL E PROPOSTA PARA MITIGAÇÃO.** 2024. 131p. (Tese - Doutorado em Produção Vegetal) – Universidade Federal dos Vales do Jequitinhonha e Mucuri, Diamantina, 2024.

O aumento do uso de agrotóxicos nas lavouras acompanhou a expansão das áreas agrícolas e aumentou os debates sobre os possíveis efeitos negativos do uso destes produtos. Apesar de serem essenciais no manejo de pragas, doenças e plantas daninhas, mesmo utilizados de forma correta, podem causar danos à saúde humana, ao meio ambiente e outros organismos não alvo. O Brasil é um dos maiores consumidores de agrotóxicos e as legislações que regulamentam seu uso evoluíram ao longo do tempo. Porém, questões relacionadas à gestão dos resíduos dos agrotóxicos não acompanharam essa evolução. Logo, é fundamental que sejam sugeridas melhorias na gestão destes resíduos e propostas ferramentas sustentáveis para mitigar os possíveis impactos negativos. Uma ferramenta viável e de baixo custo é a fitorremediação. Esta tese tem como objetivo abordar os principais aspectos das legislações ambientais brasileiras e suas implicações na gestão de resíduos de agrotóxicos, analisar a gestão desses resíduos em alimentos, água e solo no Brasil, e explorar a fitorremediação como uma tecnologia verde para descontaminação ambiental. A legislação brasileira, embora avançada, ainda enfrenta desafios na implementação efetiva e fiscalização, sendo essencial para a proteção ambiental e a saúde pública. A criação de um comitê gestor interinstitucional e uma plataforma digital unificada para facilitar o compartilhamento de informações podem facilitar a gestão de resíduos de agrotóxicos no Brasil. Como proposta de mitigação, a fitorremediação de herbicidas se mostrou eficiente para descontaminação de áreas com resíduos de herbicidas e proteção de cursos hídricos.

Palavras-chave: Contaminação ambiental; fitorremediação; legislações ambientais; manejo de resíduos.

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SUMMARY

GENERAL INTRODUCTION

The considerable increase in the world's population in recent decades has led to increased food production, which required the modernization of agriculture and the expansion of new agricultural areas (Giller et al., 2021). In Brazil, one of the largest food producers in the world, the adoption of new technologies since the 1970s has led to significant increases in production (Cabral et al., 2022). In addition, government incentives combined with new technologies have supported the expansion of agricultural frontiers to regions such as the Cerrado (Cabral et al., 2022).

Among the technologies used to maintain high productivity is using pesticides to control pests, diseases, and weeds that harm crops. Although the use of pesticides has facilitated crop management, their intensive use has also brought considerable challenges to public health and environmental preservation (Rani et al., 2021). The management of pesticide residues, despite being a fundamental issue, has not kept pace with the modernization of production. Therefore, using these products is a major concern due to the contamination of soil, water, and food, as well as the adverse impacts on human health and the environment (Rani et al., 2021).

In Brazil, the decentralization of data and the difficulty in accessing relevant information on the use and disposal of pesticides make it difficult to implement effective policies and adequate monitoring. To address these challenges, the recent enactment of Law 14,785/2023 introduced unified registration and information systems that aim to centralize and integrate data to promote greater coordination between regulatory agencies such as MAPA, ANVISA, and IBAMA (Brazil, 2023). This integrated and systematic approach can represent a significant advance in managing pesticide residues in the country. In addition to environmental contamination concerns, pesticides, especially herbicides such as glyphosate, in transgenic crops have been the subject of intense scientific debate (Kniss, 2017). Weed resistance to glyphosate and the need to return to the use of pre-emergent herbicides highlight the complexity of chemical management in modern agriculture (Fogliatto et al., 2020; Ribeiro et al., 2021) and the importance of proposing ways to mitigate the problems caused by pesticides.

In this context, phytoremediation emerges as a promising technology for decontaminating areas affected by herbicide residues, promoting the protection of water resources and the decontamination of areas (Barroso et al., 2023). However, the effectiveness of phytoremediation varies according to the plant species used and the environmental conditions, highlighting the need for additional research to make this technology viable as a practical and sustainable solution (Barroso et al., 2023).

In this sense, this thesis aims to address the main aspects of Brazilian environmental legislation and its implications for the management of pesticide residues, analyze the management of these residues in food, water, and soil in Brazil, and explore phytoremediation as a green technology for environmental decontamination. A detailed review of current practices and emerging technologies aims to identify gaps and propose improvements that guarantee more efficient and sustainable management of pesticide residues, ensuring environmental protection and public health.

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SCIENTIFIC ARTICLE I

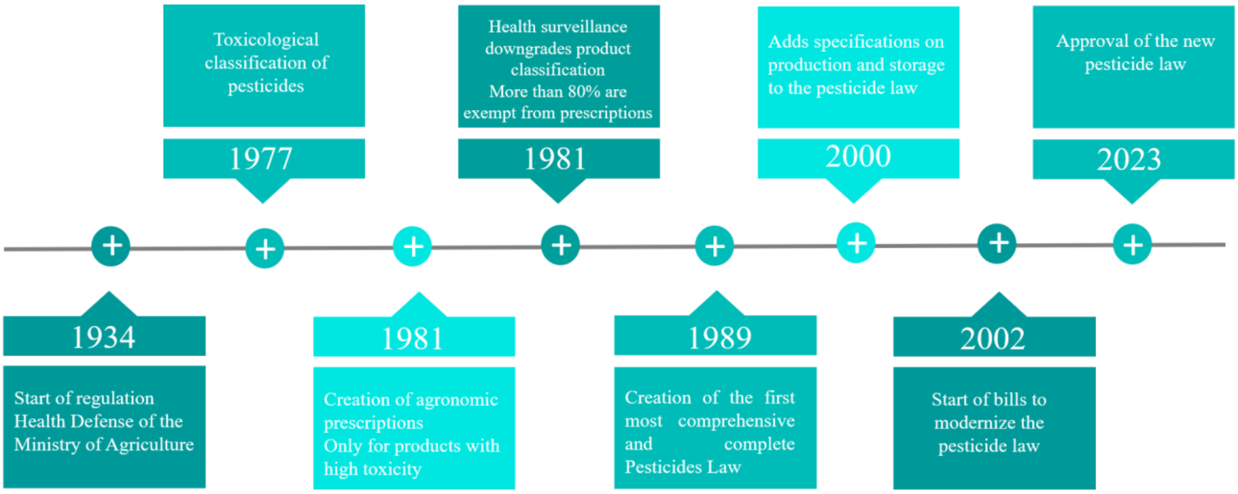
Pesticide Residues in Brazil: Analysis of Environmental Legislation and Regulations

Abstract

The use of pesticides in food cultivation has been a facilitator in this sector, as it eliminates or controls the pests responsible for the reduction in production, helping with crop management. Pesticides began to be used on a large scale in Brazil, and as a result, the legislation surrounding the use of these chemical products was changed over time to modernize them. However, some points related to pesticide residue management are still incipient and decentralized, which makes management difficult. This work aimed to analyze the regulation of pesticides in Brazil, addressing the primary legislation and their roles in managing pesticide residues. The National Environmental Policy Law, the New Forest Code and, the Biodiversity Law were analyzed. Also noteworthy are the Environmental Crimes Law, CONAMA resolutions nº 465/2014 and nº 420/2009, which establish criteria for the disposal of empty packaging and pesticide residues and soil quality, respectively. In addition to environmental laws, the new Pesticides Law centralizes research, production, commercialization, and waste disposal, establishing a rigorous system of registration and inspection to guarantee environmental and human safety. Brazilian legislation, although advanced, still faces challenges in effective implementation and oversight, but it is crucial for environmental protection and public health.

Keywords: Brazilian Laws; Sustainable Management; Pesticide Residues.

Graphical abstract



1. Introduction

The modernization of agriculture on a global scale occurred with the so-called Green Revolution, which incorporated technological innovations into agricultural production to increase food production (Serra et al., 2016). In Brazil, these techniques, introduced in the 1960s and 1970s, occurred through government incentives while agricultural frontiers expanded to the Cerrado regions (Dutra and Souza, 2017). Among the technologies introduced, improved seeds, farm machinery, and chemical inputs, such as fertilizers and pesticides, stand out (Serra et al., 2016).

The use of pesticides in food cultivation has facilitated this sector since it eliminates or controls pests responsible for decreased production, assisting in crop management (Sharifzadeh et al., 2018). However, pesticides have come to be used on a large scale in Brazil. As a result, the legislation surrounding the use of these chemical products has undergone several changes over time. These changes aim to meet the demands of the production sector and environmental and human health-related sectors.

The expansion of pesticide options helps plan the rotation of action mechanisms, which helps to avoid or reduce the risks of selecting resistant biotypes of pests. However, use in doses above the recommended level and unregistered crops causes environmental contamination problems, food residues, and health risks (Carvalho, 2017). Therefore, inspection by specialized agencies and the determination of limits and rules on the use, production, marketing, advertising, and registration of products, among others, are essential to minimize risks to human health, protect the environment, and ensure the effectiveness of the pesticide in its intended purpose. In addition, other aspects such as packaging and waste disposal, concerns about the applicator, and mitigation of the negative impacts of pesticide use must be considered when using these products.

Brazil has comprehensive and complex environmental legislation, and several environmental laws and regulations address pesticide residues. However, no specific law deals with this issue in isolation, which can be a hindrance to proposing a more comprehensive management of pesticide residues in the environment, mainly. In this context, this work aimed to address the main aspects of Brazilian environmental laws and how they can impact society and directly manage pesticide residues in the environment.

2. Use of pesticides and related problems

Modern agriculture causes several environmental problems, some due to the use of chemicals in crops. It is estimated that 64% of agricultural land worldwide is at risk of pesticide pollution (Tang et al., 2021) and that 2.5 billion hectares are contaminated with more than one molecule (Hough, 2021). Brazil is one of the largest consumers of pesticides in the world, consuming around 719,507 tons in 2021 (FAOSTAT, 2022). In addition, it uses a significant amount of product per hectare, approximately 10.9 kg/ha (FAOSTAT, 2022). Among the pesticides used, herbicides are the most prominent, around 61.49%, followed by fungicides (16.05%), insecticides (11.09%), and others (11.37%) (IBAMA, 2022). The ten most commercialized products in Brazil are glyphosate, 2,4-D, atrazine, mancozeb, chlorothalonil, acephate, diquat, chlorpyrifos, methomyl, and malathion (IBAMA, 2022).

In the case of herbicides, there is a tremendous scientific debate about the increase in the application of glyphosate, among other molecules, in transgenic crops (Kniss, 2017). With the rapid advancement of genetically modified crops, there has been a decrease in the number of herbicides; however, there has been an increase in the use of glyphosate (Benbrook, 2016). As a result, the high occurrence of new biotypes of weeds resistant to glyphosate (Bain et al., 2017) leads to the need to return to the use of traditional pre-emergent herbicides (Fogliatto et al., 2020; Ribeiro et al., 2021). Due to product and environmental characteristics, pre-emergent and residual herbicides generally remain in the soil for long periods. However, there is no management of the quantity of these products in the soil or systems with technology to contain residues in the environment.

Glyphosate is undergoing restrictions in the European Union (EU) following information from the International Agency for Research on Cancer (IARC), an agency linked to the World Health Organization (WHO), which released studies on its potential chronic effect as a cause of cancer (Davoren and Schiestl, 2018). This product is the most commercialized in Brazil, with most of its products classified as unlikely to cause acute harm (category 5) (ANVISA, 2019). Other products banned in the European Union and registered in Brazil and the United States are mancozeb, atrazine, acephate, chlorothalonil, and chlorpyrifos (FIOCRUZ, 2023; EPA, 2024).

Mancozeb is a fungicide widely used in several countries, has a long persistence in the environment, and can accumulate in biological tissues, causing damage to the health of mammals, including problems in the reproductive system and development (Bianchi et al., 2020; Runkle et al., 2020). Chlorothalonil is a fungicide that has high residues in the environment and has multiple potential routes of exposure to animals and humans, affecting metabolic pathways of development, endocrine, genetic, and reproductive, mainly in aquatic organisms and amphibians (Tao et al., 2024). Atrazine is a herbicide with a half-life of more than 60 days. Its residues are commonly found in surface waters and are related to problems in the neural and reproductive systems (Sadeghnia et al., 2022). Acephate and chlorpyrifos are insecticides belonging to the chemical group of organophosphates, which pose a significant risk to human and environmental health due to the effects of these compounds over time, making monitoring in soil, food, water, and air significant (Carneiro et al., 2015; Da Cunha et al., 2023). The toxicity of insecticides to non-target pollinators is also relevant since many of these products have harmful effects and can affect sustainable food production (Ara and Haque 2021). Even when these products were not banned in the EU, the Maximum Residue Limit (MRL) in food was lower than those accepted in Brazil, which has limits up to 10 times higher, such as acephate applied to citrus (PARA, 2024; EFSA, 2024). The MRL is measured in milligrams of pesticide residues per kilogram of agricultural crop to ensure that the residues do not pose a risk to the health of people and animals. The Codex Alimentarius is a joint commission of the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO) and is the body that determines the MRLs for pesticides in agricultural products, but allows each country the freedom to adopt or not the values established by the Codex.

The National Plan for Residue and Contaminant Control – PNCRC/Animal is a risk management tool adopted by the Ministry of Agriculture and Livestock (MAPA) to ensure the chemical safety of foods of animal origin in Brazil (PNCRC, 2023). Established by Normative Instruction SDA No. 42 of December 20, 1999, and currently regulated by Anvisa Ordinance No. 1,081, of September 27, 2023, the program involves annual sampling and testing plans for eggs, milk, honey, and animals intended for slaughter in establishments under Federal Inspection (PNCRC, 2023).

The implementation of the PNCRC/Animal is coordinated by the Secretariat of Agricultural Defense (SDA/MAPA), involving the Department of Inspection of Products of

Animal Origin (DIPOA), the Department of Inspection of Livestock Inputs (DFIP), the General Coordination of Laboratory Support (CGAL) and the General Coordination of Intelligence and Strategy (CGIE) (PNCRC, 2023).

The Federal Inspection Service collects the samples, allowing the traceability of the rural origin of the batches (PNCRC, 2023). In case of violation of the limits, investigation subprograms are established to identify the causes, apply sanctions, and control the risks of new violations (PNCRC, 2023). Properties that violate the limits are subjected to a particular testing regime until five consecutive batches present compliant results, ensuring food safety (PNCRC, 2023).

In Brazil, pesticide residue limits in plant-based foods are monitored by the National Program for Residue and Contaminant Control – PNCRC/Vegetal and by the Pesticide Residue Analysis Program in Food (PARA).

The PNCRC/Vegetal was established by Ordinance SDA No. 574 of May 9, 2022, and consists of a set of actions related to the official control of residues and contaminants in plant-based products intended for the domestic, imported, and export markets (Brazil, 2022a). MAPA Normative Instruction No. 31 of August 15, 2013, establishes the procedures to be adopted within the scope of the Ministry of Agriculture and Livestock (MAPA) in the detection of pesticide residues and chemical, physical, and biological contaminants, as established in specific ANVISA legislation, in plant products, their by-products, and standardized residues of economic value (Brazil, 2013a).

The Pesticide Residue Analysis Program in Food (PARA) is coordinated by the National Health Surveillance Agency (Anvisa) in conjunction with state and municipal health surveillance agencies and state public health laboratories. PARA aims to structure a service to evaluate and promote food safety regarding pesticide residues, and it uses controls carried out in the United States and the European Union as references (PARA, 2024). The results obtained by PARA make it possible to diagnose the use of pesticides in foods of plant origin. Consequently, subsidies are provided for implementing regulatory, inspection, and educational actions. In Brazil, the registration of pesticides differs from other products regulated by Anvisa, as there is no legal provision for its renewal. Once granted, the registration is valid indefinitely, despite the constant evolution of technical-scientific knowledge about these products, which may reveal new aspects and risks after registration (PARA, 2019). Toxicological reevaluation is a technical and legal instrument for reviewing the safety of pesticides based on new monitoring information or scientific research (PARA, 2019). This practice is essential to reduce the toxicity standard of approved active ingredients over time, removing more toxic products and preventing the registration of new, more dangerous pesticides (PARA, 2019). In addition to determining whether active ingredients meet the registration criteria, reevaluation can restrict their use in specific situations. Anvisa developed RDC No. 221/2018 to regulate this process, establishing clear and objective criteria that ensure greater transparency and effectiveness (Brazil, 2018). The selection of active ingredients for reevaluation considers evidence of health risks, such as human exposure to pesticides through marketing data, human poisonings, and residue monitoring (Brazil, 2018). The conclusions of the reassessment may result in maintaining the registration without changes, changing the formulation or application method, restricting or prohibiting its use, or canceling the registration of the active ingredient (Brazil, 2018). Another vital contribution of PARA is identifying the presence of pesticides that are not authorized for specific crops. Insecticides and fungicides are the most problematic when it comes to food residues, some with more than 20 irregular detections related to upper permitted limits and active ingredients not authorized for the crop in which they were detected or prohibited in Brazil (PARA, 2019).

Herbicide residues are rarely found above the limit in food (PARA, 2019). Herbicide residues in the environment are the biggest problem for this class. Herbicide residues in the environment can cause poisoning of subsequent crops or non-target organisms close to the application areas. Environmental damage generated by the arrival of herbicides in watercourses causes a substantial impact on the aquatic ecosystem, notably on phytoplankton. In Brazil, damage caused by the drift of hormonal herbicides to other crops has already been reported (Brochado et al., 2023), atrazine, 2,4-D and glyphosate residues in freshwater (Brovini et al., 2021), and residues in native species (Ferreira et al., 2019). Despite the significant biodegradation of herbicides in tropical environments such as Brazil, many products are toxic to microorganisms capable of carrying out this degradation (Barroso et al., 2020). Furthermore, some have a long half-life, persisting for a long time in the environment (Paula et al., 2023).

Due to the streamlining of pesticide registration in recent years, there has been a significant increase in the number of products since 2015/2016, reaching 652 products formulated in 2022, including biological and organic products (Figure 1A). Of the total number of chemical products registered in 2022, 35 are formulated based on new active ingredients and 168 are formulated based on equivalent technical products (MAPA, 2023) (Figure 1B). On the other hand, in recent decades, there has been an advance in the safety of the products used, with lower dosages used per hectare and higher LD50, which characterizes lower toxicity of the products. Registering a new product necessarily implies lower toxicity since, by law, it is impossible to register a product similar to an existing one that is more toxic (Brazil, 2023).

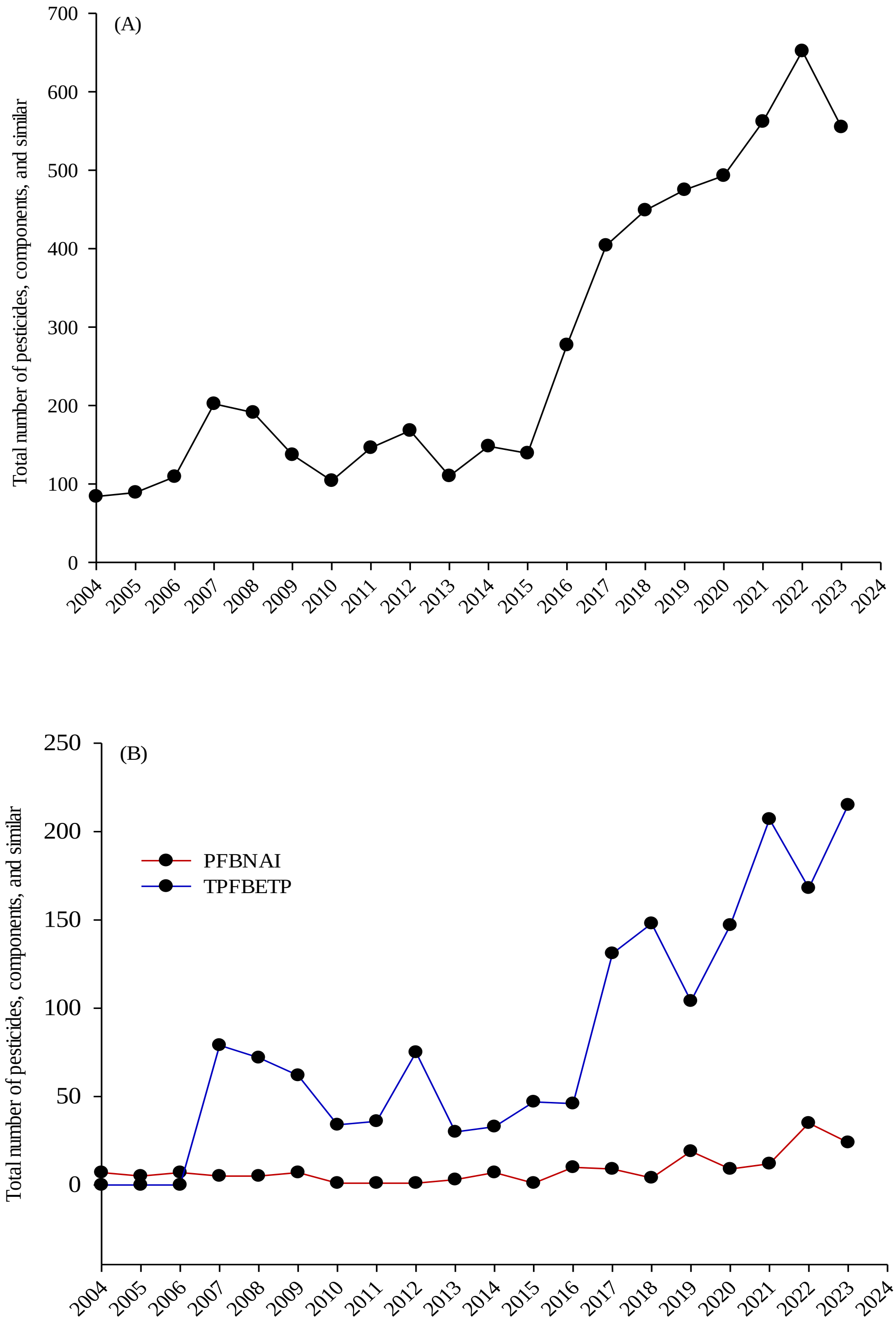


Figure 1. Total number of pesticides, components, and similar products registered in Brazil in recent years. Prepared based on data from MAPA, 2023. PFBNAI: Product Formulated Based on New Active Ingredient. TPFBETP: Technical Product Formulated Based on Equivalent Technical Product.

Regarding toxicity to human health, of the total number of products registered in 2022, the year with the highest number of registrations to date, two products were extremely toxic, ten were highly toxic, 25 were moderately toxic, 81 were slightly toxic, 210 considered unlikely to cause acute harm, and 324 unclassified (MAPA, 2023). Regarding environmental hazards, in 2022, 20 products were classified as highly hazardous to the environment, 254 very hazardous to the environment, 226 hazardous to the environment, and 152 slightly hazardous to the environment (MAPA, 2023).

The significant increase in the number of product registrations observed in recent years may be mainly related to political issues in the country, given that there have been several changes in leadership in the agencies responsible for the pesticide registration process (ANVISA, IBAMA, and MAPA), which opted for debureaucratization in the product registration processes.

3. The Pesticide Law in Brazil

3.1 History

In 1934, Brazil began to adapt the regulations for producing, using, and selling pesticides through Decree No. 24,114 of the Plant Health Defense of the Ministry of Agriculture (Brazil, 1934). It was only in 1977 that the same agency established a classification on the toxicology of pesticides with Ordinance 749 (Terra and Pelaez, 2009). However, this regulation lasted only five months, as the Ordinance was revoked in the same year. In 1980, a new classification was carried out through two ordinances, No. 04 and No. 05, of the National Division of Health Surveillance of the Ministry of Health (Terra and Pelaez, 2009).

In the 1980s, through Ordinance No. 2 of 1981, the Ministry of Agriculture created the agronomic prescription for the sale of pesticides (Terra and Pelaez, 2009). The prescription-only covered pesticides of extreme and high toxicity classes, excluding those of medium or low toxicity from the requirements. However, the mandatory use of prescriptions was subject to pressure from pesticide manufacturing companies. One month after it became compulsory, the toxicology classification was changed by Ordinance No. 7 of 1981 of the Health

Surveillance Agency, by which 80% of pesticides belonging to the extreme and high toxicity classes became part of the medium classes, being exempted from prescriptions (Terra and Pelaez, 2009). The Ordinance in question remained in force until 1985, when it was revoked by Ordinance No. 10 of the Health Surveillance Agency itself, reestablishing the validity of Ordinances No. 04 and 05 of 1980 (Terra and Pelaez, 2009).

The most significant advance involving the use of pesticides occurred after the enactment of Law 7,802 on June 11, 1989, known as the “Pesticide Law” (Brazil, 1989). This law was amended, in part, by Law No. 9,974 of June 6, 2000 (Brazil, 2000). The Pesticides Law provides for research, experimentation, production, packaging and labeling, transportation, storage, marketing, commercial advertising, use, import, final destination of waste and packaging, registration, classification, control, inspection, and supervision of pesticides, their components and the like (Brazil, 2002a).

Law No. 7,802/89 was regulated by Decree No. 4,074 of January 4, 2002 (Brazil, 2002b) and, subsequently, Decree No. 10,833 of October 7, 2021, amended the previous one that regulated Law No. 7,802 of July 11, 1989 (Brazil, 2021). The regulation of pesticides in Brazil applies the command and control system. That is, there is direct regulation, with norms and standards to be followed by manufacturers, under penalty of rejection of registrations. This system is considered rigorous when compared to other countries. It is based on phytosanitary assessments (by the Ministry of Agriculture and Livestock - MAPA), toxicological assessments (by the National Health Surveillance Agency - ANVISA), and environmental assessments (by the Brazilian Institute of the Environment and Renewable Natural Resources - IBAMA) (Camargo et al. 2020). This tripartite system of analysis and regulation seeks to ensure that pesticides registered in Brazil meet safety criteria for human health and the environment, as well as agronomic efficacy (Camargo et al. 2020).

Over the years, several Bills have been proposed to change Law No. 7,802 of July 11, 1989, one of the first being Bill No. 6,299 of 2002, which proposed to modify the registration procedures for pesticides, their components and the like (Brazil, 2002a). Initially, this bill proposed prior registration of only the active ingredient, recognizing the similarity of equivalent products in their physical, chemical, and toxicological characteristics. In addition, it suggested that legislation regarding the destruction of pesticide packaging, its components, and the like could be the exclusive responsibility of the Union. This Bill was expanded with others on similar topics over the years.

In an Extraordinary Deliberative Meeting in June 2022, a substitute for the original Bill and its appendices (Bill 1,459/2022) was approved by a Special Committee and subsequently forwarded for analysis by the Plenary of the Chamber of Deputies (Brazil, 2022b). The text underwent modifications and remained in process in the Chamber of Deputies and the Senate until the new Pesticides Law, Law 14,785 of December 27, 2023, was approved in 2023 (Brazil, 2023).

3.2 New Regulatory Framework for Pesticides in Brazil

Law 14,785 of December 27, 2023, and its predecessor, Law No. 7,802 of July 11, 1989, determine that pesticides can only be used in the country if they are registered with a competent federal agency, following the specific guidelines and requirements of each sector responsible for environmental hazard assessments, toxicological classification, and evaluation in crops (Brazil, 1989; Brazil, 2023).

ANVISA, as an agency linked to the Ministry of Health, was created in 1999 by Law No. 9,782/1999 to institutionalize and legitimize the parameters for assessing the toxicity of toxic products used in agriculture, as well as their risks to health and the environment (Brazil, 1999). The responsibilities of these agencies include regulating, analyzing, controlling, and monitoring products and services that pose health risks due to pesticides, their components and related substances, and other chemical substances of toxicological interest (Brazil, 1999).

In 2019, ANVISA approved Brazil's new regulatory framework for pesticides (ANVISA, 2029). This new regulation originated from public consultations held in 2011, 2015, 2016, and 2018 and a public hearing in 2018. Its main objective was to adapt to the standards of the Globally Harmonized System of Classification and Labeling of Chemicals (GHS) to strengthen international efforts regarding the environmentally safe management of chemical products (ANVISA, 2019). The GHS defines the classification for product labeling according to the death outcome analyzed in acute toxicological studies (ANVISA, 2019). The adoption of the GHS by the Brazilian government was justified because the GHS allows the evaluation of pesticides by analogy. An authority can look for similarities in the formula of a product already approved by Anvisa and, thus, assess whether a new pesticide has the same toxicological evaluation to obtain registration. As a result, the period for releasing the pesticide tends to be shorter. In addition, 53 countries have already fully implemented the GHS, and 12 countries have partially implemented it.

The proposals were approved in these Public Consultations, creating three Collegiate Board Resolutions (RDCs) and a Normative Instruction (IN), which together form the New Regulatory Framework for Pesticides. The first resolution - RDC No. 294, of July 29, 2019, provides for the “criteria for toxicological evaluation and classification, prioritization of analysis and comparison of the toxicological action of pesticides, components, similar products, and wood preservatives, and contains other provisions” (Brazil, 2019a). The second resolution - RDC No. 295, of July 29, 2019, deals with the “criteria for evaluating the dietary risk resulting from human exposure and pesticide residues, within the scope of Anvisa, and contains other provisions” (Brazil, 2019b). The third - RDC No. 296, of July 29, 2019, establishes “toxicological information for labels and leaflets of pesticides, similar products and wood preservatives" (Brazil, 2019c). Normative Instruction No. 34, of July 29, 2019, which also makes up the New Regulatory Framework, "establishes and publicizes the list of components not authorized for use in pesticides and similar products" (Brazil, 2019d). The new regulatory framework was enacted on July 31, 2019, establishing a one-year deadline for companies to adapt to the new rules (ANVISA, 2019).

In this way, toxicity classifications were expanded from four to five categories, with their respective names and colors on modified product labels. In addition, an "unclassified" item was included for products with shallow potential for harm, such as those of biological origin. Comparisons between the old and current classifications are listed in the table below (Table 1).

Table 1. Changes in the designation of toxicological classes of pesticides

Old	Current
Category 1	
Extremely toxic; red band: Causes skin corrosion. In the eyes, it causes corneal opacity that may or may not be reversible within seven days, in addition to causing persistent irritation in the area.	- Extremely toxic; red band: Fatal if swallowed, in contact with skin, or inhaled. - Highly toxic; red band: Same. The difference is in the amount of exposure to the product.
Category 2	
Highly toxic; yellow band: Causes severe skin irritation. In the eyes, it does not cause corneal opacity; it only causes reversible irritation in 7 days.	Moderately toxic; yellow band: Causes poisoning if ingested, in contact with skin, or inhaled
Category 3	
Moderately toxic; blue band: Causes moderate skin irritation. It does not cause corneal opacity in the eyes, only irritation that is reversible within 72 hours.	- Slightly toxic; blue band: Harmful if swallowed, in contact with skin, or inhaled. - Unlikely to cause acute harm; blue band: May be harmful if swallowed, in contact with skin, or inhaled.

Category 4	
Slightly toxic; green band: May cause mild skin irritation. In the eyes, it does not cause corneal opacity, only irritation reversible within 24 hours.	Not classified; green band: No risks or recommendations.

They were prepared by the authors with data from ANVISA, 2019.

There are several types of classification related to human health poisoning that are used for toxicological classifications and standards for pesticide leaflets and labeling: acute poisoning, which has a severe and corrosive or fatal effect; subacute poisoning, which manifests symptoms such as headache, weakness, vomiting, among others, within a few days; and chronic poisoning, which reveals long-term damage, according to continuous direct or indirect exposure to the pesticide and consists of symptoms such as insomnia, infertility, congenital malformations, miscarriages, depression, and other effects (London, 2012).

Although toxicity classifications have been expanded, the effects analyzed for "category 1" have been restricted to the scope of mortality, which has led products previously considered to have a high degree of toxicity to be considered less toxic, even though they can still cause serious harm to health. Based on reversible skin irritation, those classified as "Highly toxic" became "Moderately toxic" and no longer evaluated the potential reversible effect. The same pattern was observed for "category 3". Products that were previously classified as slightly toxic due to mild irritation were now classified as having no risks or recommendations. Thus, information related to dermal, ocular, and inhalation irritation and sensitivity will only serve to establish the communication of the product's hazards, which is done by presenting information on the product labels. After reclassification, more than 90% of the pesticides included in class I (extremely toxic) were reclassified as IV or V, slightly toxic or unlikely to cause acute harm (Brazil, 2019a).

Regarding risk communication, pesticides that are considered harmful if ingested, inhaled or in contact with skin (classes IV, V) will no longer display the skull and crossbones symbol, traditionally used to indicate danger. Instead, they will have an exclamation mark with the warning word “caution”. In addition, pesticides that may be dangerous if ingested, inhaled, or in contact with skin will no longer display any warning symbol and will be classified as “unlikely to cause acute harm”.

Before the New Regulatory Framework was approved, one of the regulations used to classify pesticides was Ordinance No. 3 of January 16, 1992, which established guidelines and requirements of the Ministry of Health regarding authorization for registration, renewal of registration, and extension of use of pesticides and similar products (Brazil, 1992). This ordinance presents the LD50 values for each category, as is done in RDC No. 294 of July 29, 2019. Note a decrease in the LD50 values between the regulations. For example, for “Category 1 – Extremely Toxic”, in the 1992 ordinance, the LD50 for the oral route of exposure was ≤ 20 mg/ka, while in the current RDC, this value is ≤ 5 mg/ka. The reduction in the LD50 value means more toxic products can be registered compared to the previous classification since the lower the LD50, the more toxic the product. This change allows the import, production, and use of highly toxic pesticides, potentially increasing the consumer population and causing health damage (EM, 2019).

Another critical point is related to the possible synergistic effects of pesticide mixtures. Many workers and end consumers may be exposed to several products applied to crops, increasing toxic effects. The studies cited in RDC No. 294 consider calculating exposure doses for individual products.

Adherence to the GHS can facilitate the import and export of plant products between countries that adhere to this system since it is a unified classification system. However, a significant scientific debate has arisen around this new regulatory framework since the reclassification only highlights the death of non-target organisms as a severe acute effect through intoxication via inhalation oral or dermal routes (Lima, 2020).

3.3 New Pesticides Law

Law 14,785 of December 27, 2023, provides for research, experimentation, production, packaging, labeling, transportation, storage, marketing, use, import, export, final destination of waste and packaging, registration, classification, control, inspection and supervision of pesticides, environmental control products, their technical products and similar products (Brazil, 2023). The law in force repeals Laws No. 7,802 of July 11, 1989, and 9,974 of June 6, 2000, and parts of annexes of Laws No. 6,938 of August 31, 1981, and 9,782 of January 26, 1999 (Brazil, 2023).

In "chapter 1" of the Pesticides Law, the preliminary provisions are dealt with, the main ones being: a) it defines that pesticides and environmental control products will be regulated by this law, products and agents intended for the protection of urban and industrial environments will be governed by Law No. 6,360, of 1976 and adjuvant products are also not regulated by this law and will have specific regulations; b) it defines essential terms and concepts; c) it establishes that pesticides and environmental control products can only be used if previously authorized or registered by a federal agency; d) it establishes deadlines for the completion of registrations and their changes, ranging from 24 months for new products to 30 days for Temporary Special Registration (RET); e) it creates the Temporary Special Registration (RET) for new products intended for research and experimentation; f) it authorizes educational, technical assistance and research entities to carry out experimentation and provide technical reports; g) it defines criteria for authorization of use, considering maximum residue limits established by federal or international agencies; h) requires risk analysis for new registrations and changes in use that imply an increase in dosage or the inclusion of new crops; among others (Brazil, 2023).

The registration of pesticides, technical products, and similar products in Brazil is carried out by the sector responsible for agriculture, the Ministry of Agriculture and Livestock (MAPA) (Brazil, 2023). The environmental sector, the Ministry of Environment and Climate Change (MMA), is responsible for registering ecological control products, technical products, and similar products (Brazil, 2023). The difference between these products is mainly related to their intended use. Products registered by MAPA are applied directly to crops, pastures, planted forests, and during the storage of agricultural products. In contrast, those registered by MMA are used for native forests, natural ecosystems, and water environments to protect these environments from pests and harmful organisms (Brazil, 2023). However, all products have the same objective: to control pests, diseases, and plants that are harmful to the environment in which they are found.

The requirements for the registration of pesticides, environmental control products, and similar products must follow the Globally Harmonized System of Classification and Labeling of Chemicals (GHS), the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS), and the Codex Alimentarius (Brazil, 2023). The risk management decision-making process will be based on risk analysis, and the registration of pesticides, environmental control products, and similar products that present an unacceptable risk to humans or the environment is prohibited, as they remain unsafe, even with the implementation of risk management measures (Brazil, 2023). In addition, risk analysis is mandatory for granting registration of pesticides and environmental control products (Brazil, 2023).

The procedures adopted by Brazil for registering pesticides and similar products are considered rigorous when compared to other countries, such as the USA, and are based on phytosanitary (Ministry of Agriculture and Livestock - MAPA), toxicological (National Health Surveillance Agency - ANVISA) and environmental (Brazilian Institute of the Environment and Renewable Natural Resources - IBAMA) assessments (Camargo et al. 2020). It is also

Anvisa's responsibility to monitor pesticide residues in products of plant origin (Brazil, 2023). This tripartite system of analysis and regulation seeks to ensure that pesticides registered in Brazil meet safety criteria for human health and the environment, as well as agronomic efficacy (Camargo et al. 2020). It is the responsibility of the States, the Federal District, and the Municipalities to legislate supplementarily on the use, production, consumption, trade, and storage of pesticides and environmental control products, their components, and the like, as well as to monitor their use, consumption, trade, storage and internal transport (Brazil, 2023).

The prescription of pesticides and similar products must be made by professionals in the field and, among other information, it is necessary to present the crop and area or volumes treated; place of application and address; commercial name of the product used; quantity of the commercial product used; precautions for use and general recommendations regarding human health, domestic animals and environmental protection (Brazil, 2023). These procedures aim at the safe use of pesticides and similar products, reducing the risks of their use. In addition, users of these products must return empty packaging, their lids, and any post-consumer residues of the products to the commercial establishments where they were purchased, according to the instructions provided in the respective leaflets (Brazil, 2023). The return can be intermediated by receiving posts or centers and itinerant receiving actions, as long as they are authorized and inspected by the competent agency (Brazil, 2023). Companies that produce and sell pesticides, environmental control products, and similar products are responsible for disposing of empty packaging and any post-consumer waste from the products they manufacture and sell, with a view to their reuse, recycling, or destruction after they are returned by users and through inspections, in compliance with the rules and instructions of the competent bodies (Brazil, 2023).

Those responsible for marketing, prescribing, and applying the products may be liable for damages to the environment and third parties, especially regarding the correct disposal of the products and packaging (Brazil, 2023). Anyone who produces, imports, sells, transports, applies, provides services, or disposes of leftovers and empty packaging of pesticides, environmental control products, and similar products in breach of the requirements established in the relevant legislation will be subject to the sanctions established in this Law, which range from warnings, fines, suspension of registrations, seizure of products, among others, and may result in imprisonment of 3 to 9 years plus the fine (Brazil, 2023).

Although this law provides, at times, for the disposal of packaging and waste, as described throughout this topic, few articles objectively address this topic, indicating a management plan for this waste and its monitoring. This law also does not state how the control and monitoring of waste in the environment, such as in water or areas of native vegetation, should be carried out. Comparing Law 14.785/2023 with Law No. 7.802/1989, it is possible to observe little progress in this subject.

3.3.1 Main Changes Between Laws 7,802/1989 and 14,785/2023

The main changes between the 1989 and 2023 Laws are related to deadlines and rules for marketing.

The new legislation establishes varying deadlines, from 30 days to 2 years, for the inclusion and modification of the registration of pesticides, environmental control products, and similar products, depending on the nature of the request (Brazil, 2023). This new deadline is a response to the long waiting time, which currently reaches seven years, while in European countries, the process is completed in a few months (Brazil, 2023). New products require a maximum period of 24 months, while those intended for research and experimentation can obtain a special temporary registration (RET), with the request being analyzed within 30 days by the Ministry of Agriculture (Brazil, 2023). Generic products, formulated exclusively from an equivalent technical product, have a maximum period of 12 months for registration (Brazil, 2023). The president of the republic vetoed some of the proposals in the Bill that placed the

Ministry of Agriculture and Livestock (MAPA) in a leading role in reanalyzing pesticides and the environmental sector in charge of reanalyzing ecological control products. However, Congress overturned some vetoes. Among the vetoes denied was Subparagraph V of §5 of Art. 4 and the Caput and sole paragraph of Art. 28, which exclusively assigns to MAPA and the environmental sector, respectively, the function of coordinating the reanalyzes of the risks of pesticides and environmental control products (Portal da Câmara, 2024). The bill provided for creating an assessment and registration fee to finance the Federal Agricultural Fund (FFAP). Still, this provision was vetoed due to its unconstitutionality since it did not specify bases and rates (Brasil, 2023). The legislation mentions several sources of resources that could make up the FFAP, including donations and resources from the Union (Brazil, 2023).

The new law amends the explicit prohibition on registering products containing carcinogenic substances or substances that cause deformities and hormonal disorders, replacing it with a ban on registering products that present an "unacceptable risk" to human health or the environment (Brazil, 2023). In addition, the possibility of challenging or canceling registration by trade associations, consumer protection organizations, environmentalists, and political parties was removed (Brazil, 2023).

Fines for violations related to non-compliance with the legislation were significantly increased, ranging from R$2,000 to R$2 million, and may be cumulative and doubled in the event of a repeat offense (Brazil, 2023). Inspections may be carried out in partnership with state agencies, which will receive part of the revenue from the fines (Brazil, 2023). The law establishes prison sentences for various offenses, including the production, storage, and sale of unregistered or unauthorized pesticides, with aggravating factors in cases of damage to the environment or public health (Brazil, 2023).

The new law establishes the Unified System of Information, Petition, and Electronic Assessment (Sispa), coordinated by the federal agency responsible for the agriculture sector, with the objective of: adopting a single system for evaluating applications for registration and changes to the registration of pesticides; providing information on the progress of processes related to pesticides; facilitating the presentation, registration, and assessment of data and information submitted by registering companies; facilitating the reception of data and information related to the sale of pesticides and related products; ensuring the security of confidential information and industrial secrets under penalty of liability; implementing, maintaining, and making available data and information on the total quantities of products, by category, imported, produced, exported, and sold in the country, as well as non-sold products; maintain a registry and make available information on companies and areas authorized for research and experimentation of pesticides and similar products; allow electronic interaction with companies registering pesticides and similar products; proceed with the mandatory electronic submission of all requests for registration processes and changes to the registration of pesticides and similar products (Brazil, 2023).

The new law establishes the Unified System for the Registration and Use of Computerized Pesticides and Environmental Control Products, with a national scope, which will be implemented, maintained, and updated by the registering agencies within the scope of their competences (Brazil, 2023). Establishments that produce, handle, import, and export, institutions dedicated to research and experimentation, distributors, legally qualified professionals, farmers who use them, and service providers for third parties in the application of pesticides and environmental control products must be registered in this system (Brazil, 2023). The registering agencies will regulate the System within the scope of their competencies. They will be structured by electronically capturing data from agronomic prescriptions issued by legally qualified professionals (Brazil, 2023).

4. Other Laws and Regulations on Pesticide Residues

Brazil has comprehensive and complex environmental legislation. One of the first laws to address the protection of environmental quality is the 1988 Federal Constitution Article 225, which establishes the right of all to an ecologically balanced environment and imposes on the government and the community the duty to protect and preserve it for present and future generations (Brazil, 1988).

In addition to the Federal Constitution, Law No. 6,938/1981 was a significant milestone in the country's environmental regulation, as it established the National Environmental Policy, its purposes and mechanisms for formulation and application, including the creation of the National Environmental System (SISNAMA) and the National Environmental Council (CONAMA) (Brazil, 1981).

Law No. 6,938/1981 establishes Brazil's principles, objectives, instruments, and mechanisms for protecting and improving environmental quality (Brazil, 1981). This law aims to preserve, improve, and restore ecological quality conducive to life, to ensure conditions for socio-economic development, national security interests, and the protection of the dignity of human life (Brazil, 1981). Among the instruments established, the following stand out: environmental licensing, environmental impact assessment, and environmental control and zoning, which apply to the use of pesticides and the management of their residues (Brazil, 1981). Although Law No. 6,938/1981 does not explicitly address pesticide residues, its environmental policy mechanisms and instruments can be used to regulate and control the use of pesticides, preventing ecological contamination by their residues.

More recently, Law No. 12,651/2012, known as the New Forest Code, was also created to protect natural resources (Brazil, 2012). It establishes standards for protecting native vegetation in permanent preservation areas (APPs), legal reserves, and other protected areas (Brazil, 2012). The law prohibits the use of pesticides in APPs. It imposes restrictions on the use of these substances in legal reserve areas, which contributes to the reduction of environmental contamination by pesticide residues (Brazil, 2012). In addition, the Forest Code promotes the conservation of soil and water resources, which indirectly helps to protect the environment against the impacts of pesticide residues.

Law No. 13,123/2015 (Biodiversity Law) regulates access to genetic heritage and associated traditional knowledge and the sharing of benefits for the conservation and sustainable use of biodiversity (Brazil, 2015). Although the law focuses on biodiversity and traditional knowledge, biodiversity conservation can be harmed by environmental contamination by pesticide residues (Brazil, 2015). Thus, the effective implementation of this law includes sustainable agricultural practices that minimize the use of pesticides and their impacts.

As for pesticide residues in drinking water, Consolidation Ordinance No. 5 of September 28, 2017, specifically Annex XX, deals with this issue. This ordinance consolidates standards on the actions and health services of the Unified Health System (SUS) and, among other things, establishes the potability standards for water for human consumption (Brazil, 2017). Annex XX of Consolidation Ordinance No. 5 establishes parameters and maximum permitted limits for various contaminants in drinking water, including chemical and biological substances, such as pesticides (Brazil, 2017). It defines the responsibilities of the competent bodies for monitoring and inspecting the quality of water intended for human consumption, aiming to guarantee the safety and health of the population (Brazil, 2017).

Finally, the standards that deal with the use of biological products and their use in organic agriculture can help reduce pesticide residues, as they regulate the use of these products, which tend to be less toxic and have less impact on the environment. The principal regulations are MAPA Normative Instruction No. 27/2006, which establishes procedures for the registration of microbiological products used in the control of agricultural pests; MAPA Normative Instruction No. 19/2013, which establishes the criteria and procedures for the registration of phytosanitary products with approved use for organic agriculture, including biological products; Joint Normative Instruction ANVISA/IBAMA/MAPA No. 5/2021, which regulates the registration of biological products for agricultural use, detailing the procedures and requirements for the toxicological, ecotoxicological and agronomic evaluation of these products (Brazil, 2006; Brazil, 2013b; Brazil, 2021a).

Some regulations that deal more specifically with pesticide residues are the Environmental Crimes Law, Conama Resolution No. 465/2014, and CONAMA Resolution No. 420/2009.

4.1 Environmental Crimes Law

In addition to Law 14,785 of December 27, 2023, Law No. 9,605/1998 (Environmental Crimes Law) also establishes criminal and administrative sanctions for conduct and activities that harm the environment (Brazil, 1998). This law is one of the most important environmental protection laws in Brazil. It covers a wide range of ecological offenses, including those related to the use and disposal of pesticides.

The Environmental Crimes Law is divided into five main chapters covering general provisions, crimes against the environment, administrative offenses, criminal and administrative sanctions, and final provisions (Brazil, 1998). With regard to pesticide residues, the most relevant articles deal with crimes against flora and pollution.

Regarding crimes against flora, the law states that the production, processing, packaging, import, export, marketing, supply, transportation, storage, safekeeping, or use of products or substances that are toxic, dangerous, or harmful to human health or the environment, in violation of the requirements established in laws or regulations, may be subject to imprisonment of 1 to 4 years and a fine (Brazil, 1998). This text applies to the improper use of pesticides, including the improper disposal of their residues.

Regarding pollution crimes, it is stated that causing pollution of any nature at levels that result or may result in harm to human health or that cause the death of animals or significant destruction of flora may also result in imprisonment of 1 to 4 years and a fine (Brazil, 1998). Environmental contamination by pesticide residues is subject to this law.

Applying the sanctions provided for in Law No. 9,605/1998 is the responsibility of environmental agencies and police authorities (Brazil, 1998). Monitoring compliance with standards regarding the use of pesticides and the disposal of their residues is carried out by agencies such as the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA), State and Municipal Environmental Secretariats, and other regulatory agencies (Brazil, 1998).

4.2 Conama Resolution No. 465/2014

The National Environmental Council (CONAMA) is the advisory and deliberative body of the National Environmental System (SISNAMA). It was established by Law 6,938/81, which establishes the National Environmental Policy, regulated by Decree 99,274/90 (Brazil, 1981; Brazil, 1990). CONAMA Resolution No. 465 of December 5, 2014, establishes criteria and procedures for disposing of empty pesticide containers and pesticide residues, aiming at environmental protection and public health (Brazil, 2014). The resolution is one of the standards that complement Brazilian legislation on the use and management of pesticides.

The main objectives of this resolution are to establish criteria and procedures for the environmentally appropriate final disposal of empty pesticide containers and their residues and promote reverse logistics, that is, the return of empty packaging to manufacturers so that it can be recycled, reused, or destroyed safely (Brazil, 2014).

The responsibility for correctly disposing of packaging and waste is fourfold: users, traders and cooperatives, manufacturers, and environmental agencies (Brazil, 2014). Farmers must triple wash or pressure wash rigid packaging immediately after use, according to manufacturers' recommendations; temporarily store empty packaging safely until it is returned; and return empty packaging and waste to authorized collection points within one year from the date of purchase (Brazil, 2014). Traders and cooperatives are responsible for informing users about the obligation to return empty packaging, maintaining collection points for empty packaging, and ensuring that they are duly authorized and operational (Brazil, 2014). Manufacturers must be responsible for implementing reverse logistics systems for empty packaging, organizing collection, transportation, and proper final disposal, ensuring the existence of sufficient collection points to meet user demand (Brazil, 2014). Environmental agencies are responsible for monitoring compliance with the standards established by the resolution, promoting educational and awareness-raising actions on the importance of the correct disposal of empty packaging and pesticide residues (Brazil, 2014).

The procedures for final disposal include recycling, which is a priority for washed rigid packaging, which must be sent for recycling at authorized facilities; incineration or disposal in landfills for packaging that cannot be recycled, including contaminated packaging, which must be sent for incineration or final disposal in licensed industrial landfills (Brazil, 2014).

CONAMA Resolution No. 465/2014 is essential for the environmentally appropriate management of pesticide residues in Brazil. It aims to minimize adverse environmental impacts and protect public health by promoting sustainable practices in managing packaging and pesticide waste (Brazil, 2014). By regulating reverse logistics and holding all stakeholders accountable, the resolution contributes to sustainability and preserving natural resources.

4.3 CONAMA Resolution No. 420/2009

CONAMA Resolution No. 420 of December 28, 2009, establishes criteria and guiding values for soil quality regarding the presence of chemical substances, including pesticides (Brazil, 2009). The main objective of this resolution is to protect soil quality, prevent contamination, and promote the remediation of areas already impacted by harmful substances (Brazil, 2009).

The main objectives of this resolution are to establish criteria for assessing soil quality about the presence of chemical substances; to define guiding values for the prevention, investigation, and remediation of soil contamination; to promote environmentally appropriate management of contaminated areas, protecting human health and the environment (Brazil, 2009).

The resolution defines three types of guiding values for the concentration of chemical substances in the soil: the Quality Reference Value (VRQ), Prevention Value (VP), and VI (Investigation Value) (Brazil, 2009). The VQR represents the natural concentration of a chemical substance in the soil, based on areas not impacted by human activities, and serves as a reference for identifying the anomalous presence of chemical substances in the soil (Brazil, 2009). The VP is the maximum concentration of a chemical substance in the soil that does not risk human health and the environment; values above the VP indicate the need for more detailed investigation (Brazil, 2009). VI is the concentration of a chemical substance in the soil above, which is a potential risk to human health and the environment, requiring investigation and, if necessary, remediation actions (Brazil, 2009). The VI is divided into two values: one for areas with residential use and another for areas with industrial use (Brazil, 2009).

This resolution is essential for the management of contaminated areas. Management consists of a few main steps: identifying areas potentially contaminated by pesticides and other chemical substances, carrying out preliminary and detailed studies to assess the extent of contamination, collecting soil samples, and performing laboratory analyses to determine the concentrations of chemical substances. Comparison of the concentrations found with the guideline values defined in the resolution; development and implementation of remediation plans for areas that present concentrations of chemical substances above the Investigation

Values; remediation techniques may include the removal of contaminated soil, in situ treatment, among others; continuous monitoring of the remediated areas to ensure that the levels of chemical substances remain within safe limits, rehabilitation of the areas for safe use according to their original or planned destination (Brazil, 2009).

CONAMA Resolution No. 420/2009 is relevant to pesticide residues because it provides prevention values, helping to prevent pesticide residues from reaching levels that could cause damage to the soil and the environment. In addition, it provides clear guidelines for the investigation and remediation of soils contaminated by pesticides, ensuring that these areas are treated appropriately. By defining values that protect human health and the environment, the resolution promotes the safe management of agricultural regions and other places where pesticides are used.

5. Final considerations

The laws and regulations discussed provide a comprehensive overview of pesticide waste management in Brazil, highlighting the importance of strict regulation for environmental protection and public health. The new Pesticide Law (Law 14,785/2023) represents a significant advance by consolidating several aspects of pesticide management, from research to the final disposal of waste. Reducing bureaucracy in registration and creating specific deadlines for different registration types demonstrate an effort to streamline processes and ensure excellent safety in using these products.

Other laws, such as the Federal Constitution of 1988, the National Environmental Policy Law, the New Forest Code, and the Biodiversity Law, complement this framework by establishing general guidelines for environmental protection and the sustainable use of natural resources. The Environmental Crimes Act and CONAMA resolutions no. 465/2014 and no. 420/2009 reinforces the importance of proper waste disposal and soil quality, imposing sanctions for violations and promoting sustainable practices.

Despite progress, there are challenges in effectively implementing these laws, such as adequate monitoring and raising awareness among the various stakeholders involved. Prospects include strengthening educational actions, improving monitoring systems, and adapting statutes to new technologies and agricultural practices. Integrating public policies and collaboration between the agricultural, environmental, and health sectors are essential to promote more effective and sustainable pesticide waste management, ensuring the preservation of the environment and the health of future generations.

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ARTIGO CIENTÍFICO II

Pesticide Residue Management in Brazil

Abstract

Brazil is one of the world's largest food producers; to guarantee its high production, it is also a large consumer of pesticides. However, pesticide waste management in Brazil faces challenges due to data decentralization and demanding access to information. This work aimed to analyze how pesticide residues in food, water, and soil are managed in Brazil, as well as to propose improvements for more efficient management. Law 14,785/2023 aims to resolve these issues by creating the Unified System for Registration and Use of Pesticides and Environmental Control Products and the Unified Electronic Information, Petition and Assessment System (Sispa). These systems centralize data and improve coordination between bodies such as MAPA, ANVISA, and IBAMA. The proposal includes the creation of an interinstitutional steering committee and a unified digital platform to facilitate information sharing. A National Pesticide Residue Management Program also establishes specific goals to reduce environmental and food contamination, promote sustainable agricultural practices, and monitor pesticide residues. Continuous training and educational campaigns are essential to strengthen management. Funding and partnerships with research institutions, NGOs, and governments are fundamental to the program's effectiveness.

Keywords: Pesticides in food; environmental contamination; pesticide management program.

1. Introduction

Pesticide residue management is a worldwide challenge for public health and environmental preservation, especially in Brazil. The increasing use of chemicals in the agricultural sector has raised concerns about soil, water, and food contamination, as well as adverse impacts on human health and the environment (Tudi et al., 2021). The decentralization of data and the difficulty in accessing relevant information on the use and disposal of pesticides have increased these challenges, making it difficult to implement effective policies and adequate monitoring.

The absence of an integrated management system and the lack of transparency in data are significant barriers to the efficient management of pesticide residues. Although several non-governmental organizations (NGOs) work in the environmental area, few focus specific efforts on the problem of toxic chemicals, which contributes to the lack of detailed information on locations and levels of contamination.

Recognizing these gaps, Law 14.785/2023 was recently enacted to transform pesticide waste management in the country (Brazil, 2023). This legislation introduces two fundamental systems: the Unified System for Registration and Use of Pesticides and Environmental Control Products and the Unified System for Information, Petition, and Electronic Assessment (Sispa) (Brazil, 2023). These systems aim to centralize and integrate data related to the use and disposal of pesticides, promoting greater coordination between regulatory agencies such as MAPA, ANVISA, and IBAMA.

The integrated and systematic approach provided for in the new legislation represents a significant advance in managing pesticide waste in Brazil (Brazil, 2023). Coordination between agencies and digital technologies for monitoring and assessment is essential to ensure food safety, environmental protection, and public health.

Therefore, this work aims to analyze how pesticide residues are managed in Brazil's food, water, and soil and propose improvements for more efficient management.

2. Analysis and Diagnosis

Brazil is one of the largest food producers in the world (FAO, 2021), and to maintain high production, it is necessary to mainly use pesticides to control pests, diseases, and weeds. For this reason, the country is known as a large consumer of these chemical products (FAOSTAT, 2022). In recent years, there has been a considerable increase in the use of pesticides in Brazil, which is related to the rise in its planted area and the expansion of agricultural frontiers. From 2009 to 2022, the total sales of products more than doubled, rising from 306,785.10 to 800,652.17 tons per year (IBAMA, 2022).

As for the pesticides used, herbicides are the most used (61.49%), followed by fungicides (16.05%), insecticides (11.09%), and others (11.37%) (IBAMA, 2022). The ten states that consume the most of these products are Mato Grosso (22.07%), São Paulo (12.46%), Paraná (9.96%), Goiás (8.15%) and Rio Grande do Sul (8.11%), Minas Gerais (6.77%), Mato Grosso do Sul (6.09%), Bahia (4.86%), Tocantins (2.20%) and Pará (1.95%), the others and those not defined total 17.38% (IBAMA, 2022). The ten most commercialized active ingredients in Brazil are glyphosate, 2,4-D, atrazine, mancozeb, chlorothalonil, acephate, diquat, chlorpyrifos, methomyl, and malathion (IBAMA, 2022).

Brazil produces several types of food and products from agribusiness. In 2022 alone, the most significant areas planted or destined for harvest were for soybeans (41,141,725 ha), corn (21,284,279 ha), wheat (3,167,615 ha), beans (2,714,611 ha) and cotton (1,648,928 ha) (IBGE, 2022). As for the crops that use the most pesticides, soybeans (54%), corn (18%), cotton (7%), pasture (6%), and sugarcane (4%) are the most prominent (AGROLINK, 2022). Some crops are not responsible for the most significant consumption in total quantity, as they occupy small areas in Brazil. Still, they consume the most considerable quantities of product per planted area, which are tomatoes (52.5 kg/ha), potatoes (28.8 kg/ha), citrus (12.4 kg/ha), cotton (5.9 kg/ha), and coffee (4.2 kg/ha) (AGROLINK, 2022).

For pesticides to be used on crops, the products must be registered with the Ministry of Agriculture and Livestock (MAPA). The registration process for a new product must follow Law 14,785 of December 27, 2023 (Brazil, 2023). Studies on human and environmental toxicity are required to register products, and those that present an unacceptable risk are not approved in Brazil (Brazil, 2023). Despite the strict legislation on the production and release of pesticides in Brazil, several reports of poisoning problems exist.

The intensive use of pesticides in Brazil raises serious concerns regarding the chemical residues in food, water, and the environment. These products can leave residues in our daily food, posing a potential risk to human health (Ali et al., 2021). In addition, pesticides can contaminate water resources, affecting drinking water quality and aquatic ecosystems (Ali et al., 2021). These products can persist in the soil and impact biodiversity, altering local fauna and flora (Ali et al., 2021). Agricultural expansion and the increase in the use of pesticides require effective public policies and more sustainable farming practices to minimize these negative impacts, ensuring food security and environmental preservation.

2.1 Pesticide residues in food

In Brazil, the leading programs for monitoring pesticides in food are the National Plan for Residue and Contaminant Control – PNCRC/Animal and the Pesticide Residue Analysis Program in Food (PARA), under the responsibility of the Ministry of Agriculture and Livestock (MAPA) and the National Health Surveillance Agency (Anvisa), respectively.

The National Plan for Residue and Contaminant Control (PNCRC/Animal) is a risk management tool implemented by the Ministry of Agriculture and Livestock (MAPA) to ensure the chemical safety of foods of animal origin produced in Brazil (MAPA, 2024). The program's scope includes annual sampling and testing plans for eggs, milk, honey, and animals destined for slaughter in establishments under federal inspection (MAPA, 2024). The tests cover various substances, including pesticides (MAPA, 2024).

The planning and implementation of the PNCRC/Animal are coordinated by several administrative units of the Secretariat of Agricultural Defense (SDA/MAPA), including the Department of Inspection of Products of Animal Origin (DIPOA), the Department of Inspection of Livestock Inputs (DFIP), the General Coordination of Laboratory Support (CGAL) and the General Coordination of Intelligence and Strategy (CGIE) (MAPA, 2024).

The Federal Inspection Service collects samples from batches of animals and products from a single source, which allows traceability to the rural property of origin (MAPA, 2024). In the event of a violation of the limits, investigation subprograms are established to inspect the sampled batch's rural property of origin, identify the violation's causes, apply possible administrative sanctions, and control the risk of new abuses (MAPA, 2024).

The latest results of the PNCRC are from 2023, and pesticide residues are monitored using multi-residue and multi-assay methods (MAPA, 2024). Multi-residue pesticide analysis allows the detection of different types of pesticides (insecticides, herbicides, fungicides, etc.) in a single food sample using techniques such as chromatography. Multi-assay analysis involves the application of multiple analytical procedures to detect different classes of pesticides simultaneously. It may include specific tests for groups of compounds, such as organophosphates, carbamates, and pyrethroids.

In the latest report provided in 2023, eggs and milk were non-compliant, with 1.52% and 1.18%, respectively, of the samples containing pesticide residues (PNCRC, 2023). The egg sample included a higher residue of fipronil, and the milk sample contained chlorpyrifos, both insecticides (PNCRC, 2023). Other foods analyzed, such as poultry, slaughtered cattle, horses, honey, farmed fish, and pigs, according to the PNCRC, complied with residues below the established limits (PNCRC, 2023).

In Brazil, the monitoring of pesticide residues in foods of plant origin is carried out by the National Program for the Control of Residues and Contaminants – PNCRC/Vegetal and by the Program for the Analysis of Pesticide Residues in Food (PARA).

In the latest report from the National Residue and Contaminant Control Program – PNCRC/Vegetal, in 2020, 853 samples were analyzed in the states of Alagoas (AL), Amazonas (AM), Ceará (CE), Distrito Federal (DF), Maranhão (MA), Minas Gerais (MG), Mato Grosso do Sul (MS), Mato Grosso (MT), Paraíba (PB), Pernambuco (PE), Paraná (PR), Rio Grande do Norte (RN), Rio Grande do Sul (RS), Santa Catarina (SC), Sergipe (SE), São Paulo (SP) and Tocantins (TO) (PNCRC/Vegetal, 2024). Of these samples, 82.41% complied, and 17.59% were non-compliant (PNCRC/Vegetal, 2024). Twelve foods were evaluated, namely rice, citrus fruits, potatoes, wheat flour, bananas, grapes, carrots, pineapples, tomatoes, beans (Phaseolus vulgaris), bell peppers, and beans (Vigna unguiculata) (PNCRC/Vegetal, 2024). Among the foods analyzed, bell peppers and beans (Vigna unguiculata) had the lowest percentage of compliance, 36.25%, and 23.33%, respectively (PNCRC/Vegetal, 2024). The report provided by PNCRC/Vegetal does not provide data on the types of non-compliant pesticides and in which crops they would be present.

The Pesticide Residue Analysis Program in Food is coordinated by the National Health Surveillance Agency (Anvisa) in conjunction with state and municipal health surveillance agencies and state public health laboratories (PARA, 2024). PARA is integrated into Anvisa's strategic planning as an essential post-market surveillance action due to its scope, representativeness concerning Brazilian food consumption, and contribution to food safety (PARA, 2024). The program's main objective is to monitor pesticide residues in foods of plant origin, aiming to reduce health risks arising from exposure to these substances through diet. This is done by assessing irregularities and health risks based on the results of the analyses of the collected samples (PARA, 2024).

PARA's activities are nationwide and structured so that plant-based foods are collected in all Federative Units (UFs) retail markets (PARA, 2024). The results of the analyses are evaluated by Anvisa, which maps the distribution of pesticide residues in food, adopting mitigating measures in cases of irregularities or health risks (PARA, 2024). Thus, the program contributes to food safety, guiding production chains on nonconformities in their production processes and encouraging the adoption good agricultural practices.

One of the stages of Anvisa's assessment is dietary risk, which analyzes the probability of adverse health effects from ingesting food with pesticide residues (PARA, 2022). This assessment derives parameters such as Acute Reference Dose (DRfA), Acceptable Daily Intake (ADI), and Maximum Residue Limit (MRL) (PARA, 2022). The MRL is the maximum amount of pesticide residue allowed in food, resulting from the appropriate pesticide use, and is expressed in milligrams per kilogram of food (PARA, 2022). Collections are made weekly, and the program's monitoring verifies whether the application of pesticides is being carried out correctly (PARA, 2022).

In the last multi-year plan, from 2017 to 2022, 36 foods were analyzed in three annual cycles, representing 80% of the plant-based foods consumed by the Brazilian population (PARA, 2022). In the 2018-2019 cycle, 14 foods were analyzed, 3,296 samples were collected, 272 pesticides were researched, 84 municipalities and 26 states were studied (PARA, 2022). In the 2022 cycle, 13 foods, 1,772 samples, and 311 pesticides were researched, as well as 79 collection municipalities and 25 states (PARA, 2022).

In the 2018-2019 cycle, 74.4% of the samples were considered satisfactory, with 33.2% showing no residue and 41.2% showing residue within the acceptable limit; 25.6% were non-compliant (PARA, 2022). Among the non-conformities, 21.1% were residues of products not permitted for the crop, 2.4% were residues above the maximum permissible limit, 0.49% were residues of products prohibited in Brazil, 0.06% were residues of unregistered products and

1.5% with more than one non-conformity (PARA, 2022). Regarding active ingredients banned or not authorized for use in Brazil, 21 samples (0.6% of the 3,296 samples analyzed) presented pesticide residues under these conditions (PARA, 2022). The active ingredients found were carbofuran (16 samples), methamidophos (1 sample), prochloraz (3 samples) and triforine (1 sample). Carbofuran residues were detected in 16 samples collected in the 2018-2019 cycle. Eight were orange, six were papaya, one was cucumber, and one was grape (PARA, 2022). The residues of this active ingredient, prohibited in Brazil since 2017, may have resulted from the use of carbosulfan, which is permitted in Brazil to date for cotton, sugarcane, eucalyptus, tobacco, corn, and soybean crops (PARA, 2022).

In the 2022 cycle, 75% of the samples were considered satisfactory, with 41.1% showing no residues and 33.9% showing residues within the acceptable limit; 25% were non-compliant (PARA, 2022). Among the non-conformities, 15% were residues of products not permitted for the crop, 4% were residues above the maximum permissible limit, 0.06% were residues of products prohibited in Brazil, 0.3% were residues of unregistered products, and 5.66% with more than one non-conformity (PARA, 2022). One orange sample presented carbofuran residue (0.1% of the 1,772 samples analyzed) regarding the active ingredients prohibited or for unauthorized use in Brazil. In addition, one strawberry sample presented fenthione residues (0.1% of the 1,772 samples analyzed). The reported residue of carbofuran, banned in Brazil since 2017, may have resulted from using carbosulfan, which is currently permitted in Brazil for cotton, sugarcane, eucalyptus, tobacco, corn, and soybean crops. Regarding active ingredients never evaluated in Brazil, six samples (0.3%) presented residues under these conditions, detecting chlorpyrifos-methyl, for which no products are registered in the country.

If a pesticide residue is found in a food in a concentration equal to or lower than the MRL, the food is considered safe for the consumer concerning that pesticide (PARA, 2022). The MRL is an agronomic parameter derived from field studies that simulate the correct use of the pesticide (PARA, 2022). It is related to food safety regarding the presence of pesticide residues. It is a component of calculating exposure and dietary risk assessment before registering a pesticide or authorizing new crops (PARA, 2022). A specific evaluation is required when residues above the MRL or unauthorized residues are detected (PARA, 2022). This assessment compares the expected exposure to acute (DRfA) and chronic (IDA) toxicological parameters. If the exposure exceeds these parameters, there is a potential risk to the consumer's health (PARA, 2022).

In 21 samples, the potential acute risk to the consumer was identified, 18 from the 2018-2019 cycle and three from the 2022 cycle (PARA, 2022). Orange was the product that presented the highest percentage of exceedances of the DRfA (PARA, 2022). Most DRfA exceedances were related to carbosulfan and its metabolite carbofuran (PARA, 2022). However, there was a reduction in the percentage of orange samples with a potential acute risk situation from 2013 to 2022 (PARA, 2022). In 2017, the use of carbofuran was banned, and carbosulfan was excluded from citrus crops (PARA, 2022).

The results of the PARA are essential for directing actions such as toxicological reevaluation of pesticides, control of food traceability, determination of restrictions for registered products, improvements in the registration of pesticides for crops with insufficient phytosanitary support, training, and improvements in the National Health Surveillance System, among others (PARA, 2022). Furthermore, the program has demonstrated progress over the years, such as an increase in the number of crops and pesticides monitored, a reduction in the rates of potential acute risk, the establishment of new partnerships, and improvements in the logistics of assessments (PARA, 2022). Thus, it can be considered a practical and highly relevant program for preventing human health problems related to food contamination by pesticides.

The results provided by the PNCRC and PARA do not provide information on the production sites, which makes it impossible to conduct a more in-depth analysis of the origin of non-compliant foods. The data provided only concern the type of food and the number and percentage of non-compliant samples. One proposal for improving these programs is to disclose the data more thoroughly and openly, including the location of the food's origin and collection dates. For vegetables, for example, food traceability could be used throughout the production chain, as proposed by the Joint Normative Instruction ANVISA-MAPA No. 02 of February 7, 2018 (Brazil, 2018). The Joint Normative Instruction ANVISA-MAPA No. 02 of February 7, 2018, defines the procedures for applying traceability throughout the production chain of fresh vegetable products intended for human consumption for monitoring and controlling pesticide residues throughout the national territory (Brazil, 2018). Using this data, it would be possible to map the areas with the highest non-compliance rates and analyze the region's environmental, agrarian and social characteristics. This action would facilitate a joint study by agencies such as MAPA, ANVISA, IBAMA, and research bodies to propose more efficient management.

The graphic summary for the food residue analysis management program is shown in the figure below (Figure 1).

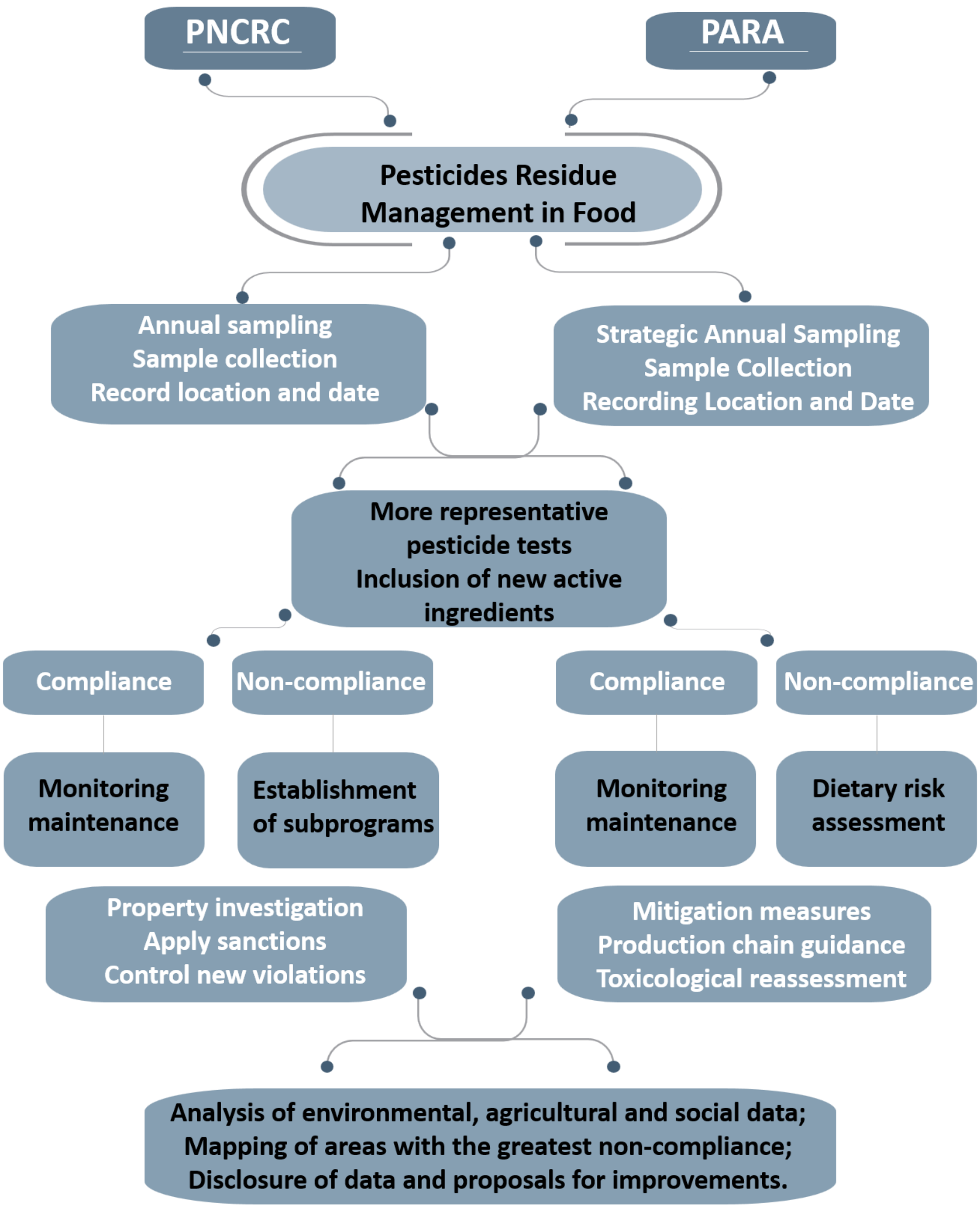

Figure 1. Graphic summary for pesticide residue management in food with proposals for improvements.

2.2 Pesticide residues in water

The monitoring of pesticide residues in water in Brazil is carried out mainly by the National Program for Monitoring the Quality of Water for Human Consumption (Vigiagua). The program consists of a series of measures continuously implemented by public health authorities in various areas of activity, aiming to ensure the population has access to water in adequate quantities and with a quality compatible with the potability standards established by current legislation (Vigiagua, 2024).

The Information System for Monitoring the Quality of Water for Human Consumption (Sisagua) is a Vigiagua tool designed to assist in the management of health risks, using data routinely generated by Health Surveillance professionals and those responsible for water supply services (Vigiagua, 2024). This system allows the generation of information on water quality, including the presence of pesticides, facilitating planning, decision-making, and the implementation of health actions related to water intended for human consumption.

Vigiagua analyzes the presence of 27 pesticides in drinking water, namely: 2,4-D + 2,4,5-T, alachlor, aldicarb + aldicarbesulfone + aldicarbesulfoxide, aldrin + dieldrin, atrazine, carbendazim + benomyl, carbofuran, chlordane, chlorpyrifos + chlorpyrifos-oxon, DDT + DDD + DDE, diuron, endosulfan, endrin, glyphosate + AMPA, lindane (gamma HCH), mancozeb, methamidophos, metolachloro, molinate, methyl parathion, pendimentalin, permethrin, profenofos, simazine, tebuconazole, terbufos, trifluralin (Vigiagua, 2024). Sisagua contains data from 3930 Brazilian municipalities, but although the program indicates biannual analyses, data has been missing for some years in several Brazilian states (Sisagua, 2024).

The latest evaluations made were: 2022, Federal District (DF) – 2022, Goiás (GO) – 2022, Mato Grosso (MT) – 2022, Mato Grosso do Sul (MS) – 2022, Paraná (PR) – 2022, Rio Grande do Sul (RS) – 2022, Santa Catarina (SC) – 2022 (Vigiagua, 2024). No data were found on pesticide residues in the state of Amapá (AP) in water (Vigiagua, 2024).

Pesticide residues are quantified in treatment plants in several Brazilian cities, and the results are classified into detections with values above and below the maximum permitted value (VMP) (Vigiagua, 2024). The VMP is the limit considered safe for human health. The highest detections of residues below the VMP were in the states of Acre, Amazonas, Bahia, Piauí, and Sergipe, with more than 74% of pesticides detected in water for human consumption (Figure 2A). Among these, only Bahia is among the ten states that consume the most pesticides, indicating that residue problems may not be associated with the amount of product used but instead with other issues such as the correct way of use, monitoring, or the types of products most used and their characteristics.

As for detections of pesticide residues in water above the maximum permitted limit, only five states were found: Roraima, Goiás, Tocantins, Minas Gerais, and São Paulo (Figure 2B). Goiás, Tocantins, Minas Gerais, and São Paulo are the ten states that consume the most pesticides. In this case, higher consumption may be related to higher detections of residues above the permitted limits.

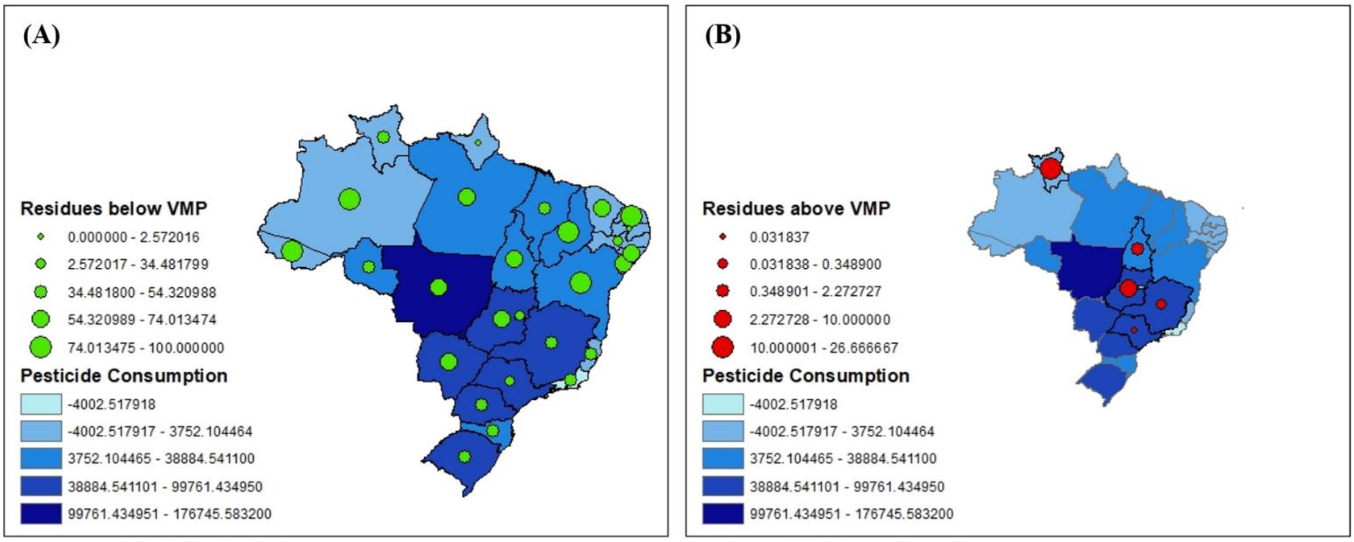

Figure 2. Data on pesticide consumption by the Brazilian state (tons of active ingredient) and pesticide residues in water (percentage of residue detection below (A) and above (B) the Maximum Permitted Value (VMP). The negative value for RJ means the quantity of pesticide returned because it was not used. Data source (IBAMA, 2024; Vigiagua, 2024).

The highest pesticide detections in water, both at concentrations above and below the VMP, were alachlor in the North region (3,007 detections), aldrin + dieldrin in the Northeast region (2,016 detections), aldrin + dieldrin in the Southeast region (28,813 detections), DDT + DDD + DDE in the Central-West region (2,370 detections), and aldrin + dieldrin in the South region (18,707 detections) (Table 1). None of these products are among the ten most consumed in Brazil; however, most of the products detected are very persistent in the environment. The half-lives of Aldrin and dieldrin are long; both are organophosphate insecticides; Aldrin can reach seven years (Pattnaik et al., 2020). DDD can get ten years and DDT 15 years (Pattnaik et al., 2020). Except for Alachlor, all other products are banned in Brazil, but because they persist for a long time in the environment, they are still found mainly in water.

One of the problems with analyzing water based on maximum permitted limits is that the potential synergistic effect of the presence of several pesticides in the water is not taken into account. Several cities have more than one pesticide in the water, especially in São Paulo (Vigiagua, 2024). Even if the water contains all 27 pesticides at limits below the VMP, it is considered safe for consumption. Furthermore, 20 of the 27 pesticides listed are considered highly dangerous by the “Pesticide Action Network International,” a group formed by non-governmental organizations that monitor the effects of pesticides (PAN, 2018).

Table 1. Number of pesticide residue detections above or below the Maximum Permitted Value (VMP) in drinking water in Brazilian states. Data source: Vigiagua, 2024.

	Região Nordeste																										
	Total de análises	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo
Agrotóxico	AL (2022)			BA (2022)			CE (2022)			MA (2022)			PB (2015)			PE (2022)			PI (2022)			RN (2018)			SE (2022)		
2,4-D + 2,4,5-T	95	0	91	246	0	214	46	0	41	375	0	198	81	0	1	x	0	x	28	0	24	1	0	1	50	0	37
Alachlor	575	0	389	566	0	535	76	0	41	375	0	198	81	0	1	25	0	8	28	0	24	1	0	1	48	0	35
Aldicarbe+ Aldicarbesulfona + Aldicarbesulfóxido	575	0	389	446	0	417	68	0	42	375	0	198	81	0	1	x	0	x	24	0	24	1	0	1	49	0	36
Aldrin + Dieldrin	575	0	382	165	0	133	75	0	42	375	0	198	81	0	1	23	0	5	28	0	24	1	0	1	50	0	37
Atrazine	97	0	93	408	0	381	76	0	42	375	0	198	81	0	2	24	0	8	28	0	24	1	0	1	46	0	34
Carbendazim + benomil	128	0	121	213	0	186	45	0	41	375	0	198	81	0	2	x	0	x	28	0	24	1	0	1	47	0	34
Carbofurano	573	0	387	445	0	415	29	0	21	375	0	198	81	0	2	x	0	x	24	0	24	1	0	1	50	0	37
Clordano	155	0	133	108	0	80	14	0	7	375	0	198	81	0	3	25	0	7	28	0	24	1	0	1	47	0	35
Clorpirifós + clorpirifós-oxon	573	0	388	432	0	405	47	0	41	375	0	198	81	0	3	25	0	7	24	0	24	1	0	1	48	0	36
DDT + DDD + DDE	574	0	388	569	0	537	74	0	42	350	0	195	81	0	3	25	0	x	28	0	24	1	0	1	46	0	34
Diuron	575	0	389	442	0	411	45	0	41	375	0	198	81	0	3	x	0	x	24	0	24	1	0	1	48	0	36
Endossulfan	x	x	x	38	0	21	68	0	42	375	0	x	81	0	3	25	0	7	4	0	24	1	0	1	x	0	x
Endrin	3	0	0	38	0	21	71	0	42	375	0	x	x	x	x	25	0	7	4	0	24	1	0	1	x	0	x
Glyphosate + AMPA	570	0	386	649	0	557	67	0	41	375	0	198	x	x	x	x	0	x	28	0	24	1	0	1	45	0	30
Lindano (gama HCH)	573	0	387	562	0	532	74	0	42	375	0	198	x	x	x	25	0	7	28	0	24	1	0	1	42	0	32
Mancozebe	124	0	116	67	0	41	45	0	41	375	0	198	x	x	x	x	0	x	28	0	24	1	0	1	47	0	35
Metamidofós	101	0	94	406	0	380	45	0	41	375	0	198	x	x	x	x	0	x	28	0	24	1	0	1	48	0	36
Metolachloro	569	0	386	438	0	406	71	0	41	375	0	198	x	x	x	24	0	7	28	0	24	1	0	1	47	0	35
Molinato	575	0	389	567	0	536	45	0	41	375	0	198	x	x	x	8	0	9	24	0	24	1	0	1	47	0	35
Parationa metílica	x	x	x	38	0	22	45	0	41	375	0	x	x	x	x	25	0	4	x	0	x	1	0	1	x	0	x
Pendimentalina	x	x	x	37	0	21	67	0	42	375	0	x	x	x	x	8	0	8	x	0	x	1	0	1	x	0	x
Permetrina	x	x	x	37	0	21	67	0	42	375	0	x	x	x	x	x	0	4	x	0	x	1	0	1	x	0	x
Profenofós	575	0	389	192	0	164	45	0	41	375	0	198	x	x	x	25	0	7	24	0	24	1	0	1	46	0	35
Simazina	575	0	389	448	0	416	77	0	42	375	0	198	x	x	x	24	0	7	28	0	24	1	0	1	46	0	34
Tebuconazol	575	0	389	444	0	414	46	0	41	375	0	198	x	x	x	24	0	7	24	0	24	1	0	1	48	0	36
Terbufós	573	0	388	283	0	252	45	0	41	375	0	198	x	x	x	24	0	7	24	0	24	1	0	1	48	0	36
Trifluralin	575	0	389	541	0	509	45	0	42	375	0	198	x	x	x	25	0	8	27	0	24	1	0	1	46	0	34
Total	9883	0	6852	8825	0	8027	1518	0	1064	10100	0	4353	972	0	25	409	0	124	591	0	576	27	0	27	1039	0	769

	Região Norte																	
	Total de análises	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo
Agrotóxico	AC (2022)			AM (2021)			PA (2022)			RO (2015)			RR (2015)			TO (2022)		
2,4-D + 2,4,5-T	1	0	1	74	0	74	391	0	236	4	0	2	6	1	0	664	0	439
Alachlor	1	0	1	105	0	74	393	0	236	4	0	2	6	1	0	707	0	455
Aldicarbe+ Aldicarbesulfona + Aldicarbesulfóxido	1	0	1	83	0	74	394	0	237	x	x	x	x	x	x	710	0	466
Aldrin + Dieldrin	1	0	1	105	0	74	394	0	237	4	0	2	4	0	3	724	1	466
Atrazine	1	0	1	105	0	74	394	0	237	4	0	2	6	1	0	715	0	462
Carbendazim + benomil	1	0	1	74	0	74	394	0	237	x	x	x	x	x	x	609	0	402
Carbofurano	1	0	1	83	0	74	393	0	237	x	x	x	x	x	x	700	0	459
Clordano	1	0	1	105	0	74	393	0	235	4	0	2	x	x	x	594	0	382
Clorpirifós + clorpirifós-oxon	1	0	1	74	0	74	394	0	237	x	x	x	x	x	x	706	0	463
DDT + DDD + DDE	1	0	1	105	0	74	395	0	238	4	0	2	6	1	0	711	0	464
Diuron	1	0	1	74	0	74	393	0	238		x	x	x	x	x	706	0	463
Endossulfan	x	x	x	105	0	74	x	x	X	4	0	2	6	0	6	45	0	37
Endrin	x	x	x	105	0	74	x	x	X	4	0	2	5	1	0	34	0	19
Glyphosate + AMPA	1	0	1	83	0	74	394	0	238	4	0	2	1	1	0	712	0	462
Lindano (gama HCH)	1	0	1	105	0	74	393	0	238	3	0	2	5	1	0	715	0	458
Mancozebe	1	0	1	74	0	74	394	0	238	x	x	x	x	x	x	563	0	371
Metamidofós	1	0	1	74	0	74	393	0	238	x	x	x	5	0	5	568	0	375
Metolachloro	1	0	1	105	0	74	392	0	237	4	0	2	6	0	6	695	0	450
Molinato	1	0	1	83	0	74	x	x	x	1	0	1	x	x	x	702	0	462
Parationa metílica	x	x	x	74	0	74	x	x	x	3	0	1	6	0	6	46	0	33
Pendimentalina	x	x	x	83	0	74	x	x	x	1	0	1	6	0	6	38	0	35
Permetrina	x	x	x	83	0	74	393	0	238	2	0	1	x	x	x	40	0	36
Profenofós	1	0	1	74	0	74	393	0	238	x	x	x	6	0	6	702	0	461
Simazina	1	0	1	105	0	74	394	0	238	4	0	2	1	1	0	712	0	461
Tebuconazol	1	0	1	74	0	74	392	0	237	x	x	x	x	x	x	698	0	460
Terbufós	1	0	1	74	0	74	393	0	238	x	x	x	6	0	6	697	0	459
Trifluralin	x	x	x	105	0	74	393	0	238	4	0	2	x	x	x	708	0	460
Total	21	0	21	2393	0	1998	8652	0	5221	58	0	30	81	8	44	15221	1	9960

Região Sudeste

	Total de análises	VPM acima	VPM abaixo	Total de análises	VPM acima	VPM abaixo	Total de análises	VPM acima	VPM abaixo	Total de análises	VPM acima	VPM abaixo
Agrotóxico	ES (2022)			MG (2022)			RJ (2022)			SP (2022)		
2,4-D + 2,4,5-T	119	0	74	1943	0	117	535	0	271	13004	0	4090
Alachlor	424	0	187	2202	0	1510	568	0	282	17429	0	5942
Aldicarbe+ Aldicarbesulfona + Aldicarbesulfóxido	414	0	189	2204	0	1510	538	0	280	17439	0	5960
Aldrin + Dieldrin	425	0	189	2251	2	1653	569	0	282	17503	1	5938
Atrazine	209	0	81	1967	0	1196	553	0	274	15175	0	5311
Carbendazim + benomil	355	0	183	1930	0	1251	497	0	277	13203	0	4276
Carbofurano	413	0	189	2189	0	1388	538	0	277	17453	1	5964
Clordano	423	0	186	2209	0	1639	540	0	274	16589	0	5347
Clorpirifós + clorpirifós-oxon	114	0	76	2185	0	1551	540	0	282	17387	0	5988
DDT + DDD + DDE	426	0	189	2250	2	1395	569	0	282	17462	0	5920
Diuron	408	0	189	2092	0	1339	503	0	279	17330	0	5963
Endossulfan	71	0	33	570	0	333	94	0	28	5740	0	2295
Endrin	159	0	38	584	1	335	166	0	30	5779	0	2283
Glyphosate + AMPA	415	0	180	2172	2	1541	561	0	292	17017	0	5934
Lindano (gama HCH)	424	0	187	2250	0	1670	568	0	281	17016	0	5811
Mancozebe	192	0	83	1326	0	860	499	0	275	13670	0	4545
Metamidofós	192	0	83	1330	0	850	488	0	273	15210	0	5318
Metolachloro	424	0	187	2206	1	1318	568	0	281	17371	0	5920
Molinato	413	0	189	2198	2	1477	538	0	281	17346	0	5922
Parationa metílica	128	0	22	414	0	284	74	0	27	5137	0	2259
Pendimentalina	129	0	21	518	0	320	105	0	29	5599	0	2242
Permetrina	139	0	31	530	0	338	105	0	27	5622	0	2243
Profenofós	408	0	189	2057	0	1435	497	0	279	17075	0	5868
Simazina	424	0	187	2217	1	1465	564	0	280	17470	0	5960
Tebuconazol	407	0	188	2166	0	1362	496	0	279	17216	0	5942
Terbufós	408	0	189	22164	1	1509	500	0	280	17196	0	5916
Trifluralin	424	0	187	2225	1	1657	565	0	280	17331	0	5932
Total	8487	0	3726	68349	13	31303	12338	0	6282	391769	2	135,089

Região Centro-oeste

	Total de análises	VPM acima	VPM abaixo	Total de análises	VPM acima	VPM abaixo	Total de análises	VPM acima	VPM abaixo	Total de análises	VPM acima	VPM abaixo

Agrotóxico	DF (2022)			GO (2022)			MS (2022)			MT (2022)		
2,4-D + 2,4,5-T	x	x	x	24	0	10	211	0	163	460	0	276
Alachlor	x	x	x	493	0	292	421	0	256	488	0	291
Aldicarbe+ Aldicarbesulfona + Aldicarbesulfóxido	5	0	0	22	0	10	398	0	232	461	0	298
Aldrin + Dieldrin	x	x	x	494	1	290	427	0	256	489	0	294
Atrazine	12	0	5	492	0	287	344	0	200	362	0	221
Carbendazim + benomil	x	x	x	18	0	7	259	0	186	398	0	256
Carbofurano	5	0	0	491	0	291	400	0	234	458	0	298
Clordano	x	x	x	480	2	285	405	0	247	491	0	299
Clorpirifós + clorpirifós-oxon	x	x	x	449	1	267	424	0	256	458	0	298
DDT + DDD + DDE	61	0	50	493	0	291	428	0	255	491	0	301
Diuron	x	x	x	19	0	8	389	0	232	428	0	279
Endossulfan	x	x	x	465	1	279	43	0	33	58	0	20
Endrin	x	x	x	473	0	282	38	0	28	68	0	21
Glyphosate + AMPA	x	x	x	201	0	115	401	0	234	487	0	299
Lindano (gama HCH)	x	x	x	486	0	289	424	0	253	492	0	301
Mancozebe	58	0	0	16	0	7	327	0	194	359	0	218
Metamidofós	5	0	0	18	0	8	293	0	159	362	0	220
Metolachloro	x	x	x	486	0	286	422	0	256	483	0	295
Molinato	x	x	x	479	0	286	428	0	256	451	0	297
Parationa metílica	x	x	x	276	0	246	37	0	32	32	0	14
Pendimentalina	x	x	x	470	1	280	39	0	33	19	0	14
Permetrina	x	x	x	470	0	281	39	0	33	19	0	15
Profenofós	58	0	0	21	0	10	419	0	254	420	0	277
Simazina	12	0	5	486	0	288	428	0	255	481	0	298
Tebuconazol	5	0	0	20	0	9	419	0	255	438	0	295
Terbufós	x	x	x	18	0	8	423	0	256	442	0	295
Trifluralin	x	x	x	479	0	284	427	0	256	466	0	279
Total	221	0	60	8339	6	4996	8713	0	5304	10061	0	6269

Região Sul									
	Total de análises	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo	**Total de análises**	VPM acima	VPM abaixo
Agrotóxico	PR(2022)			RS (2022)			SC (2022)		
2,4-D + 2,4,5-T	325	0	149	1831	0	903	3458	0	1869

Alachlor	3170	0	1629	3654	0	1828	5468	0	2925
Aldicarbe+ Aldicarbesulfona + Aldicarbesulfóxido	3162	0	1626	3659	0	1830	5437	0	2922
Aldrin + Dieldrin	3180	0	1633	3655	0	1829	5480	0	2930
Atrazine	316	0	143	1849	0	924	3529	0	1909
Carbendazim + benomil	319	0	187	1846	0	915	3378	0	1863
Carbofurano	3158	0	1621	3659	0	1829	5439	0	2922
Clordano	3143	0	1611	3611	0	1812	5419	0	2905
Clorpirifós + clorpirifós-oxon	3137	0	1578	3654	0	1825	5442	0	2895
DDT + DDD + DDE	3167	0	1617	3642	0	1827	5412	0	2921
Diuron	3161	0	1625	3659	0	1829	5409	0	2902
Endossulfan	37	0	10	1688	0	829	1853	0	910
Endrin	41	0	10	1688	0	829	1889	0	926
Glyphosate + AMPA	3160	0	1628	3386	0	1944	5163	0	3025
Lindano (gama HCH)	3167	0	1624	3634	0	1820	5449	0	2914
Mancozebe	322	0	193	1853	0	921	3519	0	1947
Metamidofós	310	0	181	1851	0	920	3441	0	1904
Metolachloro	3177	0	1634	3654	0	1828	5466	0	2923
Molinato	3157	0	1623	3656	0	1830	5447	0	2930
Parationa metílica	16	0	5	1687	0	830	1832	0	919
Pendimentalina	31	0	10	1686	0	829	1804	0	909
Permetrina	32	0	11	1687	0	830	1802	0	909
Profenofós	3149	0	1621	3656	0	1829	5416	0	2907
Simazina	3168	0	1628	3655	0	1830	5461	0	2922
Tebuconazol	3160	0	1625	3657	0	1828	5429	0	2922
Terbufós	3162	0	1621	3655	0	1827	5429	0	2918
Trifluralin	3172	0	1627	3624	0	1828	5468	0	2922
Total	55499	0	28470	79436	0	39903	118739	0	63770

The results provided by SISAGUA rarely provide data on water treatment sites. One way to improve the monitoring of pesticide residues in water could be by mapping and making the water collection points available. Based on this data, it would be possible to analyze locations where the residues could be coming from and propose ways to mitigate them. An analysis of the region's environmental, agrarian and social characteristics is essential for efficiently managing pesticide residues in water, and this would also facilitate a joint study by agencies such as MAPA, ANVISA, and IBAMA.

The summary for the food residue analysis management program is shown in the figure below (Figure 3).

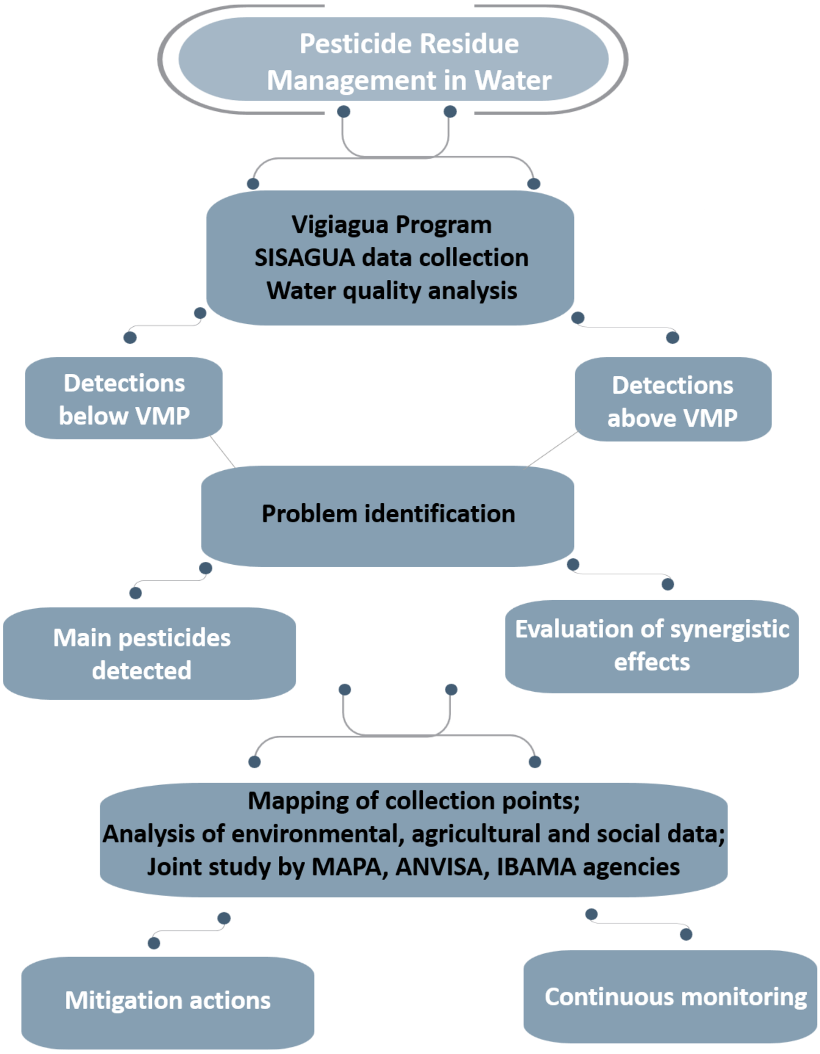

Figure 3. Graphic summary for pesticide residue management in water with proposals for improvements.

2.3 Pesticide residues in the soil

Information on monitoring pesticide residues in soil is scarcer than for food or water. Some national programs for sustainable soil and watershed management include the National Program for Soil Interpretation Surveys in Brazil and the National Program for Sustainable Soil and Water Management in Micro-Watersheds. However, none have identified critical contamination points and forms of mitigation.

Brazil has a large planted area treated with pesticides, and despite already being reported as a critical point for contamination by these products (Tang and Maggi, 2021), the identification of contamination points, as well as the management of these residues, is still a topic most addressed by research institutions in the country. Research results are made available separately by several studies that indicate the location of pesticide contamination since no data is provided online by national or state systems (Fernandes et al., 2020).

One of the latest reviews evaluated approximately 220 soil samples, identifying approximately 55 types of pesticides in the soils between 1995 and 2018 (Fernandes et al., 2020). Among the pesticides detected, 46% were insecticides, 29% were fungicides, 23% were herbicides, and 2% were acaricides (Fernandes et al., 2020). In addition, most of the pesticides detected (58%) were from the organochlorine chemical class (Fernandes et al., 2020). In this study, only 46% of the Brazilian states were listed: Amazonas, Bahia, Maranhão, Mato Grosso, Minas Gerais, Pará, Paraná, Rondônia, Rio de Janeiro, Rio Grande do Sul, Santa Catarina and São Paulo (Fernandes et al., 2020). The highest pesticide concentrations were detected in Pará, Rio de Janeiro, and Paraná (Fernandes et al., 2020). In agricultural soils, higher concentrations of pesticides such as trifluralin, alachlor, endosulfan alpha, and beta, and aldrin were observed (Fernandes et al., 2020). Residential soils showed higher concentrations of DDT and HCH and their respective metabolites (Fernandes et al., 2020). However, concentrations in residential soils were higher than in agricultural soils (Fernandes et al., 2020).

The half-life of pesticides in soil is an important attribute to be observed, as it is related to the greater risk of exposure to these products. It is estimated that pesticide residues in approximately 1.88 million km2 of agricultural land exceeded 1 mg kg-1 soil−1 for more than 180 days a year. These regions are located mainly in China (0.83 million km2), Brazil (0.23 million km2) and the United States (0.17 million km2) (Tang and Maggi, 2021).

The most significant concern with pesticide residues in the soil is in areas with large crops such as soybeans, corn, wheat, beans, and cotton, Brazil's most widely planted species. The map below shows the total area planted with these crops by state (Figure 4). Coincidentally, the highest consumption of pesticides is also observed in the areas with the most significant area planted with these crops (Figure 4). This is expected since large productions require more pesticides to control pests, diseases, and weeds. Therefore, in these areas, monitoring pesticides in the soil must be more rigorous, thus avoiding contamination of the environment.

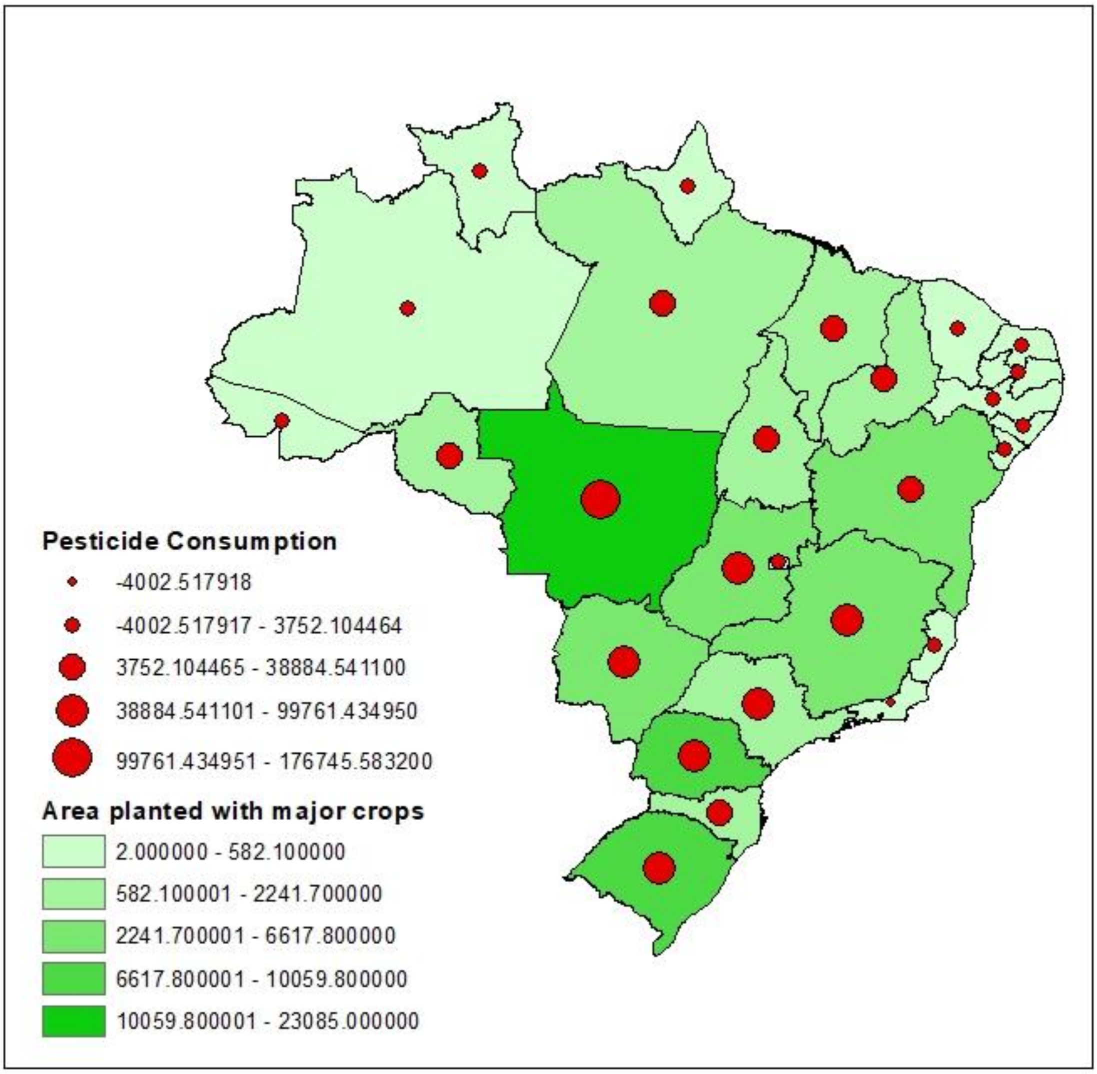

Figure 4. The sum of the area planted with soybeans, corn, wheat, beans, and cotton and the total consumption of pesticides by the Brazilian state for the 2022/2023 harvest. The author prepared the map based on data from CONAB, 2024, and IBAMA, 2022.

The lack of unified results on contamination sites, concentrations, and identified types of pesticides makes it challenging to propose monitoring and mitigating these products in Brazilian soils. In addition, half-life estimates tend to be inaccurate due to Brazil's sizeable territorial extension, which results in a great diversity of soil and climate characteristics. Following the National Program for Monitoring Water Quality for Human Consumption (Vigiagua) example, a program could be implemented to monitor soil quality, including detecting pesticides in strategic points such as agricultural areas and native areas close to production areas. Based on this data, mitigation plans could be drawn up, such as implementing green areas with phytoremediation species to reduce pesticide residues in the soil and prevent these products from reaching the water. In addition, it would be possible to promote more excellent monitoring in areas of more significant contamination and identify related problems.

The graphic summary for the food residue analysis management program is shown in the figure below (Figure 5).

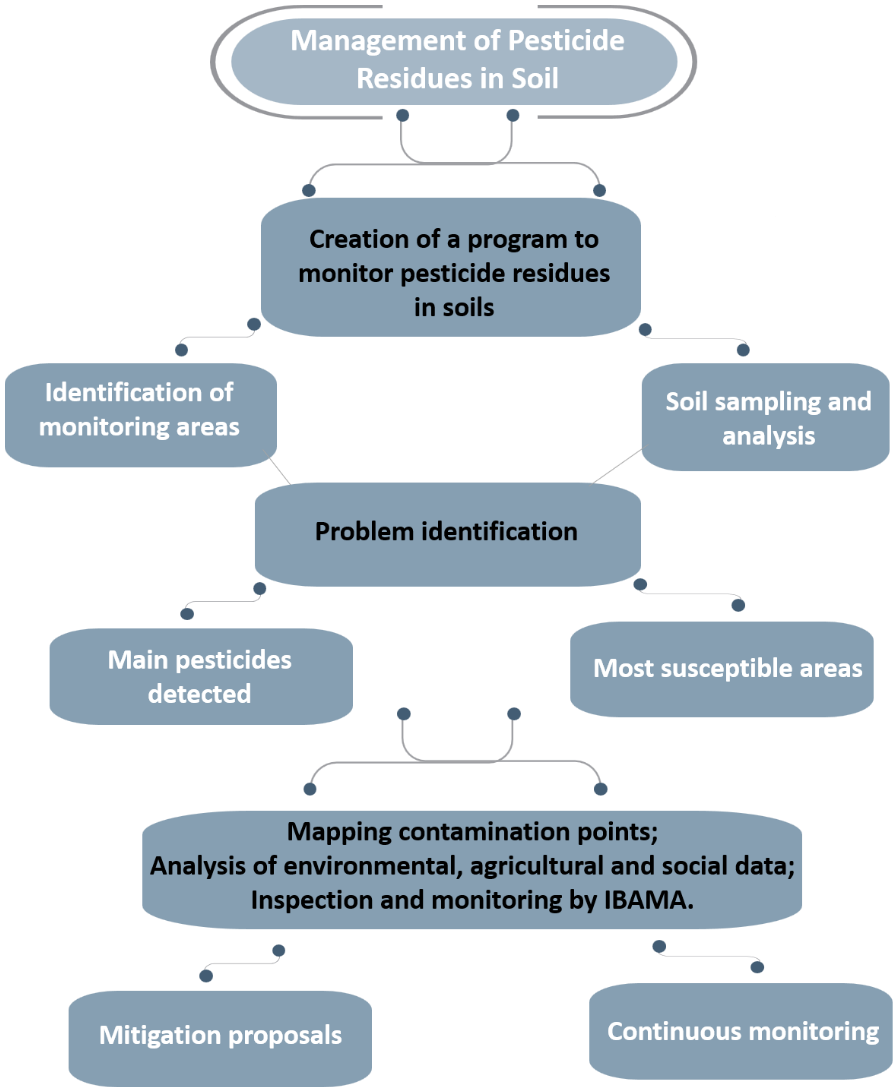

Figure 5. Graphic summary for pesticide residues in soil with proposals for improvements.

3. Unified Management Proposal

From the data presented for analysis and diagnosis, it is possible to observe how decentralization and difficulty in accessing data can be a barrier to managing and handling pesticide residues. In Brazil, many NGOs deal with environmental issues, but only a few specifically address toxic chemical products such as pesticides. Some of them are: Associação de Combates aos Poluentes (ACPO), Associação de Trabalhadores Expostos a Produtos Químicos (ATESQ), Rede de Ação sobre Agrotóxicos e suas Alternativas na América Latina (RAPAL), Associação para a Proteção do Meio Ambiente de Cianorte (APROMAQ) and Toxisphera (Environmental Health Association). However, none provide complete data or reports on contamination locations by pesticide residues. In this sense, Brazil's unified management of pesticide residues is proposed as of Law 14.785 of December 27, 2023. In this law, articles 22 and 58 establish the Unified System for Registration and Use of Pesticides and Environmental Control Products and the Unified System for Information, Petition, and Electronic Evaluation (Brazil, 2023).

According to Law 14.785/2023, the Unified System for Registration and Use of Pesticides and Computerized Environmental Control Products will be the responsibility of the registering agencies (Brazil, 2023). The Ministry of Agriculture and Livestock (MAPA), the National Health Surveillance Agency (ANVISA), and the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) will be the agencies responsible for implementing, maintaining and updating the system within their remits (Brazil, 2023). This involves collaboration to ensure that data is synchronized and that regulatory guidelines are being followed consistently.

The Unified System for the Registration and Use of Pesticides and Computerized Environmental Control Products must include all establishments involved in the pesticide chain, such as producers, handlers, importers, exporters, research institutions, distributors, qualified professionals, farmers and service providers (Brazil, 2023). This registry ensures that all parties involved are monitored and regulated.

Data from the Unified System for the Registration and Use of Agrochemicals and Computerized Environmental Control Products must be captured electronically through agronomic prescriptions, which will be filled out by legally qualified professionals (Brazil, 2023). This allows real-time monitoring of the use of agrochemicals, facilitating the detection of irregularities and the implementation of corrective actions.

The minimum content of the Electronic Agronomic Prescription includes clear identification of the person responsible for the use of the agrochemical; specification of the crop treated and the area covered for monitoring correct application; geographic precision of the application to allow tracking and control; information on the specific product used to facilitate the identification of possible problems; exact quantity of the product to ensure that application limits are respected; methods used in the application to verify compliance with good practices; time-lapse recording of the application for monitoring and planning; information on the necessary care to protect human and animal health and the environment; details of the technical manager, the applicator and the user to ensure accountability and transparency (Brazil, 2023).

The Unified Electronic Information, Petition and Assessment System (Sispa) aims to: create a centralized system for assessing pesticide registrations and changes to registrations, eliminating redundancies and improving the efficiency of the regulatory process; promote transparency in the progress of processes related to pesticides, allowing companies and interested parties to monitor the status of their requests based on the provision of this information; simplify the process of submitting and assessing data presented by registering companies, promoting agility in assessments; receive and efficiently process data related to the marketing of pesticides, ensuring compliance with regulations; implement robust measures to protect sensitive information and industrial secrets, taking responsibility for their integrity and confidentiality; maintain detailed records on the quantity of imported, produced, exported and marketed products, in addition to non-marketed products, for better market control; promote the maintenance of an updated registry of companies and areas authorized for research and experimentation of pesticides, promoting transparency and traceability; facilitate communication between registrant companies and regulatory agencies through electronic platforms; promote mandatory electronic submission of all registration and amendment requests, aiming at the efficiency and integrity of the process (Brazil, 2023). The development and implementation of Sispa will be within 360 days from the publication of the law, and MAPA will be responsible for coordinating the development and implementation of the system and ensuring that the technical and operational requirements are met (Brazil, 2023).

The unified management of pesticide residues in Brazil, based on the articles of the new law, can be effectively achieved through the creation of integrated systems and coordination between MAPA, ANVISA, and IBAMA. The proposal aims to guarantee food safety, environmental protection, and public health while facilitating control and transparency in the use of pesticides in the country. Implementing a unified digital platform, creating a management committee, and promoting training programs are essential to achieve these objectives.

3.1 Integration between Systems and Agencies

To ensure effective and integrated management of pesticide residues in Brazil, it is strategic to create a National Pesticide Residue Management Program based on the creation of robust coordination between regulatory agencies, including MAPA, ANVISA, and IBAMA (Figure 6). Creating an inter-institutional steering committee and developing a unified digital platform is essential to ensure efficient information exchange and to implement coordinated audit and inspection actions within the program. These initiatives aim to increase transparency, regulatory compliance, and safety in the use of pesticides, promoting a more sustainable agricultural environment that is safer for public health and the environment.

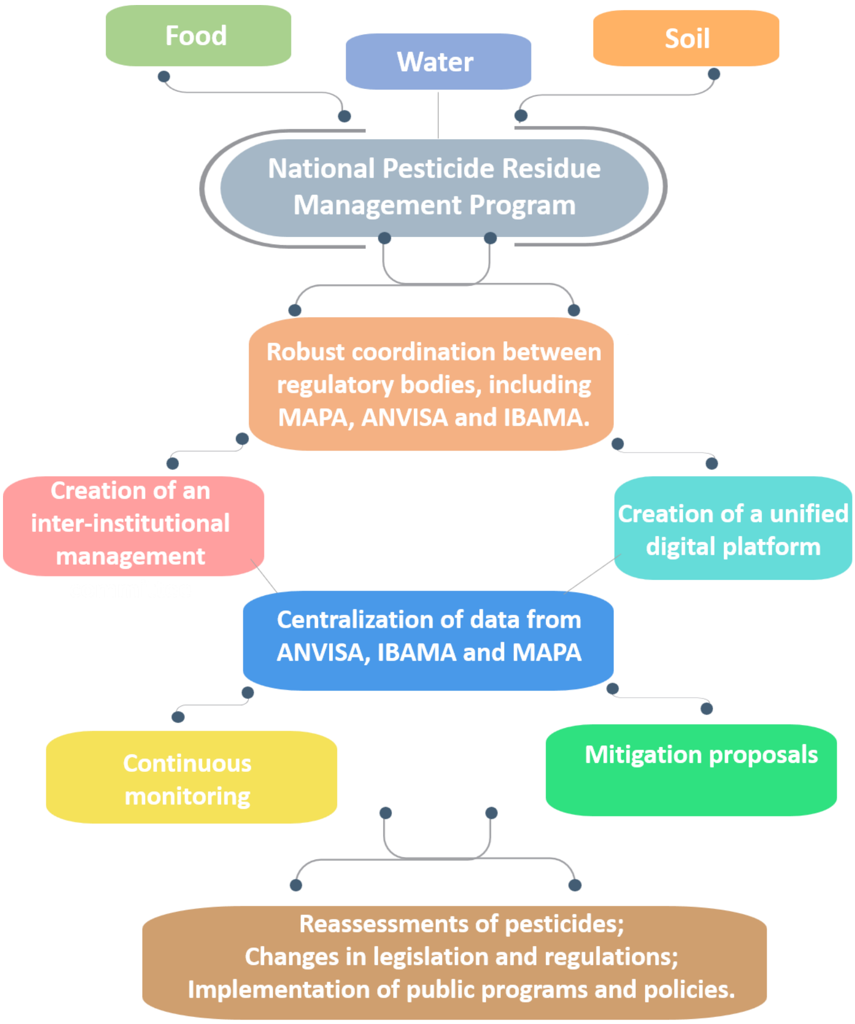

Figure 6. Graphic summary for the proposal for a National Pesticide Residue Management Program

3.1.1 About the National Pesticide Residue Management Program

A pesticide residue management program should focus primarily on monitoring to reduce environmental or food contamination, thereby maintaining the quality of the environment, food, and water. Therefore, the main objectives of the program could be to reduce the concentration of pesticide residues in soil, water, and food; to encourage the use of alternative and less harmful pest control methods; to establish an effective system for monitoring the presence of pesticide residues in the environment; to update and strengthen laws and regulations related to the use and disposal of pesticides; to increase knowledge and awareness of the impacts of pesticides and safe management practices.

Specific targets that would allow the progress of the program to be measured include: a) reviewing and updating pesticide residue legislation by the end of 2025; introducing new regulations for the safe disposal of pesticide containers by 2025; b) implementing pesticide residue monitoring systems in all agricultural regions by 2026; conducting biannual soil and water analyses in critical areas; c) increase the use of biological pesticides by 20% by 2027; train 70% of farmers in integrated pest management practices by 2026; d) reduce the concentration of pesticide residues in drinking water by 50% in the next five years, and reduce the presence of pesticide residues in food by 30% by 2028; e) legislate the adoption of buffer strips based on a literature review of tolerant species with the ability to remediate sites with probable pesticide residues; f) establish recommended sequential cropping protocols, considering green manures or forage plants capable of reducing herbicide residues applied in pre-emergence in agricultural areas; g) develop and implement awareness programs for farmers and the community in general within two years; conduct annual educational campaigns on the risks of pesticides and safe practices for their use and disposal.

To measure progress towards the established goals, it is necessary to define performance indicators, such as concentration of pesticide residues in drinking water (mg/L); percentage of foods tested with pesticide residues above permitted limits, estimated percentage of agricultural and non-agricultural areas with pesticide residues; number of farmers trained in integrated pest management practices; number of new regulations implemented; scope of awareness campaigns.

As for planning, actions are necessary, such as introducing buffer zones with phytoremediation species around water bodies to avoid contamination by runoff; promoting the use of agricultural practices that minimize the use of pesticides, such as crop rotation and the use of biological control; subsidizing the cost of biological products to make them more affordable for farmers; holding workshops and training on integrated pest management;

encouraging the use of modern monitoring equipment and training personnel to use it; establishing partnerships with universities and research institutes for regular analyses; organizing public consultations and workshops to review existing legislation; creating an inter-institutional working group to coordinate the implementation of new regulations; develop educational materials (leaflets, videos, etc.) on the safe use of pesticides; collaborate with schools and local communities to disseminate information about the risks of pesticides.

3.1.2 Interinstitutional Coordination and Collaboration

The creation of the management committee would have as members representatives from MAPA, ANVISA, and IBAMA, whose functions would be to coordinate the implementation and maintenance of the systems, ensure the integration of data and information between the agencies, monitor and evaluate the effectiveness of pesticide residue management actions; develop policies and procedures for the exchange of information and inter-institutional collaboration.

To this end, creating an integrated digital platform would be necessary, unifying the data from MAPA, ANVISA, and IBAMA, each responsible for the assessments related to agronomic issues, human health, and environmental protection, respectively. A centralized interface that integrates the Registration System and Sispa would allow the efficient sharing of information and data between the agencies and the registering companies. The platform should have functionalities for submitting documents, monitoring processes, and accessing regulatory and market information.

Auditing and inspection are the joint responsibilities of MAPA, ANVISA, and IBAMA, and they should carry out regular audits and inspections to ensure compliance with established standards. The audit should include checking usage records, compliance with agronomic prescriptions, and analysis of residues in agricultural products. Based on these audit data and the data provided on the platforms, annual reports on the use of pesticides and residues detected in food, water, and soil could be published. These reports should be based on data collected by the Registration System and Sispa, providing a comprehensive overview of pesticide compliance and safety.

Based on the diagnosis and monitoring of pesticide residues, it is possible to identify the locations most vulnerable to contamination and propose forms of mitigation by directing public policies and government incentives for environmental protection and human health. Furthermore, ongoing training and educational campaigns would strengthen management as a whole, with the development of training programs for professionals qualified in issuing agronomic prescriptions and applying pesticides and promoting educational campaigns aimed at farmers and companies on good agricultural practices, safe pesticide management, and regulatory compliance.

3.1.3 Financing and partnerships

According to article 62 of law 14.785/2023, the following may be used to provide resources for the inspection and promotion of the development of phytosanitary activities and the promotion of technological innovation in the agricultural sector in plant health: budgetary resources from the Union earmarked for the same purpose; donations from individuals or legal entities, public or private, national or international; resources from the National Fund for Scientific and Technological Development (FNDCT); resources from the National Environmental Fund; other revenues that may be allocated to it (Brazil, 2023).

The resources must be applied to the development and technical instrumentation of the areas of analysis and registration of pesticides and environmental control products; development, implementation, and maintenance of Sispa; control and monitoring of activities involving the use of phytosanitary products; training in phytosanitary management and training of multipliers in phytosanitary activities and rural worker safety; education in environmental control and phytosanitary management; hiring of ad hoc consultants for technical support in analyzing the registration processes of products considered a priority by the registering agency (Brazil, 2023).

Therefore, the resources needed to create and maintain the interinstitutional management committee and the unified digital platform could come from the funding sources mentioned in the law. These resources could also be used for monitoring waste, inspection, and promoting research in the area.

Based on pre-established protocols, state, municipal, and research institutions and NGOs could work in partnership to provide data for the integrated digital platform.

4. Final considerations

Pesticide residue management in Brazil faces complex challenges due to data decentralization and difficulty accessing relevant information. Law 14.785/2023 emerges as a response to these challenges, proposing a unified system for registering and using pesticides and environmental control products and an electronic information, petition, and evaluation system. The implementation of these systems promises to increase transparency, improve monitoring, and facilitate coordination between regulatory agencies, such as the Ministry of Agriculture and Livestock (MAPA), the National Health Surveillance Agency (ANVISA), and the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA).

Data integration and inter-institutional collaboration are essential elements for the success of this initiative. Creating an inter-institutional steering committee and developing a unified digital platform are critical steps to ensure the efficient exchange of information and the implementation of coordinated audit and inspection actions. The proposal also emphasizes the importance of ongoing training and educational campaigns to strengthen pesticide residue management, promoting good agricultural practices and regulatory compliance.

In addition, the proposal for a National Pesticide Residue Management Program, with specific goals and clear performance indicators, offers a concrete path to reducing environmental and food contamination. The introduction of buffer zones with phytoremediation species, the encouragement of the use of alternative and less harmful pest control methods, and the implementation of monitoring systems are key strategies to achieve these goals. Funding and partnerships with research institutions, NGOs, and state and municipal governments are essential for the sustainability and effectiveness of the program.

Finally, Law 14.785/2023 and the proposed strategies represent a significant advance in pesticide residue management in Brazil. Coordination among regulatory agencies, integrating systems, and promoting safe management practices are essential steps to ensure food safety, environmental protection, and public health. Continued monitoring, education, and enforcement efforts will be critical to the long-term success of these initiatives.

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ARTIGO CIENTÍFICO III

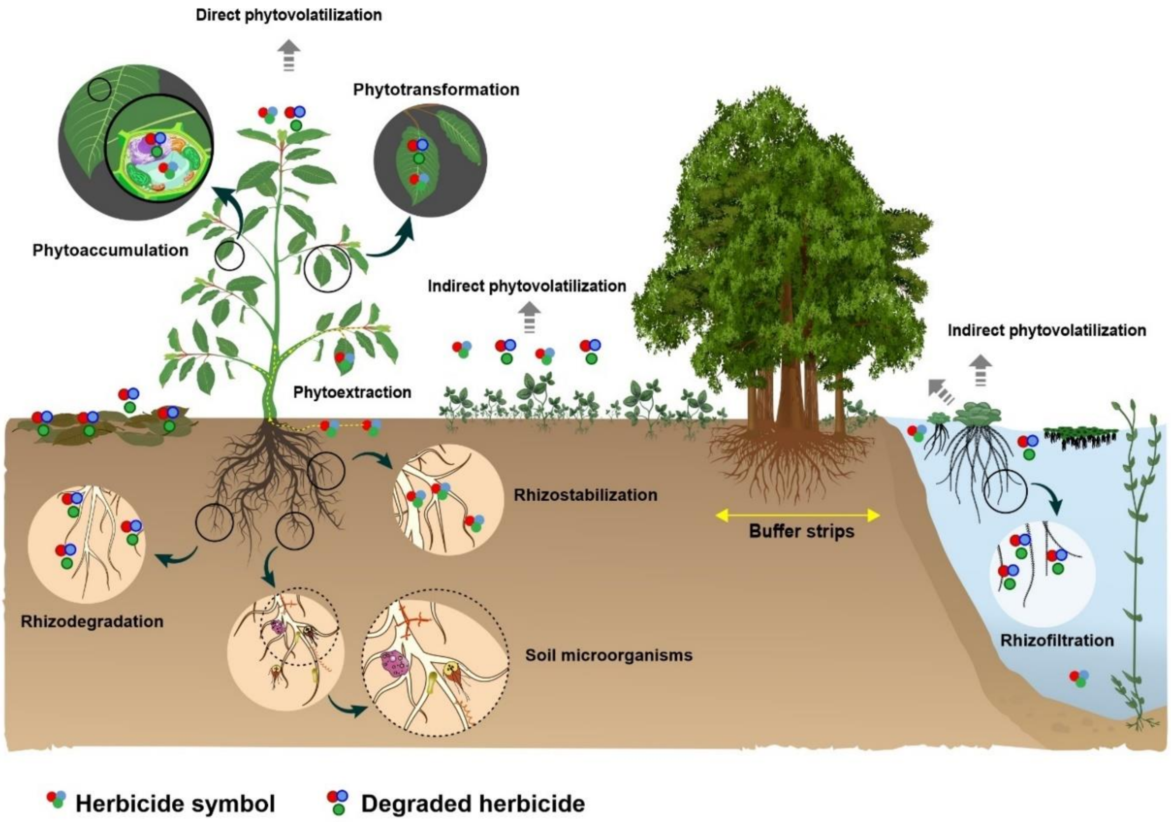
Phytoremediation: A green and low-cost technology to remediate herbicides in the environment

Abstract

Pesticide dependence is one of the main disadvantages of agriculture. Despite the advances in biological control and integrated management of plant pests and diseases in recent years, herbicides are still essential for weed control and constitute the main class of pesticides worldwide. Herbicide residues in water, soil, air, and non-target organisms are among the biggest agricultural and environmental sustainability obstacles. Therefore, we suggest an environmentally viable alternative to reduce the harmful effects of herbicide residues, a technology called phytoremediation. Remediating plants were grouped into herbaceous, arboreal, and aquatic macrophytes. Phytoremediation can reduce the loss of at least 50% of all herbicide residues to the environment. Among the herbaceous species reported as phytoremediators of herbicides, the Fabaceae family was mentioned in more than 50% of reports. This family is also among the main species of trees reported. Regarding the most reported groups of herbicides, it is observed that most of them, regardless of the group of plants, are triazines. Processes such as extraction or accumulation are the best known and reported for most herbicides. The phytoremediation may be effective against chronic or unknown herbicide toxicity. This tool can be included in proposals for management plans and specific legislation in countries, guaranteeing public policies to maintain environmental quality.

Keywords: Sustainable agriculture, pesticides, remediation, environmental service, ecosystem service.

Graphical abstract



1. Introduction

Environmental conservation and food productivity maintenance is, currently, a challenge. Modern agriculture causes several environmental problems due to the use of chemical products in crops. Globally, an estimated 64% of agricultural land is at risk of pesticide pollution (Tang et al., 2021), and 2.5 billion hectares are contaminated with more than one chemical compound (Hough, 2021). The loss of pesticides from the environment affects non-target populations (Boutin et al., 2014). The most important product group is herbicides, the most used pesticides (Sharma et al., 2019).

Risk to individual health and increased cases of weed resistance are among the most researched topics (Parlakidis et al., 2022; Mendes et al., 2022). There is an extensive scientific debate about the chemical control of weeds, especially regarding the increased application of glyphosate, among other compounds, in transgenic crops (Kniss, 2017). With the rapid advancement of genetically modified crops, a decrease in herbicides has been observed; however, glyphosate use has increased (Benbrook, 2016). As a result, the high occurrence of new glyphosate-resistant weed biotypes (Bain et al., 2017) has led to the return to traditional pre-emergent herbicides (Fogliatto et al., 2020; Ribeiro et al., 2021).

The phytoremediation technology of sites with herbicide residues is a proposal that has gained considerable scientific interest. Pre-emergent and residual herbicides remain in the soil for long due to product and environmental characteristics. However, there is no management of the quantity of these products in the soil or clean technology systems to manage residues that reach water bodies. Many plants are capable of reducing the residual herbicides in the soil (Cunningham, 1997), as well as promoting the protection of watercourses (Fiore et al., 2019) and cleaning water (Alencar et al., 2020). We observed, however, that the decontamination capacity varies among the plant species used, as well as between the herbicide chemicals and edaphoclimatic conditions. In this regard, phytoremediation can be used as a green technology in managing ecosystems and preserving the environment.

Many studies on phytoremediation have been conducted and published in recent years; still, there are unanswered questions regarding herbicide residues: (a) Is it possible to make phytoremediation feasible as a technology for managing herbicide residues in agriculture? (b) Which plant species have the potential to create barriers against herbicide residues in water bodies? (c) Which groups of plants can be recommended for specific purposes in phytoremediation technology?

This review presents phytoremediation as a green technology to decontaminate environments harmed by herbicide residues. Information surveys were conducted on primary species used in herbicide remediation and the main decontamination tools. In addition, the new technologies used and prospects for performing a program for managing herbicide residues in the environment are listed.

2. Material and methods

A systematic review was carried out involving topics within herbicide use, related problems, and environmental decontamination through phytoremediation. For this, a search was done for keywords such as pesticides, herbicides, environmental contamination, phytoremediation, and bioremediation. About 300 papers were consulted, and 134 were referenced in this review.

The review covered all relevant material on the topic, including books, journal articles, monographs, newspaper articles, historical records, government reports, theses, dissertations, and any other type of research. The search was carried out in the main databases such as Web of Science, Scopus, Scielo, Science Direct, and Google Scholar. The survey was carried out during the years 2022 and 2023 ant the results of the surveys were from the year 1997 to 2023. Data were filtered by reading the articles, and only the results of those referring to phytoremediation of herbicides were used. Then, descriptive statistics were used to group the data in tables and figures. To make the tables, information on phytoremediation species and family, phytoremediated herbicide, percentage of phytoremediation, and mechanism by which the plant decontaminated the environment was used. To make the tables, the data were grouped, and percentages were calculated for: families within plant groups, herbicide groups within plant groups, and phytoremediation mechanisms within herbicide groups. To make the tables and calculate the percentages of each group, Excel Version 2019 software was used and for the figures, CorelDRAW Standard Version 2021.

3. Use of herbicides and related problems

Herbicides are a class of pesticides intended for weed control. It is the main group of pesticides, as they represent more than 50% of all pesticides sold in the world, about 1,400,000 tons per year. The main consumer countries are the United States, China and Brazil. The main herbicides used in these countries are glyphosate, atrazine, and 2,4-D, which together represent more than 50% of sprayed herbicides. The main crops that use herbicides are soy, corn, sugar cane, wheat, rice, as they occupy large areas (FAO, 2023).

Since the Green Revolution (the 1960s), world agriculture has transformed, and herbicides have been essential inputs (Gianessi, 2013; Harwood, 2019). The most crucial pesticide of all time is glyphosate, which is used to desiccate plants and produce straw, control weeds in transgenic crops, and clean areas (Benbrook, 2016). Owing to the wide use and characteristics of the product, glyphosate has been linked to human health problems and the increase in resistant weed biotypes, which has urged the search for alternatives. (Silvia and Vidotto, 2020). The advancement of weed resistance, damage to human health, and rules of agricultural product certifiers (Richmond, 2022) have contributed to the decrease in the use of glyphosate. Consequently, glyphosate is being replaced by pre-emergent residual herbicides that have the potential to transfer between soils and water (Ye et al., 2021). Residual herbicides are essential for modern agriculture as they remain in the soil for days, months, and even years, becoming available in the soil for uptake by weed roots (Shaner, 2014).

Herbicides are used to replace plowing and harrowing to improve environmental conditions. Compared with soil tillage, herbicides reduce erosion, fuel use, greenhouse gas emissions, and nutrient runoff (Gianessi, 2013). Therefore, resuming mechanical weed-control methods is not viable. The adoption of no-tillage has also shown promise in modern intensive agriculture. However, chemical desiccation with glyphosate and other products is a fundamental step in straw formation. Due to its low toxicity, glyphosate is considered safe, especially in crops of great economic interest, such as soybean, corn, and cotton (Kniss, 2017). Besides glyphosate, several herbicides are used for weed control or pre-harvest desiccation, representing approximately half of all herbicides worldwide (Zhang, 2018).

The replacement of glyphosate with other herbicides promotes the use of residual and pre-emergent products, such as acetochlor, chlorimuron, fomesafen, flumioxazyn, imazethapyr, pyroxasulfone, s-metolachlor, and sulfentrazone. Residues of these herbicides are commonly detected and quantified in other crops (Whalen et al., 2019). These products vary in persistence in the soil (Shaner, 2014; Mesnage and Zaller, 2021), and a great challenge for farmers is to limit the action of residues in the place where they are applied and within the period determined for control. The product leaflets mentioned specific periods for planting sensitive species. Herbicide residues, such as diclosulam, hinder the cultivation of sensitive species, such as sunflowers, for ≥18 months after the application (Silva et al., 2020). However, in some situations, this information is omitted from the package leaflets, and there are reports of carryover (Dias et al., 2019).

In countries such as Brazil, Italy, Spain, China, and the United States, atrazine, sulfentrazone, glyphosate, ammonium glufosinate, terbuthylazine, fluometuron, metolachlor, alachlor, ametryn, and simazine are found in areas close to crops, mainly in waterbodies (Santos et al., 2015; Masiol et al., 2018; Herrero-Hernández et al., 2017; Li et al., 2018; Lerch et al., 2011). Some reviews with information on water contamination by herbicides, detailed products and concentrations (Ferreira et al., 2016; Baillie, 2016; Tousova et al., 2017).

Herbicide residues in the environment generate debates on the following two accounts: i) intoxication of later crops and ii) environmental damage caused by herbicides in watercourses, causing a substantial impact on the aquatic ecosystem, notably on phytoplankton. Despite the significant biodegradation capacity of herbicides, their toxic effects on several groups of soil microorganisms have already been reported; however, many chronic effects are underestimated or unknown (Zhang, 2018; Barroso et al., 2020; Parlakidis et al., 2022). Official communication vehicles, such as the Ministry of Agriculture (MAPA, 2022), Agricultural

Marketing Service (AMS, 2022), and FAOSTAT (FAO, 2022), currently list products registered for sale with additional information, such as restrictions on use and grace periods.

The use of herbicides is essential; therefore, environmental services should be researched as mechanisms for eliminating or reducing potentially harmful residues in natural resources. The answer may lie in the floristic biodiversity and the ability of many plant species to tolerate residues from these products. Tolerant plants that decrease herbicide residues are categorized as phytoremediators.

4. Phytoremediation as a proposal to reduce herbicide residues

Countries with intense agriculture, such as Brazil, cultivate with the use of herbicides throughout the year with sufficient edaphic microbial activity to biodegrade pesticide residues. Microbial biodegradation is the primary remediation mechanism for herbicide residues (Sun et al., 2020). Efficient weed control can be combined with reducing the adverse effects of residues using remediation techniques. Among remedial agents, plant species have emerged as a technological innovation for herbicide residues (Blaylock, 2008). Even if herbicides are synthesized to control plant communities, selectivity is a positive feature of phytoremediation. Plant selectivity is defined as their ability to tolerate the product at a known dosage; thus, weeds are affected, and the plant of interest is preserved (Shamer, 2014).

Phytoremediation involves using photosynthetic plant systems to detoxify environments contaminated by inorganic compounds, radioactive chemical elements, petroleum-derived hydrocarbons, pesticides, explosives, chlorinated solvents, and industrial organic wastes (Flathman and Lanza, 1998; Glass, 1998). However, for herbicide residues, the business sector is still incipient, and bottlenecks may be related to identifying plants and processes that can eliminate herbicides in the environment. The soil/environment/pesticide relationship is very complex (Kaur et al., 2021); however, some processes of herbicide remediation by plants are known (Fig. 1).

Phytoextraction is a process in which plants can extract contaminants from the soil, water, and atmosphere (Kaur et al., 2021). Many Brassicaceae plants can be used for phytoextraction (Szczygłowska et al., 2011). Phytoextraction has already generated results in the field and is becoming a more common remediation technology (Kaur et al., 2021). Once plants extract herbicides, they can be placed in the roots or transported to the aerial parts, where they can be stored, metabolized, or volatilized (Kaur et al., 2021).

Phytoaccumulation, wherein plants sequester herbicides from the environment and store them in their tissues. For example, the phytoaccumulation of terbuthylazine by *Typha latifolia*, an aquatic macrophyte, has been reported (Papadopoulos and Zalidis, 2019). Similarly, the sulfentrazone accumulating potential of *Canavalia ensiformis* has been reported (Ferraço et al., 2019).

Phytostimulation or phytotransformation: once the herbicide is absorbed by the plant, it undergoes molecular modification, which can partially mischaracterize it or even cause complete mineralization. Atrazine is degraded inside *Poplar Trees* (Chang, 2005) or *Inga striata* (Aguiar et al., 2020). Dicamba is degraded in *T. latifolia* plants (Elsaesser et al., 2011).

Phytovolatilization: herein, the herbicide is transformed into a volatile molecule, or the original molecule is volatilized. The product is released into the atmosphere directly when the process occurs inside the plant (roots, leaves, or stems) or indirectly when many plants grow together in an area, promoting the volatilization of soil compounds (Kaur et al., 2021). Indirect phytovolatilization occurs when plants promote fluctuations in the water table or interfere with the amount of water in the soil, which promotes the release of gases (Kaur et al., 2021). In this case, many plants are required to characterize the process (Kaur et al., 2021). *Lolium multiflorum* plants can promote phytovolatilization of trifluralin (Li et al., 2001).

Rhizodegradation: Soil microorganisms are influenced by plants through exudates released into the rhizosphere, which promote the degradation of herbicides (Kaur et al., 2021).

This is an essential remediation process because microorganisms are the primary degraders of herbicides in tropical environments. The rhizodegradation of atrazine, hexazinone, and metribuzin is carried out by aquatic macrophytes, Poaceae, algae, cyanobacteria, and trees (Král'ová and Jampílek, 2022).

Rizostabilization or phytostabilization: Some plants promote stabilization of the herbicide in the rhizosphere, making it unavailable in the soil solution. The objective is to prevent or reduce herbicide migration. Stabilization can occur after binding to soil organic matter or adsorption to roots (Král'ová and Jampílek, 2022). According to Bicalho and Langenbach (2013), plants of *Cecropia hololeuca* and *Trema micranta* are capable of stabilizing atrazine.

Rizofiltration, or phytofiltration, is a process used to remediate water bodies. Herbicides are removed from water through adsorption, precipitation, or absorption in the rhizosphere of aquatic macrophytes, which sometimes involves related microorganisms (Kristanti et al., 2021).

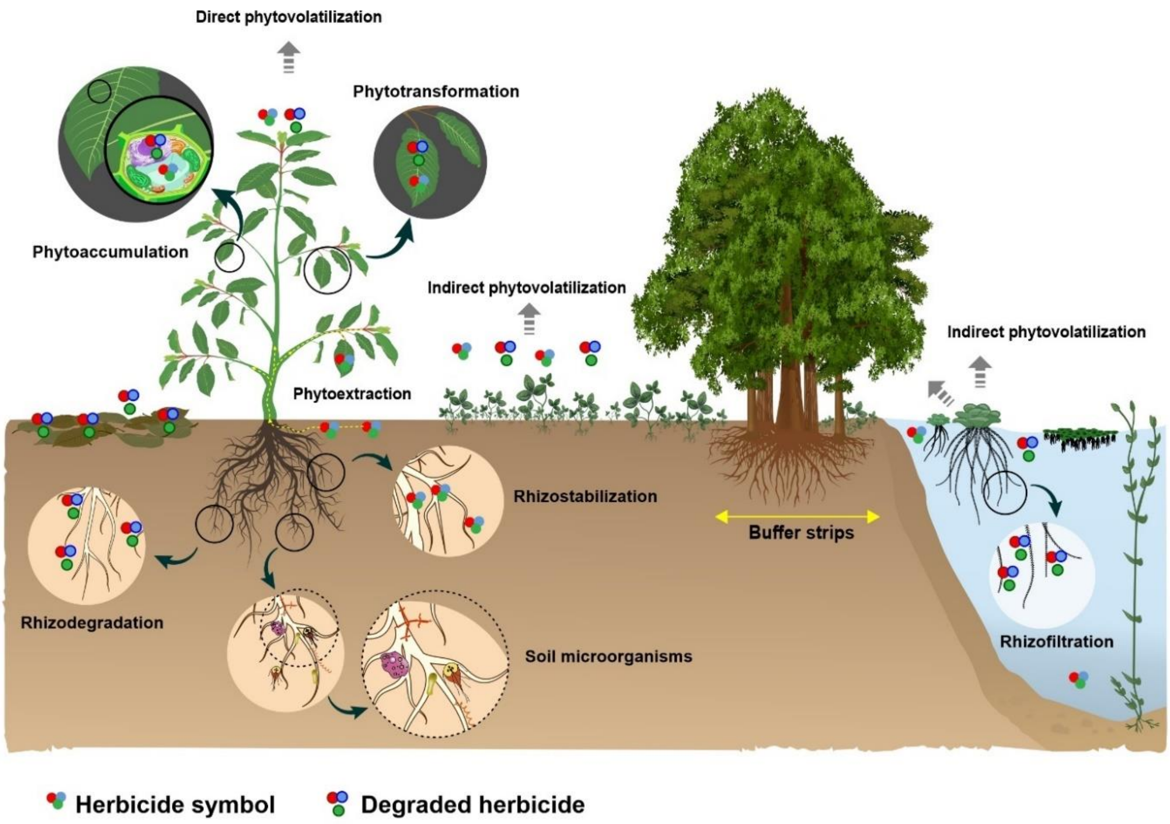


Figure 1. Phytoremediation processes are carried out by plants to decontaminate areas with herbicide residues. These processes can be classified as one of the leading green technologies for reducing herbicide residues in water bodies

Plant species and the process by which the plant will reduce herbicides in the environment are decisive in any waste management program. Herbaceous species with the potential for herbicide degradation, extraction, and accumulation are the most suitable for cultivation. These actions are observed in genetically improved small plants used as fodder or green manure and inserted into production systems (Mendes et al., 2020; Silva et al., 2020). Crop rotation is the principle behind using this group of species. The ability to reduce herbicide residues used in the previous season allows more crops during the year.

Plants arranged in buffer strips (Fig. 1) are examples of watercourse protection against herbicide residues. The herbicides reach the plants through runoff, leaching, and air and undergo the degradation processes presented (Fig. 1). In these cases, the essential process is rhizosphere degradation. Buffer strips prevent herbicides from reaching watercourses (Mcknight, 2022), despite occupying part of the arable area. For soils prone to runoff, buffer strips were efficient, reducing by up to 67% the amount of atrazine, metolachlor, and glyphosate that would reach the water (Lerch et al., 2017). Several reviews have addressed the potential use of vegetated strips (Otto et al., 2012; Burguet et al., 2018; Lorenz et al., 2021).

Considering that environmental laws in countries such as Brazil provide for the maintenance of vegetation around water matrices, herbicide phytoremediation technologies can be used for the indicated species. Perennial species from natural areas around cultivated fields can retain and extract residues from the soil and block the arrival of herbicides in water (Dos Santos et al., 2019; Fiore et al., 2019). The trees present secondary growth, which favors the accumulation of herbicides due to the lignification of the tissues and the larger plant size (Cabral, 2012). Additionally, a large volume of exploited soil allows for a better phytoremediation process because herbicides can be lost by leaching at greater depths.

In some areas marginal to water bodies, excess water is present in the soil. The discovery of herbicide residues in flooded environments or lakes is a major problem because the plants indicated for the remediation of these environments must be tolerant or adapted. Aquatic species have been proposed to remove herbicide residues from water (Olette et al., 2008; Ribeiro et al., 2019; Alencar et al., 2020, Santos, 2020).

The phytoremediation processes (Fig. 1) of herbicide sites can occur associated with the same plant or in a system with several plants. Thus, the plant biomass in this area is directly related to the phytoremediation rate. The rate can be calculated by considering the mass of the extracted product as a function of plant biomass and the time taken to reduce pesticide residue. A list of plant species by group and herbicide is presented, considering the percentage remediated and, in some cases, the phytoremediation process (Table 1, 2 and 3).

4.1 Phytoremediation processes by groups of plants and herbicides

Phytoremediation may be required in various environments with herbicide residues, both natural and agricultural. Groups and families of plants were used for this purpose. Our research showed that herbaceous species were the most frequently reported among the most researched groups for phytoremediation, followed by macrophytes and trees (Fig. 2). Herbaceous species facilitate and optimize an area's remediation in a short cultivation time due to their short cycle. In addition, there are advantages to working with herbs: availability of seeds, planting technology, other agricultural and ecological benefits to the area, and optimization of soil use.

Among the herbaceous species reported as phytoremediators of herbicides, the Fabaceae family was mentioned in more than 50% of reports. This family is also among the main species of trees reported. Legumes add value to the system by associating with nitrogen-fixing bacteria, making this nutrient available in the soil. Additionally, many Fabaceae species are direct food sources for households or domesticated animals. The family with the highest number of reports for the macrophyte group was Araceae (Fig. 2).

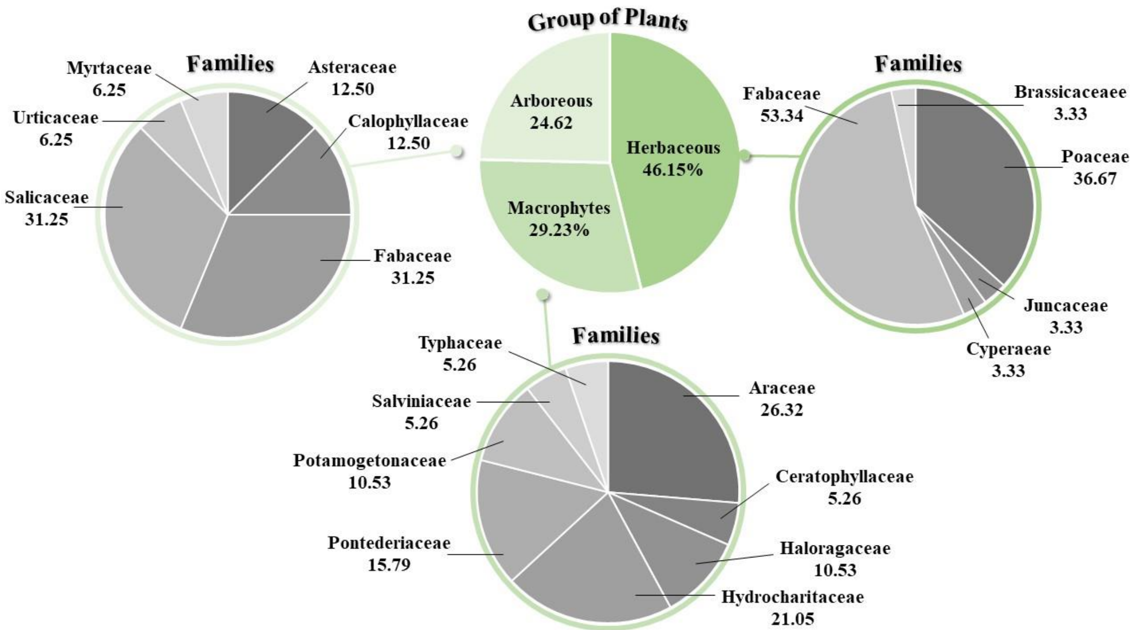


Figure 2. Percentages of plant groups and families reported as phytoremediators in environments contaminated by herbicides (Based on available published articles, see references in Table 1, 2 and 3)

Regarding the most reported groups of herbicides, it is observed that most of them, regardless of the group of plants, are triazines. Triazines, especially the herbicide atrazine, are the most researched because of their wide use in corn and sorghum crops by large agricultural producers such as the United States, Brazil, and Mexico. Atrazine is the most detected pesticide in water worldwide and has high soil mobility and persistence (Rostami et al., 2021). Triazines also persist in application areas and present significant risks to subsequent crops. However, glyphosate, the most widely used pesticide in the world, is not a significant focus of phytoremediation research (Fig. 3). This is probably because of the physical and chemical properties that make it less available and active and have a very low movement capacity (Shaner, 2014).

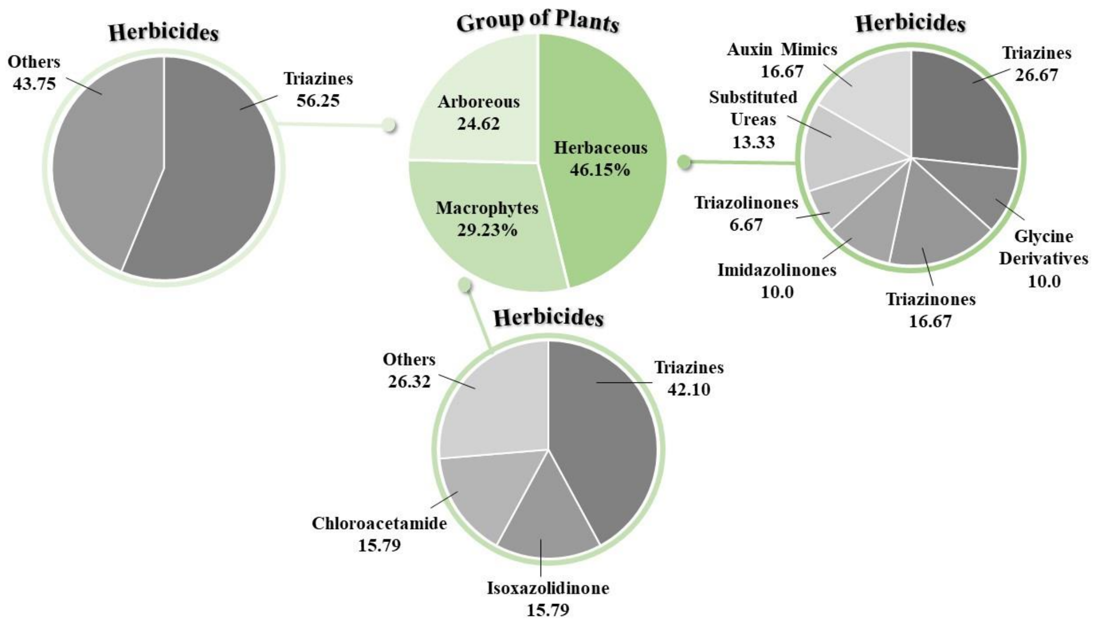


Figure 3. Leading groups of phytoremediated herbicides by plants (Based on available published articles, see references in Table 1, 2 and 3)

The processes by which plants extract or degrade herbicide residues are still poorly understood. Even for the largest group of herbicides studied, triazines, most results did not identify the process of the plant in phytoremediation of the environment (Fig. 4). Processes such as extraction or accumulation are the best known and reported for most herbicides, probably because of the greater ease of obtaining these data. However, phytostabilization and rhizodegradation are more challenging to quantify and identify (Fig. 4).

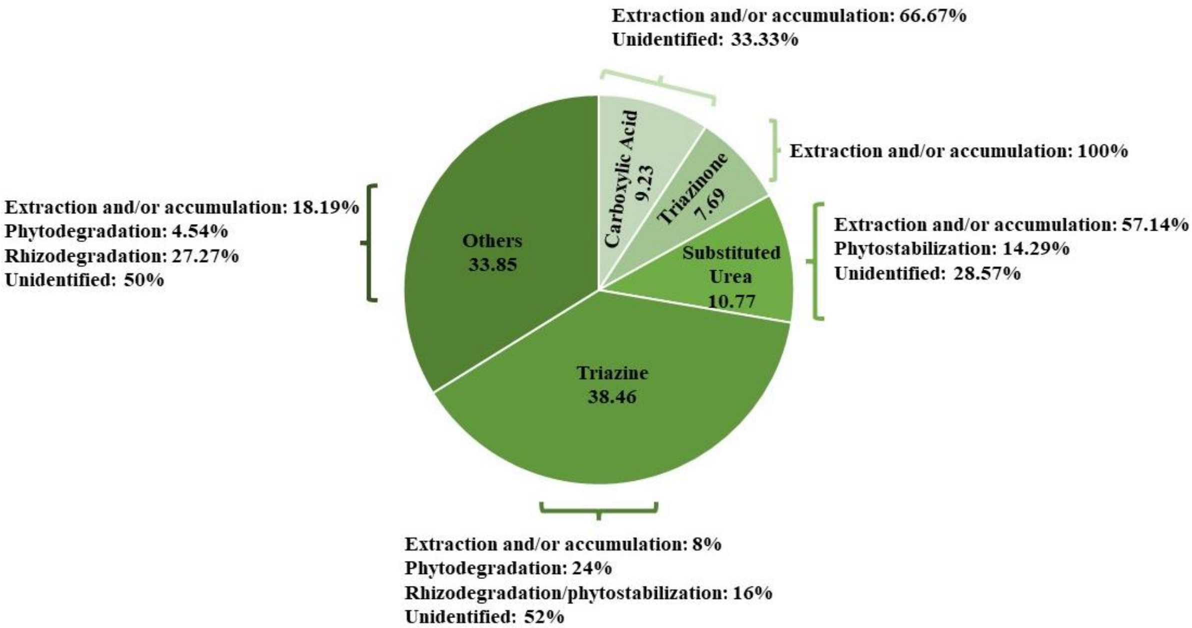


Figure 4. Phytoremediation processes by plants reported in different groups of herbicides (Based on available published articles, see references in Table 1, 2 and 3)

4.2 Phytoremediation of herbicides by herbaceous species and green manures

Green manure plants have been incorporated into production systems and are advantageous to agriculture, mainly because of their short cycle. The use of herbaceous plants in crops has increased in recent years (Ma et al., 2021; Nascimento et al., 2022). Therefore, it is essential to verify the possibility of using herbicide residues in the phytoremediation of soil.

Agricultural areas often contain unprotected soil. The application of herbicides in this environment can result in water contamination owing to the slope and other environmental characteristics. Runoff of herbicides can cause residues to reach watercourses, such as estuaries, as observed for products such as acetochlor, hexazinone, and metolachlor (Tyohemba et al., 2020). Herbaceous species can be cultivated directly in agricultural areas using rotation schemes or vegetative protection strips as conservation tools (Lin et al., 2011). For herbaceous plants, the main processes for mitigating herbicide transport are (1) increased infiltration and solute-soil interactions; (2) decreased surface water runoff velocity and promotion of sedimentbound herbicide deposition; (3) increased diversity of soil microbial communities and increased herbicide degradation; and (4) increased uptake, accumulation, and adsorption of herbicides to vegetation and soil (Reichenberger et al., 2007).

The rapid growth of *C. ensiformis*, *Glycine max,* and *Vicia sativa* has enabled the extraction and degradation of large amounts of herbicide residues in the soil, exceeding 90% of the total amount applied (Teófilo et al., 2020; Souto et al., 2020). A list containing herbaceous species with related herbicides and the percentage of remediation has been compiled and presented in Table 1.

Table 1. Herbaceous, forage, green manure, or food plants that remediate environments contaminated by herbicides

Herbaceous, Forage, Green Manure, or Food Plants					
Species	**Family**	**Herbicide**	**% remediation**	**Mechanism**	**Source**
Canavalia ensiformis	Fabaceae	imidazolinone	91.0*	Rhizodegradation	Souto et al., 2020
Canavalia *ensiformis*	Fabaceae	hexazinone	11.2**	Phytoextraction	Teófilo et al., 2020
Canavalia ensiformis	Fabaceae	sulfentrazone	65.0**	Rhizodegradation	Mielke et al., 2020
Canavalia ensiformis	Fabaceae	tebuthiuron	22.5**	Phytoextraction / Phytoaccumulation	Mendes et al., 2021
Canavalia ensiformis	Fabaceae	quinclorac	13.4**	Phytoextraction / Phytoaccumulation	Mendes et al., 2021
Canavalia spectabilis	Fabaceae	hexazinone	4.8**	Phytoextraction	Teófilo et al., 2020
Chrysopogon zizanioides	Poaceae	atrazine	9.4*	Phytodegradation	Zhang et al., 2022
Crotalaria juncea	Fabaceae	sulfentrazone	27.0**	Not identified	Santos et al., 2019
Crotalaria spectabilis	Fabaceae	tebuthiuron	4.5**	Phytoextraction / Phytoaccumulation	Mendes et al., 2021
Crotalaria spectabilis	Fabaceae	quinclorac	1.7**	Phytoextraction / Phytoaccumulation	Mendes et al., 2021
Cynodon dactylon	Poaceae	glyphosate	7.0*	Not identified	Jacklin et al., 2020
Dactylis glomerata	Poaceae	terbuthylazine	73.0**	Not identified	Buono et al., 2016
Festuca arundinacea	Poaceae	atrazine	30.0*	Rhizodegradation / Phytostabilization	Sánchez et al., 2017
Festuca *arundinacea*	Poaceae	terbuthylazine	73.0**	Not identified	Buono et al., 2016
Glycine max	Fabaceae	imidazolinone	92.0*	Rhizodegradation	Souto et al., 2020
Hordeum vulgare	Poaceae	atrazine	30.0*	Rhizodegradation / Phytostabilization	Sánchez et al., 2017
Isolepis prolifera	Cyperaceae	glyphosate	7.0*	Not identified	Jacklin et al., 2020
Juncus kraussii	Juncaceae	glyphosate	7.0*	Not identified	Jacklin et al., 2020

Lolium multiflorum	Poaceae	terbuthylazine	40.0**	Not identified	Mimmo et al., 2015
Lolium perenne	Poaceae	atrazine	30.0*	Rhizodegradation / Phytostabilization	Sánchez et al., 2017
Lupinus albus	Fabaceae	hexazinone	8.6**	Phytoextraction	Teófilo et al., 2020
Lupinus albus	Fabaceae	tebuthiuron	15.0**	Phytoextraction / Phytoaccumulation	Mendes et al., 2021
Lupinus albus	Fabaceae	quinclorac	10.0**	Phytoextraction / Phytoaccumulation	Mendes et al., 2021
Pennisetum glaucum	Poaceae	hexazinone	1.1**	Phytoextraction	Teófilo et al., 2020
Raphanus sativus	Brassicaceae	hexazinone	7.3**	Phytoextraction	Teófilo et al., 2020
Stizolobium aterrimum	Fabaceae	tebuthiuron	16.7**	Phytoextraction / Phytoaccumulation	Mendes et al., 2021
Stizolobium aterrimum	Fabaceae	quinclorac	6.2**	Phytoextraction / Phytoaccumulation	Mendes et al., 2021
Urochloa brizantha	Poaceae	picloram	-	Not identified	Braga et al., 2016
Vicia sativa	Fabaceae	imidazolinone	93.0*	Rhizodegradation	Souto et al., 2020
Zea mays	Poaceae	atrazine	30.0*	Rhizodegradation / Phytostabilization	Sánchez et al., 2017

* Percentage in relation to treatment without plant; ** Percentage in relation to the total applied dose. “-“ Not calculated.

Green manure can phytoremediate areas with herbicide residues with a long residual effect and enable the use of the soil for succeeding crops, thereby reducing the inter-harvest period (Silva et al., 2020). Soil remediation with these plants can be performed in soybean plantations, where herbicides with long residual effects prevent rotation with vegetables. Adopting this strategy allows excellent food production without the need for new areas. Planting fast-growing species in a crop rotation scheme is already considered a technological tool for the cultural control of pests, diseases, and weeds, reducing the use of pesticides in the field.

Herbicides used in pre-emergence with residual effects can harm succeeding crops, and this effect is known as carryover (Grint et al., 2022). The imidazolinone group, including diclosulam, picloram, sulfentrazone, and tebuthiuron, is among the most studied products. The mixture of imazapic and imazethapyr promotes a residual effect of ≥10 months. However, it can be reduced to 2 months in the soil if remedied by soybean, *L. multiflorum*, and *Lotus corniculatus* allowing the early cultivation of rice (Souto et al., 2015). The herbicide diclosulam, which has a carryover effect for 12 months, is concentrated in the soil by more than 50% after 2 months of cultivation of *Cajanus cajan*, *C. ensiformis*, and *Raphanus sativus* (Silva et al., 2020). In this study, the authors clarified that remediation depends on the climate and soil characteristics.

Urochloa brizantha can decrease the concentration of picloram in the soil (Braga et al., 2016). Picloram has a carryover effect of more than 12 months, and the plants of *U. brizantha* allowed the cultivation of sensitive plants 2 months after the herbicide application. According to the authors, *U. brizantha* can degrade and absorb herbicides.

The maintenance period of green manure plants in the area is also crucial, as farmers need to use the land for another crop. In this sense, the cultivation of *C. ensiformis*, *Stizolobium* *aterrimum*, and *Lupinus albus*, for only 21 days reduced tebuthiuron residues in soils by 22, 17, and 15%, respectively (Mendes et al., 2020). In the same experiment, the authors verified that 21 days were sufficient for *C. ensiformis* to decrease the concentration of quinclorac by 13%. *Helianthus annuus* cultivated for 85 days in monoculture or intercropped with *C. ensiformis* reduced the concentration of sulfentrazone in the soil by >50%; however, the residue still caused injuries in sensitive plants cultivated after harvest (Melo et al., 2019).

When growing green manure plants, the objectives are related to improving soil quality, protecting the environment, increasing the supply of nectar for pollinators, and efficient fertilization (Ma et al., 2021; Nascimento et al., 2022). Additionally, the plants were chosen to adapt to the farmer's production system. Thus, the phytoremediation capacity is an additional advantage of these plants. Because of all the benefits sought, the central plants studied were legumes (Table 1).

4.3 Phytoremediation of sites with herbicide residues by tree species

Trees are plants with a deep root system, with high rates of transpiration and exploitation of soil volume, are directly related to biodiversity, and have wide genetic variability and high capacity for relationships with various organisms, especially rhizospheric microorganisms and nitrogen fixers. Therefore, trees are suitable for herbicide phytoremediation programs (Caires et al., 2011). Trees tolerate any herbicide residue in the soil because of their biomass; thus, when it is absorbed via the roots, the phytoremediation process has already been established.

Highly soluble herbicides in soil solutions, such as atrazine, are waterbody contaminants (Yu et al., 2020). Their use is restricted to several countries, notably the European Union. However, in countries where atrazine is frequently applied, water pollution can be prevented through barriers to tree species (Fiore et al., 2019; Santos et al., 2019). For example, *Calophyllum brasiliensis* and *Inga marginata* can extract >90% of the atrazine (Fiore et al., 2019). Several authors have reported phytoremediation using trees, which has proven to be an efficient technique for recovering and conserving native areas close to the application areas (Table 2).

Enrichment with tolerant species is a way to enhance the recovery of areas, as species diversity is an essential factor in recovering the natural characteristics of the place. Additionally, tree species should be used to protect water sources as they act as natural filters to prevent or reduce the arrival of herbicides in watercourses and underground (Chellaiah and Yule, 2018). The tree component is used more in areas close to large crops and can be used for recovery or preservation. These alternative influences the characteristics of the soil, which promotes the adsorption, degradation, and absorption of herbicides (Santos et al., 2019). In addition, the litter observed in these areas contributed to increased organic matter.

Similar to green manure plants, trees are selected for planting in an area because of their positive characteristics. Legumes are the plants most studied for the phytoremediation of herbicides (Table 2). Researchers have focused on the selection of native species that are tolerant to water-contaminated herbicides, such as trifluralin, 2,4-D, atrazine, sulfentrazone, and clomazone (Cabral et al., 2017; Heemann et al., 2018; Santos et al., 2019; Ferreira et al., 2019; Aguiar et al., 2020). Historically, herbicides with high mobility have been studied in phytoremediation studies with trees. Most of these studies did not mention remediation mechanisms (Table 2); however, rhizodegradation is strongly involved in reducing waste. Unique atrazine degradation genes have been identified in the rhizospheres of *I. striata* and *Caesalpinea ferrea* (Aguiar et al., 2020). The authors reported that the complete degradation of atrazine depends on the interaction between the plant species and the microbial community associated with the rhizosphere.

Table 2. Tree plants that remediate environments contaminated by herbicides

Species	Family	Herbicide	% remediation	Mechanism	Source
Tree Plants					
Calophyllum brasiliense	Calophyllaceae	ametryn	25,0*	Not identified	Dos Santos et al., 2018
Calophyllum brasiliensis	Calophyllaceae	atrazine	92,0*	Not identified	Fiore et al., 2019
Cecropia hololeuca	Urticaceae	tebuthiuron	-	Phytostabilization	Bicalho and Langenbach, 2013
Eremanthus crotonoides	Asteraceae	ametryn	26,0*	Not identified	Dos Santos et al., 2018
Eremanthus crotonoides	Asteraceae	atrazine	-	Not identified	Aguiar et al., 2020
Eucalyptus grandis x *E. urophylla*	Myrtaceae	2.4-D	-	Not identified	Heemann et al., 2018
Hymenaea coubaril	Fabaceae	atrazine	-	Not identified	Heemann et al., 2018
Inga edulis	Fabaceae	sulfentrazone	63,0*	Not identified	Dos Santos et al., 2019
Inga marginata	Fabaceae	atrazine	92,0*	Not identified	Fiore et al., 2019
Inga striata	Fabaceae	clomazone	-	Not identified	Aguiar et al., 2020
Populus euramericana	Salicaceae	atrazine	-	Phytodegradation	Chang et al., 2005
Populus glandulosa	Salicaceae	atrazine	-	Phytodegradation	Chang et al., 2005
Populus maximowiczii	Salicaceae	atrazine	-	Phytodegradation	Chang et al., 2005

Salix alba	Salicaceae	oryzalin	-	Not identified	Baz and Fernandez, 2002
Salix nigra	Salicaceae	bentazon	15,0*	Phytodegradation	Conger and Portier, 1997
Sesbania sesban	Fabaceae	quizalofop-ethyl	-	Phytoaccumulation	Mahakavi et al., 2015
Cybistax antisyphilitica	Bignoniaceae	2,4-D	-	Not identified	Cabral et al. 2023
Cybistax antisyphilitica	Bignoniaceae	atrazine	-	Not identified	Cabral et al. 2023
Cybistax antisyphilitica	Bignoniaceae	diuron	-	Not identified	Cabral et al. 2023
Cybistax antisyphilitica	Bignoniaceae	hexazinone	-	Not identified	Cabral et al. 2023

* Percentage in relation to treatment without plant; ** Percentage in relation to the total applied dose. “-“ Not calculated.

4.4 Phytoremediation of sites with herbicide residues by macrophyte species

Herbicides are water soluble, which is an essential feature. Additionally, many products are resilient in the environment; therefore, the leading destination of residual herbicides is water deposits (Souza et al., 2020). Once in the water, these products cause several harmful effects: they impair phytoplankton photosynthesis (Fairchild et al., 1998), act as endocrine disruptors (Suzawa and Ingraham, 2008), affect animal reproduction (Bautista et al., 2018), and promote chronic intoxication in humans, among many other problems (Mierzejewska and Urbaniak, 2022). Therefore, phytoremediation by macrophytes can be a viable solution for decontamination. The effectiveness of aquatic plants, especially those that float (Fig. 1), is because they are in direct contact with the polluted environment from which the contaminants are absorbed (Maine et al., 2004).

Aquatic macrophytes are essential for many environments. They constitute a food source, shelter, and reproduction place for aquatic animals, are used as ornamentals or indicators of environmental problems, promote the cycling of nutrients, are medicinal, and are used in human food (Mansour et al., 2022). In some situations, they negatively interfere with human activities, mainly when an environmental imbalance is caused by agriculture or industry. When they encounter suitable environmental conditions, macrophytes quickly occupy the environment and produce high biomass (Mustafa and Hayder, 2021). For several groups of pollutants, including herbicides, the use of “decontamination islands” surrounded by containment barriers can be recommended to prevent the uncontrolled propagation of aquatic phytoremediation plants and to be removed after the process (Bi et al., 2019).

Chemical and physical methods are used to clean polluted water and soil (Olguín and Sánchez-Galván, 2012). However, these techniques can be costly and, in some cases, negatively impact the environment (Sakakibara et al., 2011). Phytoremediation with macrophytes is viable as long as the plant species are under control. Species such as *Salvinia* *biloba*, *Eichhornia crassipes*, and *Pistia stratiotes* can potentially extract ≤100% glyphosate and >90% clomazone from water (Silva Santos et al., 2020; Alencar et al., 2020). Macrophyte species generally have a greater capacity to degrade herbicides in other plants because of the greater availability of residues in the water compared to the soil.

According to the surveys, herbicide degradation rates or decreases in water levels exceeded 80% (Table 3). Some studies have elucidated the mechanism of phytoremediation by macrophytes. However, these plants mainly perform rhyzofiltration (Fig. 1) of herbicides and can be strategically placed at points of higher concentrations of residues according to the adaptation in the place. Many macrophyte species have already been evaluated for their ability to remove herbicides from water at a high rate of phytoremediation (Table 3).

Table 3. Macrophyte plants that remediate environments contaminated by herbicides

Macrophyte Plants					
Species	**Family**	**Herbicide**	**% remediation**	**Mechanism**	**Source**
Ceratophyllum demersum	Ceratophyllaceae	metolachlor	98.0*	Phytoextraction	Rice et al., 1997
Egeria densa	Hydrocharitaceae	saflufenacil	83.0**	Rhizodegradation	Alonso et al., 2021
Eichhornia crassipes	Pontederiaceae	clomazone	90.0**	Not identified	Alencar et al., 2020
Eichhornia crassipes	Pontederiaceae	atrazine	79.0*	Not identified	Santos, 2020
Eichhornia crassipes	Pontederiaceae	diuron	95.0*	Not identified	Santos, 2020
Elodea canadensis	Hydrocharitaceae	metolachlor	96.0*	Phytoextraction	Rice et al., 1997
Lemna minor	Hydrocharitaceae	metolachlor	77.0*	Phytoextraction	Rice et al., 1997
Lemna minor	Hydrocharitaceae	terbuthylazine	62.0**	Phytoextraction	Panfili et al., 2019
Myriophyllum spicatum	Haloragaceae	atrazine	91.0**	Not identified	Qu et al., 2017
Myriophyllum spicatum	Haloragaceae	atrazine	-	Phytodegradation	Li et al., 2019
Pistia stratiotes	Araceae	clomazone	99.0**	Not identified	Alencar et al., 2020
Pistia stratiotes	Araceae	atrazine	79.0*	Not identified	Santos, 2020
Pistia stratiotes	Araceae	diuron	94.0*	Not identified	Santos, 2021

Pistia stratiotes	Araceae	clomazone	90.0**	Not identified	Escoto et al., 2019
Pistia stratiotes	Araceae	saflufenacil	95.0**	Rhizodegradation	Alonso et al., 2021
Potamogeton crispus	Potamogetonaceae	atrazine	91.0**	Not identified	Qu et al., 2017
Potamogeton crispus	Potamogetonaceae	atrazine	-	Phytodegradation	Li et al., 2019
Salvinia biloba	Salviniaceae	glyphosate	100.0**	Not identified	Silva Santos et al., 2020
Typha latifolia	Typhaceae	terbuthylazine	23.0**	Phytoextraction	Papadopoulos and Zalidis, 2019

* Percentage in relation to treatment without plant; ** Percentage in relation to the total applied dose. “-“ Not calculated.

5. New tools applied to phytoremediation of herbicides

The use of microorganisms to optimize soil remediation is a viable tool because microbial degradation in the soil is the primary means of dissipating herbicides into the environment, especially in tropical climates (Peterson et al., 2016). Rhizodegradation and phytostimulation are biological processes by which herbicides are degraded, usually by the action of detoxifying enzymes in the rhizosphere of plants (Rainbird et al., 2018). In these processes, absorbed herbicides can be degraded in secondary metabolic pathways (Cao et al., 2018) or stimulate the soil microbiota to promote the transformation of these contaminants into compounds with less or no toxicity (Melo et al., 2017; Ma et al., 2017), which is another method of inactivating herbicides is mineralization in a carbon compound (Radosevich et al., 1997).

Bacteria and fungi are the microorganisms most reported to biodegrade herbicides (Melo et al., 2017; Egea et al., 2017; Vieira et al., 2007; Chakraborty et al., 2002). The secondary products formed during herbicide degradation can be used as a source of carbon or nitrogen for the growth of microorganisms (Barroso et al., 2020). Bioaugmentation is a process used for decontamination, in which degrading microorganisms are inoculated into a contaminated environment (Cycoń et al., 2017). Among these microorganisms, those associated with plants, such as nitrogen fixers and mycorrhizal fungi, enhance the remediation of areas (Mielke et al., 2020; Dong et al., 2016) and should be prioritized in phytoremediation programs as they benefit the development of remedial plants.

Another possibility for increasing the efficiency of species in the phytoremediation process is the use of transgenic plants (Gyulai et al., 2014; Azab et al., 2016; Yan et al., 2018). Transgenics can be used to overexpress plant genes involved in the metabolism, capture, and transport of pollutants (Doty, 2008). Furthermore, specific genes from microbes, plants, and animals can be expressed in some plants to increase their ability to tolerate, remove, and degrade contaminants (Doty, 2008). However, the use of transgenic organisms is still questionable, making this tool less environmentally applicable than previously reported.

In addition to these processes, metagenomics has been used to identify genes and metabolic pathways involved in the degradation of xenobiotics (Aguiar et al., 2020). These studies are essential for evaluating the effectiveness of the dissipation process and the mechanisms that lead to the dissipation of herbicides (Aguiar et al., 2020). The identification of these mechanisms is complex. It is usually based on the assessment of microbiota, identifying the existence of markers that indicate the individuals, genes, and enzymes involved in the degradation process (Bengtsson-Palme et al., 2014; Quince et al., 2017). Metagenomics allows the identification of taxonomic and functional groups of microorganisms related to herbicide degradation, considering the complex interactions in the rhizosphere region (Bengtsson-Palme et al., 2014; Quince et al., 2017).

6. Final considerations and future perspectives

Agricultural expansion in many countries is, sometimes, against environmental conservation measures, especially in traditional management, where chemical products are used to control weeds. One of the biggest current concerns is the availability of water, which is directly influenced by agricultural production, either by the amount used or the risk of environmental pollution of watercourses.

Water management is a goal of sustainable development. Recently, water use policies have been proposed, and legislation for contamination risk analysis, product traceability, and tax incentives for ecosystem services have been updated. However, contamination by non-target organisms and fragile sites, such as waterbodies, persists. Thus, a herbicide residue reduction program should be proposed to mitigate the harmful effects of these products, which are most commonly used. These programs must consider the need for chemical weed control through environmental and social risk analyses.

Phytoremediation can be a response to this problem by promoting the decontamination of areas with herbicide residues and optimizing the use of the same area for food production. Phytoremediation can reduce the loss of at least 50% of all herbicide residues to the environment. This tool can be included in proposals for management plans and specific legislation in countries, guaranteeing public policies to maintain environmental quality. Therefore, the knowledge of native or fast-growing species is essential for implementing phytoremediation programs. These results are highlighted in this review, and the highlighted gaps should be studied in the future. The SWOT analysis summarizes the current state of this technique (Fig. 5).

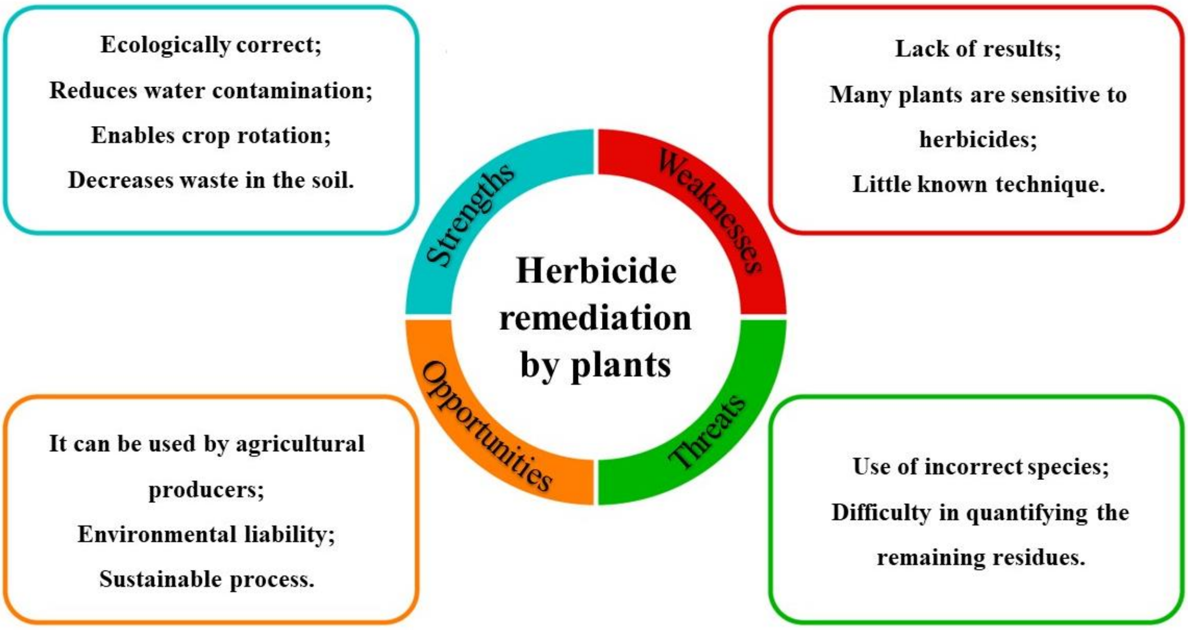


Figure 5. SWOT analysis proposal for summarizing the current status of herbicide phytoremediation

According to the systematization of information represented by the SWOT analysis, the strengths of phytoremediation on herbicide sites include protecting natural resources, soil, and water. The analysis reinforces technology's viability in responding to society's desire to preserve natural resources. The weaknesses are demonstrated by the number of reports, which is still low. However, this fact shows the potential results that can still be obtained from ongoing research and new projects. Although the sensitivity of some plant species to herbicide residues is listed as a weakness, this can be positive if these plants are used as bioindicators of residues.

Among the opportunities, we highlight that farmers can quickly adopt the phytoremediation technology because it does not require high investment or complex knowledge of species cultivation. Many phytoremediators are already commercialized and have excellent availability of seeds in the market. It is also essential to be a sustainable process because it allows additional income to the farmer. The threats are the use of unsuitable species and the difficulty in quantifying the residue of herbicides in the areas. But these threats become less relevant with the dissemination of information and training that can be offered to farmers.

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GENERAL CONCLUSION

A robust legislative framework influences pesticide waste management in Brazil, including the Pesticide Law (Law 14.785/2023) and other environmental laws. These laws aim to protect the environment and public health through strict regulations and sanctions for violations.

Despite legislative advances, the effective implementation of these laws faces challenges, such as adequate monitoring and awareness among the various stakeholders involved. The decentralization of data and difficulty accessing relevant information on pesticide waste management are obstacles that the new law may attempt to overcome through a unified registration and information system.

Coordination between regulatory agencies, such as MAPA, ANVISA, and IBAMA, is essential for effective management. Creating an inter-institutional steering committee and a unified digital platform are critical steps to ensure the efficient exchange of information and the implementation of coordinated audit and monitoring actions.

Continuous training and educational campaigns are essential to strengthen pesticide residue management. These initiatives promote good agricultural practices and regulatory compliance necessary for food safety and environmental protection. In addition, proposals to mitigate the negative impacts of pesticide use are essential since using these products is vital to maintaining high food production.

Introducing alternative and less harmful pest control methods and mitigation tools, such as phytoremediation, represents a promising approach to more sustainable production. Phytoremediation helps decontaminate affected areas, optimizes land use for food production, prevents pesticides from reaching waterways, and can be quickly adopted by farmers because it is low-cost.

Finally, effective pesticide residue management in Brazil requires a holistic approach that integrates strict regulations, inter-institutional collaboration, ongoing education, and adopting sustainable technologies, all to ensure environmental protection and public health.