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Impacts of Pesticide Exposure on Birth Outcomes and Child Health in Brazil.

Stela Barbosa Januzzi
Magister Scientiae

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Dissertation submitted to the Applied Economics Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

Adviser: Leonardo C. Borges Cardoso

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Assent:

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Author

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Adviser

To my father and my grandmother,
who are part of who I am and live on
with me in memory and in my heart.

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Completing this stage has been a challenge, but I was fortunate to have incredible people by my side who offered unwavering support throughout the journey.

“The first condition for changing reality is to understand it.”
(Eduardo Galeano)

ABSTRACT

JANUZZI, Stela Barbosa, M.Sc., Universidade Federal de Viçosa, September, 2025. **Impacts of Pesticide Exposure on Birth Outcomes and Child Health in Brazil.**. Adviser: Leonardo Chaves Borges Cardoso. Co-adviser: Loredany Consule Crespo Rodrigues.

This study aimed to investigate the impact of residential exposure to pesticides on four key child health outcomes in Brazil: low birth weight, preterm birth, infant mortality, and childhood cancer incidence. Using panel data for 5,510 Brazilian municipalities from 2019 to 2022—a period marked by a record approval of new pesticide formulations and a weakening of regulatory legislation—the research innovates by creating an exposure index. This index, developed through a shift-share approach, estimates the municipal level of pesticide exposure and serves as the primary explanatory variable in the models. To the best of our knowledge, this is the first nationwide study in Brazil to conduct such an analysis covering all municipalities. The results provide relevant estimates regarding pesticide use in Brazilian municipalities. However, no statistically significant effects were identified between the residential pesticide exposure and the health outcomes considered. This research contributes to the ongoing debate regarding pesticide use and its potential health risks, especially for vulnerable populations such as pregnant women and children. The findings highlight the need for greater transparency, strengthened regulatory enforcement, and expanded public access to environmental and health data in the country.

Keywords: child health outcomes; pesticide exposure; Brazilian municipalities; panel data

RESUMO

JANUZZI, Stela Barbosa, M.Sc., Universidade Federal de Viçosa, setembro de 2025. **Impactos da Exposição a Agrotóxicos sobre desfechos de Saúde Infantil no Brasil**. Orientador: Leonardo Chaves Borges Cardoso. Coorientadora: Loredany Consule Crespo Rodrigues.

O presente trabalho buscou investigar o impacto da exposição residencial a pesticidas sobre quatro importantes desfechos de saúde infantil no Brasil: baixo peso ao nascer, nascimento prematuro, mortalidade infantil e incidência de câncer infantil. Utilizando dados em painel para 5.510 municípios brasileiros, no período de 2019 a 2022, caracterizado pela aprovação recorde de novas formulações de pesticidas e pelo enfraquecimento da legislação regulatória, a pesquisa inova ao criar um índice de exposição, por meio da abordagem de shift-share, para estimar o nível de exposição municipal aos pesticidas, sendo essa a principal variável explicativa dos modelos. O estudo foi o primeiro do país, até onde se sabe, a realizar essa investigação a nível nacional para todos os municipios. Os resultados trazem relevantes estimativas a respeito do uso de pesticidas nos municípios brasileiros. Porém, não foi possível inferir causalidade da exposição residencial a pesticidas para nenhuma das variáveis de desfecho de saúde tratadas no estudo. A pesquisa contribui para o debate sobre o uso de pesticidas e seus potenciais riscos à saúde, principalmente de populações mais vulneráveis, como mulheres grávidas e crianças, reforçando a necessidade de maior transparência, fortalecimento da fiscalização e ampliação do acesso público a dados ambientais e de saúde no país.

Palavras-chave: desfechos de saúde infantil; exposição a pesticidas; municípios brasileiros; painel de dados

List of Figures

List of Tables

Contents

1 Introduction

Brazilian agriculture has steadily grown in prominence over the years, solidifying its position as one of the main players among the world's leading suppliers of agricultural products, such as grains and animal protein (Gaboardi et al., 2023). As such, the agricultural sector is central to the country's economy, promoting economic growth through commodity exports, which contribute to maintaining the trade balance and serve as a vital source of foreign exchange. In addition, the sector generates income and employment and contributes significantly to the Gross Domestic Product (GDP) (dos Santos et al., 2016).

According to a report by IPEA, Brazil's agricultural sector exports increased by 3.9%, while imports fell by 4.5% in 2023, compared to the previous year. The sector accounted for 48.6% of total Brazilian exports, reaching USD 165.05 billion, demonstrating its strength and importance in the national economy. Moreover, the soybean complex, which includes soybean grains and soybean meal, leads the country's production and exports, reaching a total of USD 41.04 billion in the first half of 2023 — an increase of 8.6% compared to the same period in 2022 (Ferreira & de C. Souza Jr, 2024).

Beyond Brazil's natural competitive advantages in agriculture, such as a large area of arable land, favorable climate, fertile soils and water availability, the country presents a significantly capitalized and competitive agricultural sector with a high capital-to-labor ratio, relying on sophisticated machinery, equipment, and chemical input (Lobão & Staduto, 2020). Among these chemical inputs are pesticides, which are toxic substances intentionally used on crops to control pests, weeds, rodents, fungi, and other organisms harmful to agricultural production. These pesticides, which mainly include insecticides, herbicides, and fungicides, serve to deter, prevent, control, or eliminate these pests, protecting crop yields (Mahmood et al., 2016).

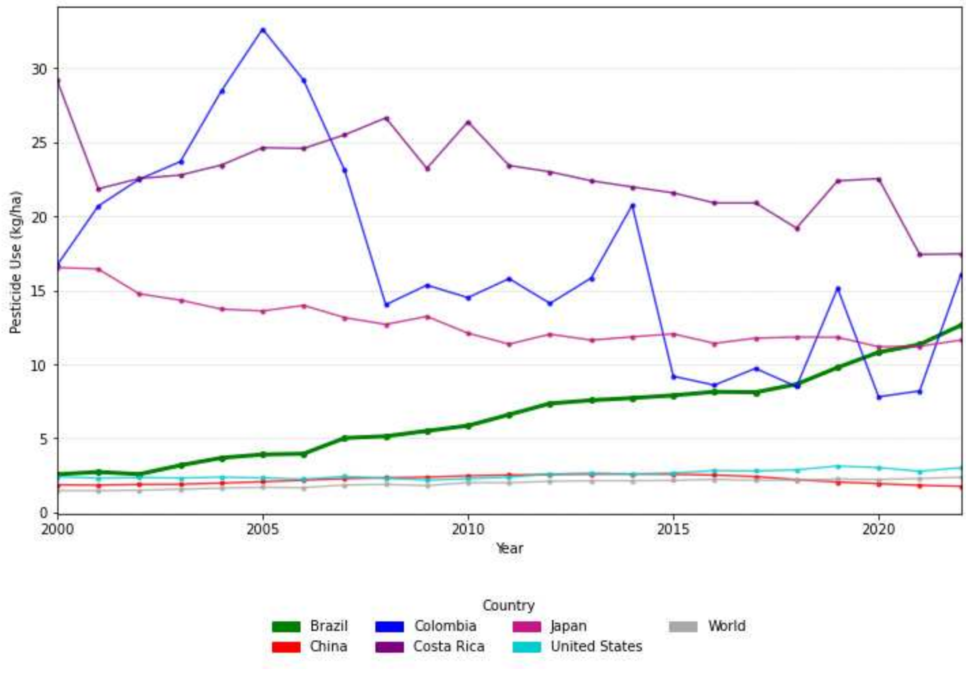
Over the years, Brazil has emerged as one of the world's largest importers and consumers of pesticides. Soybean, corn, and sugarcane alone account for nearly 70% of all agrochemical use nationwide (Pignati et al., 2017; Valadares et al., 2020). There are several factors that explain the high consumption and use of pesticides in Brazil. As a tropical country, Brazil does not experience frost or extremely cold periods that could help disrupt pest cycles, as seen in other regions. Additionally, the expansion of monoculture farming creates ecological imbalances and affects biodiversity, fostering the emergence and spread of agricultural pests and diseases. Moreover, the overall increase in agricultural production itself contributes to the rising use of pesticides (Vasconselos, 2018).

However, evidence suggests that increasing amounts of pesticides per hectare are required to sustain crop yields. This trend indicates a growing dependence on agrochemicals in Brazilian agriculture (Valadares et al., 2020). According to an IPEA report (Moraes, 2019), between

1991 and 2015, the number of pesticides applied per hectare of cultivated land in Brazil nearly quadrupled. Recent data from FAOSTAT (2024) further highlight this pattern, showing that Brazil applied, in 2022, an average of 12.6 kg of pesticides per hectare of farmland (12.6 kg/10,000 m²), compared to an average of 5,8 kg/ha in 2010. Given this trend, although pesticide use may provide short-term benefits, such as higher crop yields, reduced pest pressure, and lower production costs (Goeb et al., 2020; Moraes, 2019), in the long run it is likely to increase production costs (Valadares et al., 2020).

As illustrated in the graph below, based on data from FAOSTAT (2024), it is possible to compare pesticide use per hectare of cropland between Brazil and other countries. When compared with nations such as China and the United States, both large agricultural producers, Brazil displays notably high levels of pesticide application. However, this intensity appears less exceptional relative to countries such as Costa Rica, Colombia, and Japan, which have historically shown even higher levels of pesticide use per hectare. Nevertheless, a declining trend in pesticide intensity can be observed in these countries, whereas in Brazil the trend continues to rise.

Figure 1: Pesticide Use per Hectare of Cropland (2000–2022)



Own elaboration based on FAOSTAT(2024) extracted in Our World in Data.

Furthermore, pesticides are recognized as toxic not only to the environment but also to human health, creating negative externalities that are often challenging to detect and quantify (Devi et al., 2022; Moraes, 2019; Mahmood et al., 2016). The application methods of pesticides – such as aerial spraying, tractor-mounted equipment, or manual application by agricultural workers – result in the dispersion of these chemicals into the surrounding environment. Through processes such as evaporation, drift, and leaching, pesticides can contaminate crops, food products, water sources, air, and soil, ultimately impacting animals, plants, and humans (FAO, 2023; Pignati et al., 2014).

Focusing on the harmful effects of pesticides on humans, absorption can occur through inhalation, accidental ingestion, or skin penetration (Calzada et al., 2023). Exposure to these chemicals can be direct and acute, or indirect and chronic.

The first exposure pathway, the acute and direct exposure, is often related to occupation. Agricultural workers are exposed to pesticides through accidents and lack of adequate protection, leading to immediate effects of intoxication. Additionally, there are instances of intentional poisoning, where individuals with easy access to pesticides use them as a means of suicide (Valadares et al., 2020). From 2006 to 2018, direct pesticide exposure among agricultural workers in 141 countries led to an estimated 385 million cases of poisoning and 11,000 deaths annually (Boedeker et al., 2020). In Brazil alone, 2,548 cases of agricultural pesticide poisoning were recorded in 2017, with 61 resulting in fatalities (SINITOX, 2017).

The second pathway, the indirect and chronic pesticide exposure, may occur through the ingestion of contaminated food, drinking of contaminated water (from rivers or groundwater near sprayed areas), inhalation of contaminated air and dust, or long-term work with pesticides (Devi et al., 2022). According to Landrigan (2018), the population affected by chronic exposure is likely much larger than that directly affected by acute pesticide poisoning. This is particularly evident given that virtually the entire population may be exposed through the consumption of pesticide-treated food. Furthermore, this indirect exposure is much more challenging to quantify as its health effects often manifest over the long term.

In this context, the excessive and increasing use of pesticides in Brazil underscores the urgent need to investigate their indirect health impacts. Specifically, this study aims to examine the health impacts on individuals residing in municipalities with intensive-pesticide use, who may be more exposed by ingestion of contaminated water or inhalation of pesticide-laden air and dust than individuals residing in municipalities less pesticide-intensive.

Recent literature highlights strong correlations between chronic pesticide exposure and adverse health outcomes, particularly affecting infants and babies up to one year old living near treated agricultural areas. These populations are especially vulnerable to the harmful effects of pesticides and highly responsive to environmental conditions. Additionally, observed health abnormalities can be more directly attributed to pesticide exposure rather than other potential factors (Dias et al., 2023).

The Larsen et al. (2017) study, analyzing birth data from 1997 to 2011 in California's agricultural San Joaquin Valley, concluded that residential pesticide exposure elevated the rate of preterm births by 5% and congenital disabilities by 9%. However, these effects were observed only among mothers exposed to high pesticide levels, defined as an average exposure of 4,000 kg of pesticides throughout pregnancy. Jones (2020) concluded that increased insecticide and fungicide use was associated with higher rates of preterm birth and low birth weight in the US from 2008 to 2018. Meanwhile, Camacho & Mejia (2017) found that glyphosate spraying on coca plantations in Colombia increased the likelihood of dermatological and respiratory illnesses, as well as miscarriages. Calzada et al. (2023) found that residing near plantations during pregnancy, particularly when the first trimester coincides with periods of intensive fumigation, increases the likelihood of low birth weight and a low Apgar score by approximately 0.35 and 0.33 percentage points, respectively, during the period of 2015 to 2017, in Ecuador.

In Brazil, Dias et al. (2023) examined the impact of glyphosate use in soybean plantations on infant mortality, primarily in Brazil's Center-West and South regions, concluding that cities receiving water from rivers contaminated by these pesticides had higher infant mortality rates and low birth weight. Panis et al. (2024) found that women exposed to glyphosate, atrazine, and 2,4-D had higher rates of breast cancer compared to non-exposed women, in a case-control study conducted in a region of Paraná state from 2016 to 2019. Furthermore, Skidmore et al. (2023) concluded that the higher exposure to pesticides through soy expansion between 2008 and 2019 contributed to the rise in childhood blood-borne cancer. Moreover, Paumgartten (2020) conducted a literature review and noted that, in addition to the scarcity of studies on this topic in developing countries, most works in Brazil suffer from limitations, such as non-random sample selection, small sample sizes, imprecise exposure assessments, and multiple comparative challenges. Additionally, longitudinal studies are either absent at the national level or restricted to specific regions.

Given this discussion, it becomes evident that, compared to more developed countries, the Brazilian literature lacks comprehensive studies assessing the impact of chronic and indirect pesticide exposure on human health. The main reasons for this gap lie in the scarcity of reliable data on pesticide use in the country, which significantly limits the feasibility of quantitative analyses in this field. Moreover, measuring the chronic effects of pesticide exposure presents a methodological challenge, as it is not possible to directly capture the long-term health impacts accumulated over years of exposure. Consequently, there remains a notable absence of longitudinal studies covering the national level.

This study seeks to address this gap by examining the impact of residing in municipalities with pesticide-intensive agricultural activity on four birth and early-life health outcomes, selected based on the most consistent findings in the existing literature: low birth weight, preterm birth, infant mortality and childhood cancer. The central hypothesis of this paper is that infants and children living in municipalities characterized by pesticide-dependent agricultural production are more likely to experience adverse health outcomes. The main mechanism proposed for these effects involves maternal and early-life exposure to environmental contamination, particularly through pesticide-contaminated air and polluted water sources during pregnancy and early childhood.

To achieve its objective, this study introduces an innovative municipal-level pesticide exposure indicator, which serves as the main explanatory variable. The econometric analysis employs a two-way fixed effects panel model covering the period from 2019 to 2022 for all Brazilian municipalities. To the best of our knowledge, this is the first study to apply this approach at the national level. The results are expected to provide empirical evidence on the potential adverse effects of indirect pesticide exposure on public health. In doing so, this research aims to inform academic debate, policy design, and legislative initiatives concerning pesticide regulation and its implications for vulnerable populations. Within the field of economics, shedding light on this issue is crucial, given the potential loss of human capital and the substantial costs associated with curative healthcare that may result from indirect pesticide exposure.

To achieve its objective, this study is divided into five sections: the present introduction, the section on theoretical and empirical aspects, the methods section, the results, and finally, the conclusion.

2 Theoretical and Empirical Aspects

This section offers a detailed overview of pesticides, covering their origin, diffusion, and growth in Brazil, along with the country's regulatory frameworks. Also, it examines the most commonly used pesticides and those considered most toxic to the population. Following this, an expanded discussion addresses the impacts of pesticides on human health according to the existing literature.

2.1 Pesticides

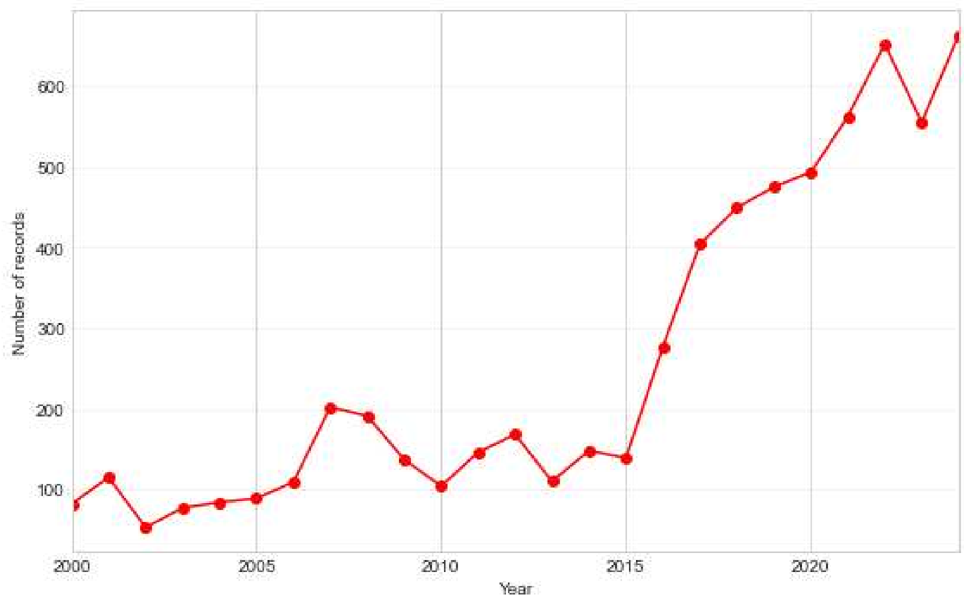
The origins of pesticides date back to the post–World War II period, when it was observed that specific chemical agents, previously used as warfare agents, could also potentially eliminate pests that threatened crops. Since then, applying these chemical inputs in agriculture has become more widespread and was encouraged as part of the so-called Green Revolution, initiated in the 1960s. This movement sought to promote ideas of modernization. It increased productivity in agriculture, based on the intensive use of machinery, fertilizers, genetically modified seeds, and pesticides (Lobão & Staduto, 2020).

In Brazil, this modernization began to take hold in the 1970s and was strongly linked to the strategic decision to establish agribusiness as a key driver of national economic development. This shift also aligned with the growth of commodity crop areas and the expansion of production in the Center-West region (dos Santos et al., 2016; Gaboardi et al., 2023). The region is now the country's largest grain-producing area, accounting for approximately 53% of the total temporary crop production of corn, soybeans, and wheat in Brazil (PAM/IBGE, 2023). Consequently, pesticide use has enhanced significantly alongside the expansion of Brazilian agribusiness, although it has also become more widespread among smallholder farmers and in family farming (Pignati et al., 2017; Panis et al., 2024; Valadares et al., 2020).

In addition, the liberalization of the agricultural sector since the 1990s has led to more flexible regulations regarding pesticide use across the country. Along with this, factors such as tax exemptions for producers, government-subsidized agricultural credits, and the political influence of major agribusiness groups have resulted in an agricultural production system increasingly reliant on pesticides, making Brazil one of the world's largest pesticide-consuming countries (Pignati et al., 2017; Moraes, 2019). This trend contrasts with that observed in developed countries, where pesticide use regulations have become much more restrictive. A European study found that hazardous pesticides banned within the EU are now being exported primarily to developing countries in Latin America, with Brazil as a leading recipient (Devi et al., 2022; Sarkar et al., 2021; Gaboardi et al., 2023). Two of the ten best-selling pesticide products in Brazil are banned in the European Union, such as Atrazine and Acephate (Gaboardi et al., 2023).

According to data from the Registro de Agrotóxicos, Componentes e Afins of the Coordenação-Geral de Agrotóxicos e Afins (CGAA) at the Ministry of Agriculture (MAPA, 2024), Brazil has reached record levels in the authorization and registration of agrochemicals. The graph below shows this trend, where the total number of new pesticide registrations is the sum of the number of approved technical products and formulated products each year in Brazil.

Figure 2: Overall Total of Pesticide Records per Year in Brazil



Own elaboration based on CGAA - MAPA(2024).

The number of new approvals surged from 277 in 2016 to 652 in 2022. Between 2010 and 2023, a total of 4,682 new agrochemical products were registered in the country. Moreover, from 2019 to 2022, during President Jair Bolsonaro's administration, pesticide approvals hit an all-time high, with 2,182 new pesticides registered, marking the largest number of approvals under any presidential term since 2003 (MAPA, 2024). The main consequence of expanding these authorizations is often a reduction in pesticide costs, which can lead to increased consumption and reinforce a cycle of intensive agrochemical use across crops, potentially resulting in higher individual pesticide exposure (Valadares et al., 2020).

Undeniably, the increased use of pesticides has granted Brazil a competitive advantage in agricultural production so far. However, weak regulation in the sector allows highly toxic chemicals to be approved and released into the soil without adequate oversight and often without the public's awareness of the environmental and human health impacts these practices entail (Moraes, 2019).

Worsening the situation, in 2022, a bill originally introduced in 2002 resurfaced in the political debate, aiming to amend key aspects of Brazil's Pesticide Law (Law No. 7,802/1989) by making regulations more lenient and less stringent. The Bill (PL) 1.459/2022 sought, among other measures, to expedite the approval process for new agrochemicals in the country; centralize decision-making on pesticide approvals within the Ministry of Agriculture, Livestock, and Food Supply (MAPA), rather than distributing authority equally among MAPA, IBAMA, and ANVISA; and replace the Hazard Assessment — which evaluates potential carcinogenic, mutagenic, and teratogenic effects — with a Risk Assessment, a shift that would loosen approval criteria for new pesticide products (Gaboardi et al., 2023; Vasconselos, 2018).

The bill was approved, giving rise to a new Pesticide Law: Law 14.785 of 2023. Although the President Luiz Inácio Lula da Silva vetoed certain provisions, such as the centralization of decision-making within MAPA, other highly concerning measures were incorporated into the new law. Notably, the explicit prohibition on registering products containing substances classified as carcinogenic or those that induce deformities, mutations, or hormonal disorders, among others, was removed. Instead, the law now states that the registration of pesticides, environmental control products, and similar substances is prohibited only if they pose an "unacceptable risk" to human health or the environment — without clearly defining the criteria for assessing such risks. Moreover, the law no longer prohibits the approval of chemical products for which Brazil lacks antidotes or preventive measures to ensure that their residues do not endanger public health or the environment (Agência Senado, 2023). In this way, despite the presidential vetoes, the approval of the new pesticide law prioritizes economic interests in agribusiness while further sidelining concerns about human health and environmental protection (Gaboardi et al., 2023).

Despite the growing literature on the impacts of pesticides on soil, water and public health, the main limitation for research on pesticide use and exposure in Brazil remains the scarcity of data. Information on pesticide consumption and usage is somewhat restricted, and no national database provides comprehensive figures on the volume of pesticides (in liters or kilograms) used across crops throughout the country (Pignati et al., 2014).

Given these limitations, papers such as Pignati et al. (2017), which aimed to conduct a spatial analysis of pesticide use across Brazil, applied the methodology proposed by Pignati et al. (2014), where pesticide usage per crop is estimated based on existing data for the state of Mato Grosso, obtained from the Mato Grosso Agricultural Defense Institute (INDEA-MT) database. This database offers annual data on pesticide quantities used on major crops in the state. By determining the average pesticide usage per hectare for each crop, this estimate can serve as a proxy for similar crops across Brazil, allowing for a nationwide approximation of pesticide application per hectare.

Based on the application of this methodology, Pignati et al. (2017) estimated that approximately 899 million liters of formulated pesticides were sprayed on 21 selected crop types across Brazil in 2015. Additionally, the authors identified the 20 most widely used active ingredients in Brazil from 2012 to 2016, including Glyphosate (herbicide), Chlorpyrifos (insecticide), 2,4-D (herbicide), Atrazine (herbicide), Mineral Oil (adjuvant), Mancozeb (fungicide), Methoxyfenozide (insecticide), Acephate (insecticide), Haloxyfop-methyl (herbicide), Lactofen (herbicide), Methomyl (insecticide), Diquat (herbicide), Picoxystrobin (fungicide), Flumetsulam (herbicide), Teflubenzuron (insecticide), Imidacloprid (insecticide), Lambda-cyhalothrin (insecticide), Imazethapyr (herbicide), Azoxystrobin (fungicide), and Flutriafol (fungicide). Among these substances, 15% are classified as extremely toxic, 25% as highly toxic, 35% as moderately toxic, and 25% as slightly toxic to humans.

In line with these findings, IBAMA (2016) indicated that the active pesticide ingredients most sold in Brazil in 2014 were, respectively: Glyphosate (194,877.84 tons), 2,4-D (36,513.55 tons), Acephate (26,190.52 tons), Mineral Oil (25,632.86 tons), and Chlorpyrifos (16,452.77 tons). More recent data from 2023 indicate that while the ranking of the most sold ingredients has remained relatively stable, there has been a significant increase in their sales volume. The top-selling ingredients in 2023 include Glyphosate and its salts (253,301.95 tons), Mancozeb (52,316.64), 2,4-D (51,872.24 tons), Acephate (49,557.98 tons), Chlorothalonil (45,533.1 tons), Atrazine (26,804.98 tons) (IBAMA, 2023).

It is important to acknowledge the limitations of Pignati et al. (2014) methodology. Although the data published by IBAMA (2016) support the study's findings, there may be discrepancies in the amount of pesticides used per hectare across different Brazilian states, which could affect the accuracy of the estimates. Additionally, the data provided by INDEA may be underestimated, considering the potential for unauthorized or unreported pesticide use by producers. Nevertheless, the authors' approach represents a viable method for estimating pesticide use by crop in the country, enabling further studies and discussions on the topic despite data limitations.

Given this discussion, many studies already associate pesticide exposure with adverse human health outcomes despite the data collection challenges that persist in Brazil. Research on this topic is essential to raise awareness of the dangers to which the entire population and future generations are exposed due to the production choices made by agricultural producers. Such studies also provide a foundation for more assertive discussions regarding the importance of pesticide regulation within the Brazilian territory.

The following subsection presents a review of both international and national literature focused on the human health impacts of residential pesticide exposure, which is the primary focus of this paper.

2.2 Pesticides and human health

The literature provides evidence that closer proximity to agricultural land tends to increase the chances of adverse health outcomes, as people residing in these areas are more exposed to pesticides applied to nearby crops (Larsen et al., 2017). Residents who live closer to pesticide-treated agricultural land tend to show higher levels of pesticide residues in household dust and/or pesticide metabolites in biological samples, as well as increased oxidative stress markers, greater DNA damage and decreased cholinesterase activity compared to those who live further away, according to the study review by Dereumeaux et al. (2020). In addition, other studies have already linked pesticide exposure among rural populations, including farmers, agricultural workers, and pesticide applicators, with conditions such as non-Hodgkin lymphoma (NHL), multiple myeloma, leukemia, and bladder, prostate, and colon cancers (Andreotti et al., 2018).

Beyond research on general health impacts, numerous studies specifically address the health of pregnant women, newborns, and children, as these groups are particularly vulnerable to environmental factors, including pesticide exposure. As debated in the review studies by Paumgartten (2020), which examines papers from Brazil, and Shirangi et al. (2011), which focuses on international studies, many of these papers addressing residential pesticide exposure rely on case studies or case-control designs, often with limited sample sizes and a focus on individuals residing in specific regions or agricultural counties. The findings from these studies often reveal high concentrations of pesticides in blood samples, urine tests, or household dust of individuals residing near pesticide-treated areas.

On the other hand, despite a substantial number of studies identifying correlations between residential pesticide exposure and adverse health outcomes — particularly in birth and reproductive health — there is no definitive consensus that such correlations always exist or that they are independent of specific factors. The review study conducted by Shirangi et al.

(2011), which analyzed 25 studies published between 1979 and 2007, revealed inconsistent findings on reproductive outcomes. Overall, the analysis indicated that the correlation between residential pesticide exposure and outcomes such as congenital malformations, stillbirth, and miscarriages is generally weak, varies depending on the specific outcome examined, and is limited by weaknesses in exposure assessment and potential confounding factors, leading to inconclusive evidence.

Furthermore, in many studies that do establish a correlation, the association depends on several factors, including the distance from pesticide application sites, the duration of exposure during fetal development, the specific trimester in which fumigation occurs, and the overall intensity of pesticide exposure (Dereumeaux et al., 2020; Larsen et al., 2017; Shirangi et al., 2011).

Although many smaller studies focus on specific regions and involve a limited number of participants, international research has employed statistical and econometric methodologies to analyze larger samples, producing more precise results, as discussed below. Moreover, these studies generally reach the consensus that chronic pesticide exposure is harmful to certain health outcomes.

Schreinemachers (2003) compared birth data from 43,634 newborns in high and low-wheat-producing counties between 1995 and 1997, across 262 agricultural counties in the Midwestern United States. At the time, more than 85% of the acreage was treated with chlorophenoxy herbicides such as 2,4-D and MCPA. Using a logistic regression model with generalized estimating equations (GEE), the study found higher rates of circulatory, respiratory, and musculoskeletal anomalies in infants born in the high wheat-producing counties.

Along the same lines, Larsen et al. (2017), analyzing 500,000 birth observations from 1997 to 2011 in the agriculturally dominant San Joaquin Valley, California, using a fixed-effects panel data model, concluded that being exposed to very high levels of agricultural pesticides, - defined by an average exposure of 4,000 kg of pesticides during pregnancy - compared to low levels, increased prematurity by 5%, birth abnormalities by 9% and preterm birth by 8%. This study highlights that proximity to agricultural fields (up to 1,000 meters) amplifies the likelihood of adverse birth outcomes, although the exact distance between these areas and each individual's residence was not specifically measured.

Furthermore, studying the relationship between pesticide exposure and infant health may be subject to endogeneity, as pesticide use could be correlated with other variables, and there may be omitted variable bias. To address this issue, Jones (2020) employed the detection of the *Spotted Wing Drosophila* (SWD) as an instrumental variable to predict pesticide use aimed at controlling the pest. These predicted pesticide usage levels were then used to estimate their impact on infant health through an instrumental variables model using the two-stage least squares (2SLS) method. The author analyzed data from infected and non-infected counties in the United States between 2008 and 2018. The results indicate that a 10% increase in insecticide and fungicide usage was associated with a 0.18 and 0.15 percentage point increase in infant prematurity, as well as a 0.08 and 0.08 percentage point increase in instances of low birth weight, respectively. These findings remained robust across alternative model specifications and falsification tests.

Calzada et al. (2023) examinated the impact of aerial fumigation of banana plantations in Ecuador on the health of newborns born near these plantations. Using a difference-in-differences (DID) approach, they found that pesticide exposure increases the likelihood of low birth weight and a low Apgar score at the first minute by approximately 0.35 and 0.33 percentage point, respectively. The authors emphasize that pesticides significantly impact newborn health when the first and second trimesters of pregnancy coincide with the season of intense fumigations. Newborns exposed to heavy fumigation during this gestational period have an average birth weight lower than those who were not exposed in between 38 and 89 grams. Furthermore, most of the effect of pesticides occurs within the first 100-150 meters around the plantation, diminishing quickly at further distances.

While there is a considerable amount of literature inferring a correlation, few papers are able to infer causality between pesticide exposure and health, which is much more difficult and is also the distinguishing feature of the work by Camacho & Mejia (2017). In this study, the authors aimed to analyze the effects of exposure to glyphosate—the most widely used herbicide globally—on the health of the Colombian population subjected to government-led aerial spraying campaigns for coca crop eradication. They gathered medical consultation data from 2003 to 2007 alongside records of the square kilometers of herbicide sprayed in each municipality. Using an individual fixed-effects regression model, which tracked the same 687,735 individuals over time, the results indicated a significant increase in the proportion of medical consultations for dermatological (0.85% increase) and respiratory issues (0.87% increase) among residents in glyphosate-exposed areas. To ensure the robustness of their findings, the authors conducted various analyses, including placebo tests and subgroup verifications, which reinforced that the observed effects were indeed linked to glyphosate exposure rather than other confounding factors.

In the case of Brazil, studies with robust results, such as the works discussed below, are relatively scarce. Skidmore et al. (2023) employed an ordinary least squares (OLS) model with fixed effects to estimate the impact of soybean production on pediatric deaths from acute lymphoblastic leukemia (ALL) in upstream soybean cultivation areas within the same watershed in the Amazon and Cerrado regions, from 2008 to 2019. The study concluded that soybean expansion in these areas contributes to rising childhood cancer rates, primarily due to exposure to contaminated water, based on the premise that soybean expansion is linked to increased pesticide use in these regions. The findings indicate that a 10-percentage-point increase in the proportion of municipal land used for soybean cultivation is associated with an additional 0.40 deaths from ALL among children under five per 10,000 people and 0.21 additional deaths among children under ten per 10,000 people. In total, the intensification of soybean farming was correlated with 123 additional childhood leukemia deaths.

Similarly, Dias et al. (2023) focused on investigating the health impacts of glyphosate. This pesticide deserves special attention and has gained prominence in academic debates as the most widely used herbicide in both the world and Brazil, primarily in soybean cultivation. Since its introduction in 1974, glyphosate has been widely considered a safe and low-toxicity agrochemical (Dias et al., 2023). In Brazil, the National Health Surveillance Agency (ANVISA) maintains that this pesticide does not violate legislative prohibitions and does not pose a significant toxicity risk (ANVISA, 2019). However, growing scientific evidence has challenged this perception. In 2015, the International Agency for Research on Cancer (IARC), a branch of the World Health Organization (WHO), classified glyphosate as “probably carcinogenic to humans”, raising concerns about its long-term health impacts (Devi et al., 2022).

Dias et al. (2023) examined the relationship between glyphosate exposure and birth outcomes of populations living in areas affected by soybean cultivation expansion. Specifically, the study focused on how glyphosate use in upstream municipalities could impact exposure in downstream municipalities within the same watershed. Glyphosate exposure was defined based on soybean cultivation intensity, and the analysis covered 1,119 municipalities, primarily in Brazil’s Center-West and South regions, the country’s main soybean-producing areas. The authors employed an instrumental variable approach, leveraging the natural suitability of certain areas for genetically modified seeds and the regulatory change that allowed their introduction. The findings showed that living in areas receiving water from rivers near glyphosate spraying zones increases infant mortality rates by 0.93 per 1,000 inhabitants, with most deaths attributed to perinatal conditions and respiratory issues. The study references multiple works suggesting that glyphosate can affect fetal development by impairing placental cells and harming unborn children in utero.

Panis et al. (2024) conducted a case-control study with 758 women living in the Southwest region of Paraná, Brazil, from 2016 to 2019, investigating the relationship between exposure to glyphosate, atrazine and 2,4-D pesticides and breast cancer. Using data on breast cancer incidence and mortality in the region, along with pesticide sales records from the Paraná State Pesticide Control and Use System (SIAGRO), the study found that women exposed to pesticides had a 41% higher breast cancer diagnosis rate and a 14% higher breast cancer mortality rate compared to state and national averages (crude OR = 1.58, 95% CI: 1.18–2.13). However, after adjusting for age, BMI, and menopausal status, this association was no longer statistically significant. Notably, residues of glyphosate, atrazine, and 2,4-D were detected in the urine of women diagnosed with breast cancer. The primary route of exposure was through unprotected handling of pesticide-contaminated items, such as washing the clothing of family members exposed to pesticides. Moreover, the study found that pesticide exposure was linked to more aggressive forms of breast cancer, with exposed women having a 54% higher risk of metastasis compared to non-exposed women. This result remained significant after Spearman correlation analysis, highlighting a direct link between pesticide exposure and cancer-related mortality.

As this discussion draws to a close, it becomes evident that significant challenges and barriers persist in the investigation of the effects of pesticides on human health. There are various approaches to assessing pesticide exposure, yet accurately measuring the distance between residences and treated areas remains a challenge. Moreover, studies employ diverse methodologies to analyze the correlation between chronic residential pesticide exposure and adverse health outcomes. Notably, most research focuses on identifying correlations, while only a few studies, such as Camacho & Mejia (2017), successfully establish causal relationships.

In the case of Brazil, research on this topic remains scarce, with the international literature — particularly for developed countries — being far more extensive than for developing nations (Dias et al., 2023). This gap, among other factors, is largely attributed to the limited availability of data on pesticide use in the country's agricultural sector, as discussed in the previous section. Additionally, according to Paumgartten (2020), no longitudinal retrospective or prospective cohort study has investigated the chronic health effects of pesticides in Brazil. Most existing research consists of ecological, cross-sectional, and case-control studies with inaccurate exposure assessments, which hinder causal inference. As a result, the morbidity and mortality attributed to pesticide exposure remain uncertain in the country, highlighting the need for large-scale prospective cohort studies.

Thus, building on previous studies and addressing existing gaps in the literature, this study aims to assess the impact of residential pesticide exposure on the health of the most vulnerable population, infants and children, at the municipal level across Brazil. Covering the period from 2019 to 2022, the research adopts a longitudinal design with a panel data model, applying a shift-share approach that enhances the robustness of the analysis—an approach that, to the best of our knowledge, has not been previously employed for this context. To achieve this, the study draws upon the methodology of Pignati et al. (2014, 2017) to develop an expanded pesticide exposure index for the entire country, using pesticide consumption data from INDEA, one of the few data sources providing pesticide usage by crop in Brazil.

The research methodology will be detailed further in the following section.

3 Methods

To achieve the objective of the study of examining the presence of adverse child health outcomes in municipalities with high pesticide use, we first construct an index to measure municipal pesticide exposure in Brazil. This indicator will serve as our primary explanatory variable to assess the impact of pesticide exposure on health outcomes by estimating a panel data model.

This section is divided into three parts. The first discusses the approach chosen to measure pesticide exposure. The second focuses on the calculation of the exposure estimator. Finally, the third part details the econometric model employed.

3.1 Strategic Approach and Calculation of the Pesticide Exposure Index

The contribution of this study lies in its attempt to estimate the effects of residential and indirect pesticide exposure across all municipalities in Brazil over a four-year period. The primary sources of residential exposure considered are contamination through air and water, supporting the hypothesis that proximity to agricultural areas contributes to negative health indicators. Therefore, chronic exposure through the ingestion of pesticide-contaminated food is not included in this study, based on the assumption that this type of exposure is widespread throughout the population, regardless of their place of residence.

Given the lack of comprehensive data on pesticide consumption and use at the local level, as previously discussed, this study is based on the methodology proposed by Pignati et al. (2014, 2017) and Dias et al. (2023) to develop the estimator of indirect pesticide exposure.

The Pignati et al. (2014) approach estimates pesticide consumption for all Brazilian municipalities by utilizing pesticide trade data from the state of Mato Grosso, obtained from the Relatório Consolidado de Comércio Agrotóxicos no Estado do Mato Grosso, published by the Mato Grosso Agricultural Defense Institute (INDEA). This database compiles information from agronomic prescriptions detailing pesticide usage across all municipalities in Mato Grosso. Specifically, it provides data on the volume (in kilograms or liters) of pesticide active ingredients intended for users within the state. This information can be filtered by municipality, region, chemical group, active ingredients, and usage across major crops.

The present study follows the same methodological steps. Using data on the total volume of all pesticide active ingredients applied to crops cultivated in the state of Mato Grosso, we calculate the average intensity of pesticide use. This measure is then used to estimate the total pesticide use for all Brazilian municipalities. This estimation serves as a proxy for pesticide exposure at the municipal level.

To construct this measure, we use pesticide application data for seven crops cultivated in Mato Grosso: soybeans, cotton, corn, sugarcane, coffee, rice, and beans. The selection criteria were based on the high levels of pesticide use associated with these crops, their relevance to Brazil's agricultural sector, and the availability of data for Mato Grosso in the Consolidated Report from which pesticide data are drawn. Furthermore, we ensured that the chosen crops are widely cultivated across the country, excluding those specific to the Mato Grosso region as well as those prevalent in other states but not commonly grown in Mato Grosso.

Thus, for Brazilian municipalities where these selected crops are cultivated and sprayed with pesticides, we assume that, on average, local populations are more exposed to pesticides the greater the pesticide intensity per crop and the larger the cultivated area within each municipality.

Data on the planted areas of these crops per municipality will be obtained from PAM – Municipal Agricultural Production, via the System of Automatic Recovery (SIDRA) from the Brazilian Institute of Geography and Statistics (IBGE). According to PAM, in 2022 the crops with the highest production value in Brazil, measured in billions of reais, were: soybeans (approximately 350), followed by corn (138), sugarcane (93), coffee (51), cotton (32.6), wheat (15.7), cassava (15.6), rice (15.5), and beans (12.3). In the state of Mato Grosso, the leading crops were soybeans (105 billion), corn (42 billion), cotton (23.4 billion), sugarcane (1.8 billion), beans (839 million), and rice (439 million) (IBGE, 2022). These figures validate the selection criteria for focusing on these specific crops. Wheat was excluded from the selection because it is a marginal crop in the state of Mato Grosso, which could lead to pesticide use data that differ substantially from other regions of Brazil. Cassava, in turn, was not included due to the lack of properly disaggregated pesticide use data in the INDEA database.

The chosen analysis period spans from 2019 to 2022, offering a comprehensive period for pesticide exposure analysis, according to the data available from INDEA. Moreover, this period coincides with the intensification of pesticide use and liberalization in the country, particularly the record liberalization of pesticides between 2019 and 2022, during the presidency of Jair Bolsonaro (MAPA, 2024). Therefore, it is a crucial period for analyzing the effects of pesticide exposure on birth outcomes.

Accordingly, the formula for constructing the Pesticide Exposure Index is presented below, along with detailed explanations of its calculation:

$$\text{ExpPesticides}_{mt} = \frac{\sum_c \left(\text{AvgMTPesticeIntensity}_c \cdot S_{c,mt}\right)}{A_m} \tag{1}$$

Where m represents each municipality in Brazil, t denotes years, and c corresponds to each of the seven crops with the highest pesticide usage: soybeans, cotton, corn, sugarcane, coffee, rice, and beans; $AvgMTPesticideIntensity$ denotes the annual mean intensity of pesticide use for crop c in the state of Mato Grosso, computed over the 2019–2022 period ; S represents the cultivated area of crop c in the municipality m and year t. A represents the total land area of each municipality m.

To construct the municipal-level pesticide exposure index, the following steps were undertaken:

1. First, the pesticide use intensity for the state of Mato Grosso was calculated for each selected crop ($AvgMTPesticideIntensity$). Data on the total quantity (in kilograms) of all active pesticide ingredients used in each of the seven crops (c), from 2019 to 2022 (t), in the state, were obtained from INDEA. This total was then divided by the total cultivated area (in hectares) of each crop in each year of Mato Grosso, with area data sourced from IBGE-SIDRA.

   Next, the average pesticide use intensity for the entire study period was computed by summing the annual pesticide intensity values (kg per hectare) for each crop across the four years and dividing by the total number of years.

   This period-average was chosen to minimize measurement errors caused by possible outliers or atypical values in any single year. Temporal variations in pesticide exposure across years are reflected through the changes in the share of cultivated area allocated to each crop (c) at the municipal level.

2. After calculating the average annual pesticide use intensity for each crop, this value is multiplied by the cultivated area of each crop in all Brazilian municipalities (Sc, mt) for each year of analysis. This procedure results in an estimated pesticide use for each crop (c) in each municipality (m) for each year.

3. Subsequently, the estimated pesticide use values for all crops are summed to generate an estimate of the total pesticide exposure for each municipality in the country.

4. Finally, this estimate of total municipal exposure is divided by the total agricultural area of each municipality (Am), to produce a normalized exposure indicator. This normalization is important because it adjusts for differences in the scale of agricultural production, providing a more accurate measure of pesticide use intensity at the municipal level. By relating total pesticide use to the size of the cultivated area, the indicator better reflects relative intensity rather than absolute volume, preventing the results from being disproportionately influenced by larger agricultural municipalities. Additionally, normalized variables tend to have lower variance across observations, improving model stability and interpretability.

Using this estimator, we obtain a pesticide exposure variable for each Brazilian municipality, based on the pesticides applied to the selected crops. This will serve as the study's primary explanatory variable. Similar calculations have been employed in previous literature, such as the study by Dias et al. (2023), which estimated residential and indirect exposure to glyphosate. Due to the lack of local-level pesticide usage data, as is also the case in this study, the authors imputed pesticide use by distributing the total glyphosate usage in Brazil — obtained at an aggregate level from IBAMA — proportionally to the soybean-planted area in each municipality and normalizing it by the municipality's total area.

Thus, Dias et al. (2023) also employed a local-level exposure estimate, based on the assumption that soybean fields are sprayed with the herbicide glyphosate. In their case, a municipality's exposure to glyphosate (i) is defined as the total estimated glyphosate usage in soybean production across all municipalities located upstream within the same watershed, divided by the total area of these upstream municipalities.

It is important to acknowledge that the chosen approach has limitations, as do other methodologies previously applied in this field. First, extrapolating pesticide consumption data from Mato Grosso to the entire country may not yield highly precise estimates, given that pesticide use in crops can vary across different Brazilian states. However, no clear evidence was found indicating significant regional differences in pesticide application for the same crop type, meaning that our approach remains valid.

Furthermore, we assume that pesticide consumption for a given crop is equivalent to pesticide exposure. Given the lack of data on pesticide use across agricultural crops in the country and the immense complexity of precisely measuring the distance between each household and cultivated areas in all Brazilian municipalities, we consider this approach to be the best possible, given the circumstances. A similar methodology was previously employed by Dias et al. (2023), as discussed above, and it is reasonable to assume that, on average, municipalities with higher production of pesticide-intensive crops indeed experience greater exposure to these chemicals.

There is also the possibility of underreporting in pesticide consumption and use, which may lead to an underestimation of the exposure levels captured in our data, for two main reasons. First, due to data limitations, our pesticide information—sourced from INDEA—is available only for the main crops produced in the state of Mato Grosso. Consequently, our municipal-level exposure index is based on just seven crops with the highest levels of pesticide use. However, actual pesticide exposure is likely to be considerably higher, given the wider variety of crops cultivated across municipalities. Second, since the pesticide consumption data relies on self-reported records by end-users, there is a strong likelihood that some pesticide applications go unreported. This includes both unregistered uses and the continued application of pesticides that have been officially banned in the country. Unfortunately, there is no way for us to fully address this limitation, and we must acknowledge the high probability that pesticide consumption is underestimated in the available data.

Despite these probable limitations, this approach will allow for estimating pesticide exposure for each selected crop and, consequently, for all Brazilian municipalities with at least one of these crops, which has never been done, to the best of our knowledge. This estimate is highly relevant as it allows for a better understanding of pesticide exposure at the municipal level in Brazil, in addition to providing clearer evidence of the broader effects to which the entire population is subjected due to the excessive use of agrochemicals on the country's soil. Given the continuous rise in the number of new chemicals approved each year in the country, this analysis is extremely relevant and of significant public interest. Moreover, the shift-share approach enhances the methodological rigor and robustness of the analysis, allowing for a more reliable assessment of the relationship between pesticide exposure and adverse child health outcomes, as discussed below.

3.2 Description of the Econometric Model

Beyond the limitations associated with estimating pesticide exposure, there is also a recurring challenge in studies examining the relationship between pesticides and health: potential endogeneity. This issue may arise for several reasons, such as measurement errors in the calculation of pesticide exposure and omitted variable bias. In the first case, if measurement error in the explanatory variable is correlated with other factors affecting birth outcomes, the estimates may be biased. Regarding omitted variables, there may be unobserved characteristics influencing health outcomes that are not captured by the variables included in the model. If these omitted variables are correlated with both pesticide use and health outcomes, this could also lead to biased estimates.

As observed in the literature, some authors employ an instrumental variable approach to address endogeneity, as seen in Dias et al. (2023) and Jones (2020). This study adopts a shift-share approach for constructing the index that serves as our main explanatory variable. By design, this method helps address potential endogeneity issues, contributing to a more reliable estimation of the relationship between pesticide exposure and the dependent variables.

Thus, as outlined in Borusyak et al. (2025), the shift-share relies on two components: shifts, which are exogenous factors that affect different units at the same time, in a heterogeneous way, and shares, which reflects a unit's exposure to these shifts. The shares are used to weight the variation in shifts for each unit. In this way, treatment $\mathbf{X}_i$ is constructed by multiplying the shifts by shares, reflecting the exposure of units to these changes. This combination allows the model to capture variations in the circumstances faced by different units. For the causal relationship between the treatment variable and the dependent variable to be valid, the instrument (the treatment variable derived from the shift-share) must be correlated with $\mathbf{X}_i$ and uncorrelated with the error term e_i, ensuring that the variation in $\mathbf{X}_i$ is exogenous.

In this analysis, the shares correspond to the proportion of total cultivated area allocated to each of the seven selected crops within each municipality (reflecting structural exposure levels). The shifts are represented by the time-varying pesticide use intensity per hectare for each crop, measured based on state-level variations in Mato Grosso. The treatment variable is constructed as the weighted sum of these two components: for each municipality and year, the pesticide exposure index is calculated by multiplying the crop-specific pesticide intensity (shifts) by the municipality-specific crop area share (shares), and summing across all crops.

This approach ensures that the treatment is plausibly exogenous to the health outcomes of interest, as it captures exposure driven by external agricultural trends rather than municipality-level health or demographic factors.

Furthermore, the models will be estimated using a two-way fixed effects panel specification, which offers additional advantages by controlling for both unobserved time-invariant characteristics at the municipal level and year-specific shocks that could affect all municipalities simultaneously. The model structure is expressed by the following equation:

$$y_{it} = \alpha + \beta \cdot \text{PesticideExposure}_{it} + \gamma Z_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{2}$$

Where y_{it} is the dependent variable, and represents the health outcome variables presented in Table 1 below; α is the intercept; $PesticideExposure_{it}$ represents the primary explanatory variable, Residential Pesticide Exposure; Z_{it} is the vector of the control variables, as specified in Table 2; β and γ are the parameters of interest, capturing the magnitude and direction of the effect of the variable on the health outcome; μ_i is the municipality fixed effects; λ_t is the time fixed affects; ε_{it} is the error term; i denotes Brazilian municipalities and t denotes years.

Discussing the study variables, we established that the majority of the variables would be expressed in rate format to ensure comparable magnitudes across all variables in the study, thereby facilitating the interpretation of the results. Consequently, variables related to birth outcomes are represented as rates per 1,000 live births, while children health variables, as well as infrastructure-related variables, are represented as rates per 100,000 inhabitants. Exceptions include the main exposure variable (pesticide exposure) and the per capita GDP variable, which were not expressed as rates. Detailed descriptions of each variable are presented in Tables 1 and 2 below.

Specifically, Table 1 presents the dependent variables, which include three distinct birth outcomes and one children health outcome. The selection of these outcomes is based on existing literature, which has provided evidence that chronic and residential pesticide exposure is associated with pregnancy complications and adverse children health outcomes (Calzada et al., 2023; Dias et al., 2023; Jones, 2020; Larsen et al., 2017; Schreinemachers, 2003; Shirangi et al., 2011; Skidmore et al., 2023). In this regard, the model will be estimated four different times, once for each dependent variable.

Table 1: Description of the dependent variables

Variables	Definition	Base Literature
infant_mort_rate	Number of deaths of children under one year of age per 1,000 live births, per year, by municipality	Dias et al., 2023
preterm_birth_rate	Number of preterm births (before 37 completed weeks of gestation) per 1,000 live births, per year, by municipality	Dias et al., 2023; Jones, 2020; Larsen et al., 2017
low_birth_weight	Number of newborns weighing less than 2,500 grams per 1,000 live births, per year, by municipality	Dias et al., 2023; Jones, 2020; Larsen et al., 2017; Calzada et al., 2023
childhood_cancer_rate	Number of children (aged 0 to 19) diagnosed with malignant neoplasm (cancer) per 100,000 children per year, by municipality	Skidmore et al., 2023; Andreotti et al., 2018

Source: Own Elaboration.

Table 2, presented below, lists the explanatory variables of the study, along with their description, data source, and expected sign of association. The primary explanatory variable is the pesticide exposure proxy, measured annually and at the municipal level. In addition, a set of control variables was included to account for socioeconomic, structural, and individual-level conditions that may influence children's health outcomes independently of pesticide exposure.

Beyond maternal characteristics and birth outcome-related variables, the model also incorporates municipal-level per capita GDP and the number of Primary Health Care Units (PHCUs) and Health Centers in each municipality. It is important to note that data on municipal per capita GDP were available only up to 2021; therefore, the 2021 values were imputed for 2022. Additionally, data on PHCUs refer specifically to the month of December for each year analyzed.

Regarding data sources, the health-related data used to construct both the dependent variables and the control variables will be obtained from various official databases available through DATASUS, the national health information system managed by the Brazilian Ministry of Health. Specifically, variables related to birth outcomes and maternal characteristics will be sourced from the Live Birth Information System (Sistema de Informações sobre Nascidos Vivos – SINASC). Variables on infant and child mortality will be extracted from the Mortality Information System (Sistema de Informações sobre Mortalidade – SIM), while data on childhood cancer cases will be retrieved from the Brazil Oncology Panel (Painel-Oncologia Brasil).

Table 2: Description of the explanatory variables

Variables	Definition	Data Source	Expected Signal
exp_pesticides (proxy)	Annual total municipal exposure to pesticides, considering the seven selected crops, normalized by the total agricultural land area in the municipality (primary explanatory variable)	INDEA-MT; PAM (IBGE)	+
mun_GPD	Annual Municipal Gross Domestic Product per capita (in thousand BRL)	SIDRA (IBGE)	-
PHCU_rate	Annual rate number of Primary Care Units and Health Centers per 100,000 inhabitants per year, by municipality	CNES (DATASUS)	
mother_prenatal	Annual rate number of mothers with seven or more prenatal care visits during pregnancy per 1,000 live births, by municipality	8* SINASC (DATASUS)	-
infant_mort	Annual rate number of deaths of children under one year of age per 1,000 live births, by municipality		+
low_weight	Annual rate number of newborns weighting less than 2,500 grams per 1,000 live births, by municipality		+
mother_adv_age	Annual rate number of mothers aged over 35 years at the time of childbirth per 1,000 live births, by municipality		+
mother_white	Annual rate number of mothers self-identifying as white per 1,000 inhabitants, by municipality		-
hospital_births	Annual rate number of births occurring in hospitals per 1,000 live births, by municipality		-
mother_educ_ _3years	Annual rate number of mothers with three or fewer years of education, per 1,000 live births, by municipality		+
mult_births	Annual rate of multiple births per 1,000 live births, by municipality		+

Source: Own Elaboration.

Population data, necessary for calculating population-based rates, will be obtained from the population estimates provided by the Brazilian Institute of Geography and Statistics (IBGE), with the exception of census years, in which case official census figures will be used. Municipal GDP per capita figures will also be sourced from IBGE. Finally, information on the number of Primary Health Care Units and Health Centers in each municipality will be extracted from the National Registry of Health Establishments (Cadastro Nacional de Estabelecimentos de Saúde – CNES).

The analysis aims to capture the impact of pesticide exposure on birth outcomes and child health. According to the literature, indirect pesticide exposure in municipalities is expected to negatively affect infant and child health (Calzada et al., 2023; Dias et al., 2023; Jones, 2020; Larsen et al., 2017; Schreinemachers, 2003; Shirangi et al., 2011; Skidmore et al., 2023). Thus, this exposure is expected to be positively related to the infant mortality rate, preterm birth rate, low birth weight and children aged 0 to 19 diagnosed with cancer.

Regarding the control variables, it is expected that advanced maternal age, low maternal education (defined as less than three years of schooling), multiple pregnancy (when a woman is pregnant with more than one child), and municipal-level rates of infant mortality, low birth weight, and preterm births will be positively associated with adverse children health outcomes (Azimi & Lotfi, 2013; Calzada et al., 2023; Dias et al., 2023; Larsen et al., 2017; Panis et al., 2024).

The literature consistently highlights that advanced maternal age (typically defined as 35 years or older) is associated with an increased risk of pregnancy complications and negative birth outcomes (Correa-de Araujo & Yoon, 2021; Frederiksen et al., 2018). In addition, mothers with lower educational attainment generally face more barriers in accessing prenatal care, health information, and other essential services, which in turn heightens the risk of complications during pregnancy, delivery, and child health in general. Similarly, multiple pregnancies are also associated with a higher probability of both obstetric complications and adverse neonatal outcomes (Larsen et al., 2017; Falcone et al., 2024; Shahraki et al., 2016; Tamirat et al., 2021).

Furthermore, municipalities with relatively high rates of infant mortality, preterm births, and low birth weight newborns may reflect broader structural deficiencies in maternal and child healthcare services. These systemic shortcomings can translate into a greater underlying vulnerability for children's health overall, potentially influencing more severe outcomes such as childhood cancer incidence (Force et al., 2019; Macinko & Mendonça, 2018; Reidpath & Allotey, 2003; Velame & Antunes, 2024).

The control variables remained — such as municipal GDP per capita, maternal race (white), the number of prenatal care visits (seven or more), birth occurring in a hospital setting, and the rate of Primary Health Care Units and Health Centers per 100,000 inhabitants —are expected to be negatively associated with adverse health outcomes in infants and children. These variables serve as important proxies for socioeconomic status, access to healthcare services, and the overall quality of maternal and child health care within each municipality. Higher levels of these indicators typically reflect better living conditions, greater availability of health services, and improved maternal care during pregnancy and childbirth, all of which are known to reduce risks of negative birth and child health outcomes. (Dias et al., 2023; Force et al., 2019; Larsen et al., 2017; Macinko & Mendonça, 2018; Trevilato et al., 2022; Reidpath & Allotey, 2003).

Higher municipal GDP per capita, a greater availability of Primary Health Care Units, and adequate prenatal care coverage serve as important proxies for the overall socioeconomic development and healthcare infrastructure of each municipality. These variables capture not only the economic capacity of the locality but also its ability to provide essential health services and preventive care to the population, including pregnant women and children (Dias et al., 2023; Guimarães et al., 2018; Larsen et al., 2017; Macinko & Mendonça, 2018).

Births occurring in hospital settings, as opposed to home deliveries or other non-institutional locations, may reflect better access to professional medical care during labor and delivery. This generally ensures that births are monitored by trained healthcare professionals and that any obstetric complications can be managed with appropriate medical infrastructure and emergency support, reducing risks to both mothers and newborns (Vedam et al., 2014).

Furthermore, being born to white mothers is frequently associated with more favorable socioeconomic conditions and better access to healthcare services in Brazil, given the country's well-documented racial and social inequalities. Including this variable aims to control for potential disparities in health outcomes that may arise from unequal access to healthcare and living conditions linked to race (Larsen et al., 2017).

The next section presents the results along with their discussion.

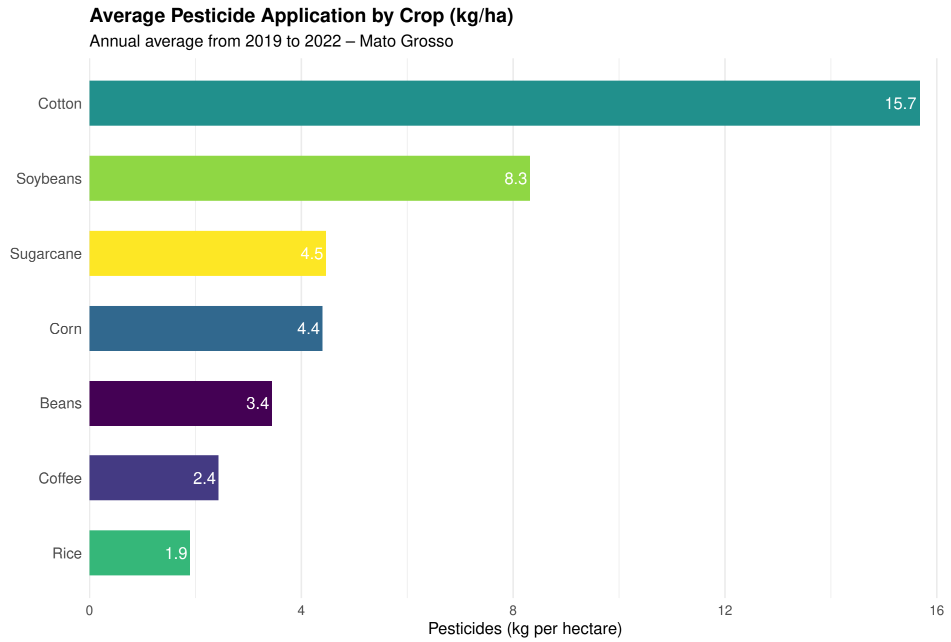
4 Results and Discussion

4.1 Descriptive Results

The residential pesticide exposure index developed in this study made it possible to assess the intensity of pesticide use across each analyzed crop. As shown in Figure 4 below, cotton stands out as the crop with the highest pesticide use per hectare, with a mean intensity that is substantially higher than that observed for other crops.

Through the normalization applied in the calculation of the exposure indicator, it was possible to distinguish the municipalities that are indeed more exposed to pesticides used in the seven analyzed crops, as they present higher application intensity per cultivated area. The underlying assumption is that the greater the amount of pesticides used in a smaller area, the higher the exposure risk for the population residing in that municipality.

Figure 3: Average pesticide use intensity for the state of Mato Grosso, by crop (2019–2022)

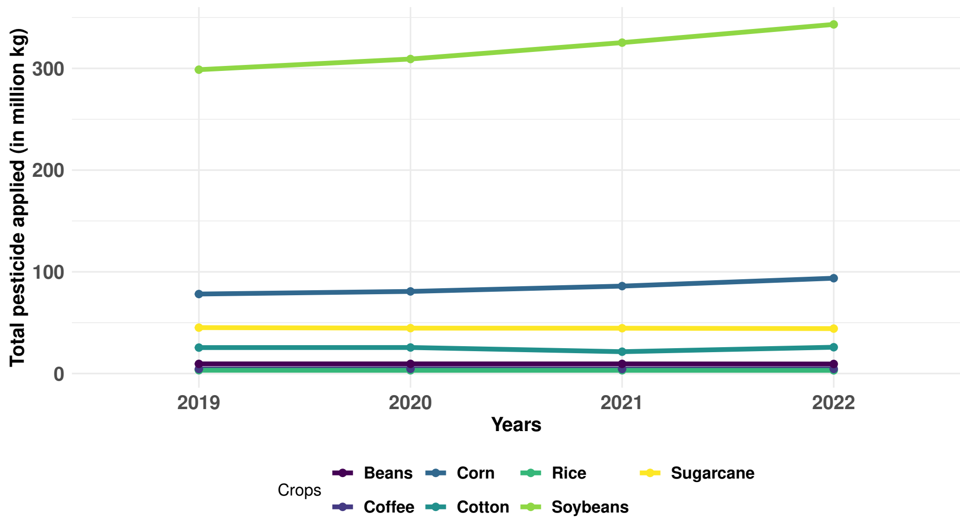


Own elaboration based on INDEA-MT and PAM-IBGE.

Using the average pesticide use intensity estimated for each crop in this study, multiplied by the cultivated area of these crops across the 5,510 municipalities included in the analysis, it was possible to estimate the total amount of pesticides applied to each crop in Brazil between 2019 and 2022. As illustrated in the figure 4 below, when considering the absolute values without normalization, soybeans stand out as by far the crop with the highest pesticide use. This result reflects the fact that soybeans are the most widely produced crop in Brazil and account for the largest cultivated area (IBGE, 2022). In 2019, the estimated pesticide use across the municipalities in the sample amounted to 298,735,688 kg, rising to 343,229,844 kg in 2022.

Below soybeans, the crops with the highest pesticide volumes are corn, followed by sugarcane, cotton, beans, coffee, and lastly rice. When comparing this total volume with the total cultivated areas of these crops across the municipalities analyzed, it becomes clear that soybeans once again lead as the crop with the largest cultivated area in Brazilian municipalities, followed by corn, sugarcane, beans, coffee, rice, and finally cotton. This comparison highlights that cotton is indeed a crop with relatively high pesticide-intensive use.

Figure 4: Sum of the total pesticide volume applied in the municipalities, by crop and year in Brazil



Own elaboration based on INDEA-MT and PAM-IBGE.

Furthermore, the table 3 below presents a comparison between the top 15 Brazilian municipalities with the highest total pesticide application volume (in kilograms) over the 2019-2022 period, and the top 15 municipalities with the highest application intensity (kilograms per hectare of cultivated area) over the same period.

By analyzing Table 3, it is possible to observe that when considering only the total pesticide volume, the municipalities with the highest levels of pesticide application are located in the state of Mato Grosso and are major producers of commodities, particularly soybeans. Sorriso, a municipality in Mato Grosso, recorded an estimated volume of 8,356,016 kilograms of total active pesticide ingredients in 2022, representing the highest volume in Brazil.

However, when taking into account the total agricultural area of each municipality, a different pattern emerges, with new municipalities appearing at the top of the pesticide intensity ranking, as they apply a relatively higher amount of pesticides per hectare. Landri Sales, a small municipality with 5,213 inhabitants (IBGE, 2025) in the state of Piauí, recorded the highest intensity of pesticide exposure, with an average of approximately 11.74 kg/ha in 2020. On that year, the municipality applied 93,697.51 kilograms of pesticides over an agricultural area of 7,980 hectares.

The municipalities with the highest levels of pesticide use intensity are concentrated in the MATOPIBA region, which comprises the states of Maranhão, Tocantins, Piauí, and Bahia. Situated within the Brazilian Cerrado, this region has emerged as one of the country's principal agricultural frontiers, driven by the rapid expansion of large-scale grain cultivation, particularly soybeans, corn and cotton. This agricultural growth, however, has been accompanied by significant environmental pressures, including extensive soil degradation and, as highlighted in this study, the intensive application of pesticides in agricultural production (da Silva & de Sousa, 2022).

Table 3: Comparison of Total Volume and Volume per Hectare of Pesticides Applied by Municipality in Brazil

	Total pesticide			**Pesticide Intensity**		
	municipality	**kg**	**year**	**municipality**	**kg/ha**	**year**
1º	Sorriso MT	8,356,016	2022	Landri Sales PI	11.74	2020
2º	Sorriso MT	8,131,709	2021	Wanderley BA	10.29	2019
3º	Sorriso MT	7,884,967	2019	Sapezal MT	9.89	2020
4º	Sorriso MT	7,783,418	2020	Sapezal MT	9.76	2019
5º	Sapezal MT	7,208,301	2022	Dom Aquino MT	9.65	2019
6º	Sapezal MT	6,823,179	2021	Dom Aquino MT	9.64	2020
7º	Sapezal MT	6,616,622	2020	Dom Aquino MT	9.61	2022
8º	Sapezal MT	6,581,927	2019	Aparecida PB	9.61	2020
9º	Campo Novo do Parecis - MT	6,554,394	2022	Sapezal MT	9.46	2022
10º	Campo Novo do Parecis - MT	6,173,144	2020	Dom Aquino MT	9.31	2021
11º	Campo Novo do Parecis - MT	6,074,194	2019	Sapezal MT	9.30	2021
12º	Campo Novo do Parecis - MT	5,925,278	2021	Tocantínia TO	9.29	2019
13º	São Desidério BA	5,739,211	2022	Campo Verde MT	9.29	2019
14º	Diamantino MT	5,609,190	2022	Campo Verde MT	9.20	2020
15º	São Desidério BA	5,451,255	2019	Riachão das Neves BA	9.11	2020

Source: Own Elaboration using data from INDEA and PAM-IBGE. The kilograms per hectare data were rounded to one decimal place.

Furthermore, Table 4 below presents the descriptive statistics for the study variables.

Most of the variables included data for 5,563 municipalities, totaling 22,252 observations throughout the study period. However, when incorporating the variable for the rate of Primary Health Care Units (PHCU), which controls for municipal health service access, the final analytical sample consisted of 21,703 observations from 5,510 Brazilian municipalities. This reduction occurred because the PHCU variable had missing data for 53 municipalities, leading the R software (used for the present study) to automatically exclude these cases from the analysis. Given that the number of excluded municipalities was relatively small, the decision was made to maintain this control variable in the model.

Regarding the pesticide exposure index, the average amount of pesticides applied per hectare of agricultural land in Brazilian municipalities over the four years of analysis was 3.66 kg/ha. The standard deviation, approximately 1.98 kg/ha, which is more than half the mean, highlights the considerable variability in pesticide exposure levels across municipalities in Brazil. The municipality with the highest exposure level, as previously mentioned, was Landri Sales, with an average of 11.74 kg/ha. Additionally, there were 648 observations with a pesticide exposure value of zero, indicating municipalities with no cultivation of any of the seven crops included in the analysis during the study period.

Table 4: Descriptive Statistics of the Explanatory Variables for Brazilian Municipalities

Variables	Mean	Std	Max	Min	N
exp_pestice	3.66	1.98	11.74	0	22,252
infant_mort_rate	12.31	12.53	181.82	0	22,252
preterm_birth_rate	114.2	43.92	629.50	0	22,252
low_birth_weight	78.90	34.36	444.44	0	22,252
childhood_cancer_rate	19.85	48.14	2573.53	0	22,252
mun_GPD	29.94	35.36	920.83	4.47	22,252
PHCU_rate	37.07	19.68	229.49	0.84	21,703
mother_prenatal	764.45	134.78	1000	30.22	22,252
mother_adv_age	146.80	55.96	571.40	0	22,252
mother_white	363.47	310.07	1000	0	22,252
hospital_births	990.30	26.09	1000	458,50	22,252
mother_educ_3years	22.74	32.34	643.06	0	22,252
mult_births	20.57	22.16	333.33	0	22,252

Source: Own Elaboration using data from SINASC, INDEA, PAM, CNES, SIDRA-IBGE, SIM and Painel-Oncologia Brasil.

The municipal per capita GDP also reveals significant socioeconomic disparities among Brazilian municipalities between 2019 and 2022. The average per capita GDP was 29.94

Brazilian reais (in thousands), but the standard deviation exceeded the mean value, suggesting a high degree of inequality. The highest per capita GDP, at 920.83 thousand reais, was observed in the municipality of Catas Altas, located in the state of Minas Gerais. This municipality exhibits a high concentration of wealth primarily linked to intensive mining activity. In contrast, the lowest per capita GDP, at 4.47 thousand reais, was recorded in Matões do Norte, in the state of Maranhão — a region that encompasses some of the poorest municipalities in Brazil, characterized by the lowest levels of per capita income in the country.

The average number of Primary Health Care Units (PHCUs) per 100,000 inhabitants was approximately 37, with the standard deviation also showing a relatively high value, indicating variability in health infrastructure across municipalities.

The national average infant mortality rate was 12.31 deaths per 1,000 live births, reflecting a concerningly high level of infant deaths. Regarding childhood cancer, the mean number of children aged 0 to 19 years diagnosed with a malignant neoplasm was 19.85 cases per 100,000 children in the same age group. The standard deviation for this variable was 48.14, highlighting substantial disparities in incidence rates across municipalities.

Finally, the average number of mothers who attended seven or more prenatal care consultations was notably high, reaching 764.45 mothers per 1,000 live births. This indicates a positive aspect of prenatal healthcare coverage in the country. Furthermore, the vast majority of births occurred in hospital settings, with an average of 990.3 hospital deliveries per 1,000 live births. The number of mothers with up to three years of schooling—representing the lowest education level after no formal education—was relatively low, with an average of 22.74 mothers per 1,000 live births.

4.2 Econometric Results

Table 5 presents the estimated effects of residential pesticide exposure on two key birth outcomes: the rate of low birth weight and the rate of preterm births. The results are reported for two model specifications for each outcome: one controlling for both municipality and year fixed effects, and another using a pooled panel model that does not account for any fixed effects.

The estimates for the two dependent variables analyzed appear markedly more significant in the pooled model than in the fixed-effects specifications. According to the pooled results, residential pesticide exposure is positively associated with both low birth weight and preterm birth, which is consistent with the findings of the existing literature.

However, once municipality and year fixed effects are included, statistical significance disappears, suggesting that the observed relationship may be capturing structural differences across municipalities rather than within-municipality variation over time. Moreover, the

Breusch–Pagan LM test for panel data indicates the presence of significant individual effects, meaning that municipality or time fixed effects are relevant. Therefore, the pooled model is not the most appropriate specification for the analysis. Consequently, the results from the fixed-effects models should be considered as the main reference.

Therefore, for both outcomes - low birth weight and preterm birth - pesticide exposure did not show statistically significant effects in any of the specifications, which goes against expectations, according to the specialized literature. Based on the present analysis, residential pesticide exposure cannot be considered a causal factor for adverse birth outcome.

Table 5: Econometric Results: Effects of Explanatory Variables on Low Birth Weight and Preterm Birth

	low_weight	*low_weight*	*preterm_birth*	*preterm_birth*
exp_pesticide	0.738 (0.669)	**1.197 .** **(0.705)**	0.790 (0.938)	**0.343 .** **(0.196)**
Control variables				
mun_GPD	-0.010 (0.016)	0.059* (0.024)	-0.028 (0.026)	0.009 (0.008)
PHCU_rate	0.036 (0.044)	0.172*** (0.044)	0.063 (0.055)	-0.038 . (0.020)
mother_prenatal	-0.044*** (0.005)	-0.027*** (0.005)	-0.079*** (0.006)	-0.032*** (0.003)
mother_adv_age	0.020* (0.009)	0.030** (0.009)	0.035** (0.011)	0.046*** (0.008)
mother_white	-0.012 . (0.007)	-0.018** (0.007)	-0.014 (0.009)	0.004** (0.001)
hospital_births	-0.022 (0.029)	-0.040 (0.029)	-0.029 (0.035)	-0.058* (0.028)
mother_educ_3years	-0.007 (0.016)	-0.044** (0.016)	-0.065*** (0.019)	0.005 (0.020)
mult_births	0.550*** (0.019)	0.553*** (0.019)	0.528*** (0.022)	0.536*** (0.020)
Observations	21,703	21,703	21,703	21,703
FE: municipality	✓		✓	
FE: year	✓		✓	
Std.Errors by municipality	✓	✓	✓	✓

Source: Own Elaboration. Robust standard errors, adjusted for clustering by municipality, are presented in parentheses. The symbols . , *, **, and *** indicate rejection of the null hypothesis at significance levels of 10%, 5%, 1% and 0.1%, respectively.

Examining the control variables in the fixed-effects estimates, it is observed that Municipal GDP *(mun_GDP)* and the availability of primary health care units *(PHCU_rate)* were not statistically significant for either of the outcomes.

On the other hand, maternal and individual-level factors played an important role. A higher number of prenatal care visits *(mother_prenatal)* was consistently associated with lower rates of both adverse outcomes, reinforcing its protective role (Dias et al., 2023; Macinko & Mendonça, 2018). Advanced maternal age *(mother_adv_age)* and multiple births *(mult_births)* were both positively and significantly associated with higher rates of low birth weight and preterm birth, aligning with established evidence in the literature (Correa-de Araujo & Yoon, 2021; Larsen et al., 2017; Falcone et al., 2024).

For the variable related to hospital births *(hospital_births)* and for the case of white mothers *(mother_white)*, no significant results were found in any specification. Furthermore, for mothers with low education levels *(mother_educ_3years)*, the coefficient sign was contrary to expectations, suggesting that lower maternal education was associated with lower chances of having children with low birth weight or preterm birth.

Table 6 presents the effects of pesticide exposure on infant mortality rates and childhood cancer rates, also considering the two specifications of controlling for both municipality and year fixed effects, and other not controlling for any fixed effects. Similar to the models discussed above, the Breusch–Pagan LM test indicated that the pooled model is not appropriate for analyzing infant mortality and childhood cancer, as fixed effects are relevant. Although the pooled estimates appeared more significant, these results are likely spurious.

Accordingly, the main explanatory variable of interest, pesticide exposure, did not exhibit statistically significant effects on either infant mortality or childhood cancer rates. The estimated coefficients for pesticide exposure were negative but not statistically significant at any conventional level, including the 10% level.

These findings suggest that, within the scope of this dataset and model specification, there is no robust evidence of a direct association between increased pesticide exposure and higher rates of infant mortality or childhood cancer in Brazilian municipalities during the study period.

Table 6: Econometric Results: Effects of Explanatory Variables on Infant Mortality and Childhood Cancer

	infant_mort	*infant_mort*	*child_cancer*	*child_cancer*
exp_pesticide	-0.077	-0.253***	-0.15	1.018***
	(0.257)	(0.046)	(1.112)	(0.180)
Control variables				
intercept		8.055***		12.872***
		(0.493)		(2.182)
mun_GPD	-0.009 .	-0.016***	-0.020	0.041***
	(0.004)	(0.002)	(0.029)	(0.009)
PHCU_rate	0.014	0.013*	-0.017	-0.003
	(0.017)	(0.005)	(0.051)	(0.021)
low_birth_weight	0.009 .	0.003	-0.039	0.015
	(0.005)	(0.003)	(0.027)	(0.019)
preterm_birth	0.034***	0.042***	0.033	0.006
	(0.004)	(0.003)	(0.025)	(0.018)
Observations	21,703	21,703	21,703	21,703
FE: municipality	✓	-	✓	-
FE: year	✓	-	✓	-
Std.Errors by municipality	✓	✓	✓	✓

Source: Own Elaboration. Robust standard errors, adjusted for clustering by municipality, are presented in parentheses. The symbols . , *, **, and *** indicate rejection of the null hypothesis at significance levels of 10%, 5%, 1% and 0.1%, respectively.

Regarding the childhood cancer model, it is clear that none of the variables reached statistical significance, indicating that the model under analysis was not able to fit the data well for this outcome.

In the case of the infant mortality model, the fit appears to be better, as the majority of the control variables were statistically significant and presented coefficients with directions consistent with what is expected in the literature, except for the *PHCU_rate*, which was not significant. A higher municipal per capita GDP *(mun_GDP)* reduces the probability of infant mortality, while higher rates of low birth weight *(low_birth_weight)* and preterm births *(preterm_birth)* increase this probability, although the magnitude of the coefficients suggests that these effects are relatively small.

Hence, the results presented in Table 6 indicate that while preterm birth is a strong predictor of infant mortality, pesticide exposure does not show a significant effect on infant mortality or childhood cancer rates within this analytical framework.

In summary, looking at the results from the municipality and year fixed-effects models, no relationship was observed between residential pesticide exposure and the four child health outcomes, low birth weight, preterm birth, infant mortality and childhood cancer. However, this finding does not imply that pesticides are harmless to human or child health. As discussed before, methodological limitations, particularly due to data scarcity, may have rendered the analysis constrained or overly abstract, relying on assumptions that could diverge from reality. Moreover, the shortened analysis period of four years may have contributed to the lack of statistical significance in the results. While birth-related outcomes allow for a reduced time frame corresponding to the gestational period of approximately nine months, in the case of the childhood cancer variable, this four-year period becomes overly restrictive, considering that the chronic effects of pesticide exposure tend to manifest in the medium and long term. Therefore, it is important to conduct further investigation into the potential health risks associated with exposure to pesticides.

Robustness checks were conducted for all models. The Hausman test indicated that fixed effects models were preferable to random effects, ensuring better control for unobserved heterogeneity across municipalities. Also, the Breusch–Pagan LM Test indicated that fixed effect models were better than the pooled model. Moreover, robust standard errors clustered at the municipal level were applied to account for potential heteroskedasticity and within-cluster correlation, thereby reducing the risk of artificially inflated significance levels. Additionally, multicollinearity diagnostics were performed to ensure that high correlations among explanatory variables did not bias the estimated coefficients.

After analyzing the results for all child health indicators, it is noticeable that no statistically significant association was found.

5 Final Remarks

This study aimed to analyze the impact of residential exposure to pesticides on four child health outcomes: low birth weight, preterm birth, infant mortality, and incidence of cancer in children aged 0 to 19 years in 5,510 Brazilian municipalities. A panel data analysis was conducted covering the period from 2019 to 2022, a time marked by an intense liberalization of pesticide regulations in Brazil.

Due to the lack of comprehensive nationwide data on pesticide use and exposure, a pesticide exposure index was developed following a shift-share approach. This allowed for a causal assessment of the relationship between pesticide exposure and child health outcomes. The exposure estimates were based on pesticide consumption data from the state of Mato Grosso, considering the seven crops with the highest pesticide use: cotton, soybeans, sugarcane, corn, rice, beans, and coffee.

The indicator made it possible to estimate the average pesticide use per hectare for each crop, as well as the total volume of pesticides used in Brazilian municipalities during the analyzed period, thereby contributing to the advancement of research in this field. Regarding the econometric results, no statistically significant association was found between pesticide exposure and the health outcomes examined in the study when using fixed-effects models.

Research on this topic in Brazil faces a fundamental challenge due to the scarcity and fragmentation of data, which makes such analyses complex and likely underestimates the true effects of pesticide exposure on human health. The limited significance and strength of the overall findings may be directly related to methodological constraints, including the short four-year analysis period, the extrapolation of data from a single state (Mato Grosso) to the entire country, and the focus on only seven crop types to estimate exposure levels, all of which are closely tied to the broader issue of data scarcity.

Despite these limitations, this study makes an important contribution by providing one of the first national-level analyses using a municipal panel design to investigate the relationship between pesticide exposure and child health outcomes in Brazil. The creation of a tailored exposure indicator and the use of robust econometric techniques help fill a critical gap in the literature. Future research would benefit greatly from more detailed and disaggregated data on pesticide application, as well as from longer observation periods, to allow for more precise and comprehensive analyses.

Finally, the debate and results highlight the urgent need for stronger public policies aimed at regulating pesticide use, improving environmental monitoring, and increasing the transparency and accessibility of pesticide-related data. Advancing research in this area and strengthening evidence-based policymaking are essential steps toward safeguarding public health, especially for vulnerable populations such as children.

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