





















THE PARADOX OF IRRIGATED FRUIT CULTURE: SOCIOENVIRONMENTAL IMPACTS AND OCCUPATIONAL HEALTH IN THE PETROLINA-JUAZEIRO HUB

O PARADOXO DA FRUTICULTURA IRRIGADA: IMPACTOS SOCIOAMBIENTAIS E A SAÚDE DO TRABALHADOR NO POLO PETROLINA-JUAZEIRO

LA PARADOJA DE LA FRUTICULTURA IRRIGADA: IMPACTOS SOCIOAMBIENTALES Y SALUD OCUPACIONAL EN EL POLO PETROLINA-JUAZEIRO

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Abstract: The rapid expansion of irrigated fruit production in the Petrolina–Juazeiro-Brazil hub has positioned the Brazilian semi-arid as a strategic agro-export region, while simultaneously intensifying socioenvironmental inequalities and occupational health risks. This paradox reflects a development model in which economic gains coexist with diffuse and often invisible forms of exposure. This study aims to analyze the socioenvironmental and health impacts associated with irrigated agribusiness, focusing on the interaction between chemical exposure, water dynamics, and territorial vulnerability. An integrative literature review was conducted using international and regional databases, complemented by grey literature. A total of 216 records were initially identified and subjected to systematic screening and eligibility procedures. The analysis was structured around three axes: biochemical-clinical, socioeconomic, and geoenvironmental. The results indicate that pesticide exposure in the region is chronic, cumulative, and mediated by environmental and social factors. Evidence shows associations with genotoxicity, endocrine disruption, and underreported chronic diseases, alongside labor precariousness and gender inequality. Contamination pathways extend through soil and water systems, amplifying exposure beyond occupational settings. The discussion reveals that these dynamics are embedded in a broader framework of environmental injustice, where

risks are unevenly distributed and structurally produced. The interaction between climate conditions, irrigation systems, and chemical use intensifies exposure, supporting the conceptualization of a chemical-hydric exposome. In conclusion, the study highlights the need for integrated regulatory approaches, improved surveillance systems, and policies that address cumulative exposure and territorial inequalities in semiarid agro-export regions.

Keywords: Exposome. Environmental Justice. Agribusiness. Chronic Exposure. Semiarid.

Resumo: A expansão acelerada da fruticultura irrigada no polo Petrolina–Juazeiro-Brasil consolidou o semiárido brasileiro como uma região estratégica para o agronegócio exportador, intensificando desigualdades socioambientais e riscos à saúde do trabalhador. Esse paradoxo revela um modelo de desenvolvimento em que ganhos econômicos coexistem com formas difusas e frequentemente invisíveis de exposição. O objetivo deste estudo foi analisar os impactos socioambientais e à saúde associados ao agronegócio irrigado, com foco na interação entre exposição química, dinâmica hídrica e vulnerabilidade territorial. Foi realizada uma revisão integrativa da literatura em bases de dados nacionais e internacionais, complementada por literatura cinzenta. Inicialmente, 216 registros foram identificados e submetidos a processos sistemáticos de triagem e elegibilidade. A análise foi estruturada em três eixos: bioquímico-clínico, socioeconômico e geoambiental. A exposição a agrotóxicos na região é crônica, cumulativa e mediada por fatores ambientais e sociais. Evidências apontam associações com genotoxicidade, desregulação endócrina e doenças crônicas subnotificadas, além de precarização do trabalho e desigualdades de gênero. As vias de contaminação se estendem por solo e água, ampliando a exposição para além do ambiente ocupacional. A discussão evidencia que essas dinâmicas estão inseridas em um contexto de injustiça ambiental, no qual os riscos são distribuídos de forma desigual e estruturalmente produzidos. A interação entre condições climáticas, irrigação e uso de insumos químicos intensifica a exposição, sustentando a noção de exposoma químico-hídrico. Conclui-se pela necessidade de políticas integradas, fortalecimento da vigilância e enfrentamento das desigualdades territoriais em regiões semiáridas.

Palavras-chave: Exposoma. Justiça Ambiental. Agronegócio. Exposição Crônica. Semiárido.

Resumen: La expansión acelerada de la fruticultura irrigada en el polo Petrolina–Juazeiro-Brasil ha consolidado el semiárido brasileño como una región estratégica para el agronegocio exportador, al mismo tiempo que ha intensificado las desigualdades socioambientales y los riesgos para la salud ocupacional. Este fenómeno refleja un modelo de desarrollo en el que los beneficios económicos coexisten con formas difusas y frecuentemente invisibles de exposición. El objetivo de este estudio fue analizar los impactos socioambientales y sanitarios asociados al agronegocio irrigado, enfocándose en la interacción entre exposición química, dinámica hídrica y vulnerabilidad territorial. Se realizó una revisión integradora de la literatura utilizando bases de datos internacionales y regionales, complementadas con literatura gris. Se identificaron inicialmente 216 registros, los cuales fueron sometidos a procesos sistemáticos de selección y elegibilidad. El análisis se estructuró en tres ejes: bioquímico-clínico, socioeconómico y geoambiental. Los resultados muestran que la exposición a pesticidas es crónica, acumulativa y mediada por factores ambientales y sociales. Se identificaron asociaciones con genotoxicidad, disrupción endocrina y enfermedades crónicas subregistradas, junto con precarización laboral y desigualdades de género. Las vías de contaminación se extienden a través del suelo y el agua, ampliando la exposición más allá del ámbito ocupacional. La discusión evidencia que estas dinámicas se inscriben en un contexto de injusticia ambiental, donde los riesgos se distribuyen de forma desigual y estructural. La interacción entre condiciones climáticas, sistemas de riego y uso de agroquímicos intensifica la exposición, respaldando el concepto de exposoma químico-hídrico. En conclusión, se destaca la necesidad de políticas integradas, fortalecimiento de los sistemas de vigilancia y reducción de las desigualdades territoriales en regiones semiáridas.

Palabras clave: Exposoma. Justicia Ambiental. Agronegocio. Exposición Crónica. Semiárido.

1 INTRODUCTION

The Petrolina–Juazeiro pole in the Northeast of Brazil has consolidated itself as a strategic agro-export hub in the Brazilian semiarid, marked by rapid integration into global fruit markets and strong dependence on irrigated production systems. This trajectory reflects a broader reorganization of territory, in which economic expansion coexists with persistent socio-environmental asymmetries. Rather than a uniform process of development, the region exhibits a fragmented landscape shaped by unequal access to resources and differentiated exposure to environmental risks (Silva, 2012; Barros, 2010).

The expansion of irrigated agriculture has intensified production cycles and reorganized spatial dynamics,

reinforcing governance structures that privilege large-scale export-oriented actors. These arrangements deepen agrarian dualities between irrigated agribusiness and marginalized traditional systems, consolidating structural inequalities within the semi-arid (Sobel, 2011; Baiardi & Ribeiro, 2023; Brandão & Rist, 2020). In this context, agribusiness operates as a socio-technical system that redistributes benefits and risks unevenly, embedding the region within global circuits of agrochemical use and environmental externalization (Bombardi, 2017; Gomes, 2019). The Petrolina–Juazeiro pole thus embodies a condensed expression of Anthropocene dynamics, where productivity gains are inseparable from ecological pressure and social vulnerability.

Scientific and regulatory frameworks addressing pesticide risks have predominantly focused on acute intoxication, overlooking the cumulative effects of chronic exposure. This limitation obscures the diffuse and multi-pathway nature of exposure in agricultural territories, where occupational, environmental, and dietary routes intersect. In Brazil, pesticide use is spatially extensive and socially uneven, disproportionately affecting rural populations (Pignati *et al.*, 2017).

Evidence links chronic exposure to genotoxic, endocrine, and neurological effects, yet these outcomes remain underreported or poorly classified within surveillance systems (Nogueira, Szwarcwald & Damacena, 2020). The Dossiê ABRASCO emphasizes the persistence of continuous exposure scenarios that escape effective monitoring and regulation (Carneiro *et al.*, 2015). In this context, the concept of the exposome provides a more comprehensive approach by integrating cumulative exposures throughout the life course. When applied to the semi-arid region, this framework reveals a context in which chemical agents interact with climatic stress and social vulnerability, supporting the formulation of the semi-arid exposome as an analytical category capable of capturing synergistic risks (Milhorance *et al.*, 2020; Gomes, 2019; Nogueira, Szwarcwald & Damacena, 2020; Souza, Silva & Pinheiro, 2022).

Water plays a central and paradoxical role in the dynamics of the Petrolina–Juazeiro hub. The São Francisco River sustains irrigated agriculture and increases the economic value of water in regional development strategies (Alcoforado de Moraes *et al.*, 2018). At the same time, it acts as a pathway for contaminant dispersion, since the intensive use of agrochemicals promotes surface runoff, leaching, and the accumulation of residues in aquatic systems (Pignati *et al.*, 2017; Nogueira, Szwarcwald & Damacena, 2020; Souza, Silva & Pinheiro, 2022; Silva *et al.*, 2014).

This dynamic extends exposure beyond occupational environments, affecting surrounding communities through diffuse contamination processes. The notion of virtual water trade reinforces this perspective by highlighting that environmental degradation and resource depletion are embedded in exported products (Nascimento & Becker, 2009). Water thus assumes a dual role: while enabling production, it also intensifies the circulation of risks, blurring the boundaries between environmental and occupational exposure (Gomes, 2019; Nogueira, Szwarcwald & Damacena, 2020).

Despite advances in the literature, the relationship between chemical exposure, hydrological processes, and climatic conditions remains fragmented across different disciplinary approaches. Studies tend to isolate biochemical, environmental, or socioeconomic dimensions, limiting the understanding of their interactions in semi-arid contexts (Brandão & Rist, 2020; Brandão, Santos & Rist, 2020; Milhorance *et al.*, 2020; Gomes, 2019).

This study addresses this gap by proposing the concept of a chemical-hydric exposome, defined as the interaction between pesticide exposure, water-mediated pathways, and environmental stressors typical of the semiarid. It also advances the notion of sacrifice zones to describe territories where economic gains are sustained through the externalization of health and environmental costs to vulnerable populations.

The objectives are to synthesize evidence across biochemical, socioeconomic, and geoenvironmental dimensions, critically examine the role of irrigated agribusiness in shaping unequal risk distributions, and develop a conceptual model linking exposome theory to environmental justice in the Brazilian semiarid.

In framing the Petrolina–Juazeiro pole as a critical site of intersecting environmental, social, and biological exposures, this study advances a shift from fragmented risk assessments toward an integrated understanding of development-induced vulnerability. By articulating the concepts of chemical-hydric exposome and sacrifice zones, the analysis moves beyond descriptive accounts to interrogate the structural conditions that normalize uneven exposure and invisibilize chronic harm. This perspective not only repositions the semiarid within global debates on planetary health and environmental justice, but also challenges prevailing narratives of agricultural modernization by exposing its underlying epidemiological and territorial costs.

2. METHODOLOGY

2.1 Study design: integrative literature review

This study was designed as an integrative literature review, a methodological approach particularly suited to complex public health and socio-environmental problems that cannot be adequately understood through a single disciplinary lens. Unlike narrowly clinical review formats, the integrative review allows the simultaneous inclusion of empirical, theoretical, and documentary studies (Torraco, 2005), making it especially appropriate for examining the intersections among agribusiness, environmental contamination, occupational exposure, and territorial vulnerability in the Petrolina–Juazeiro pole. In methodological terms, the integrative review is distinguished by its capacity to synthesize heterogeneous evidence while preserving analytical rigor, thereby enabling broader interpretive constructions and critical theoretical advances (Torraco, 2005; Mendes *et al.*, 2008; Souza *et al.*, 2010).

The epistemological justification for adopting this design lies in the nature of the research problem itself. The object of analysis is not limited to a clinical outcome or a single exposure pathway, but rather involves a multidimensional process in which environmental degradation, chronic chemical exposure, water-mediated circulation of contaminants, labor precariousness, and regional development policies interact. For this reason, a conventional systematic review, although rigorous in relation to narrowly defined questions, would impose excessive restrictions on the types of evidence eligible for analysis and would reduce the explanatory capacity required for a critical synthesis of the phenomenon. By contrast, the integrative review makes it possible to articulate results from studies with different methodological designs, scales, and disciplinary traditions, which is essential for building the conceptual proposition advanced in this article, namely the chemical-hydric exposome and the notion of sacrifice zones in the Brazilian semiarid (Torraco, 2005; Mendes *et al.*, 2008).

The review followed the classic stages recommended for integrative reviews: identification of the guiding

problem, definition of the search strategy, establishment of inclusion and exclusion criteria, critical selection of studies, extraction and organization of relevant information, and interpretive synthesis of findings (Mendes et al., 2008; Souza et al., 2010). At the same time, in order to increase transparency, reproducibility, and procedural clarity, the study adopted a PRISMA-informed logic for identification, screening, eligibility assessment, and final inclusion of records. This does not convert the present study into a conventional systematic review. Rather, it strengthens the auditability of the review process while preserving the broader analytical scope that characterizes the integrative method. In this sense, methodological rigor was pursued not through reduction of complexity, but through explicit documentation of each analytical step and coherent articulation between corpus selection and interpretive synthesis.

2.2 Search strategy and databases

The bibliographic search was conducted between October 2025 and March 2026. This time window included the stages of query refinement, database exploration, duplicate identification, title and abstract screening, full-text eligibility assessment, and final corpus consolidation. The search strategy was defined to capture literature addressing agribusiness, pesticide use, occupational and environmental health, water dynamics, and territorial processes in semiarid contexts, with special attention to the São Francisco Valley and the Petrolina-Juazeiro pole.

The following databases were used: PubMed/MEDLINE, Scopus, Web of Science, and Embase, complemented by SciELO and LILACS, in order to ensure greater sensitivity to Latin American and Brazilian scientific production published between October 2025 and March 2026. The methodological strategy was guided by the principles of the integrative review, as proposed by Torraco (2005) and operationalized in the health context by Mendes, Silveira and Galvão (2008), with support from the systematization guidelines described by Souza, Silva, & Carvalho (2010). Because the topic involves important institutional and political dimensions that are not always fully represented in indexed journals, grey literature was also consulted, particularly the ABRASCO dossier on pesticides and health. The inclusion of grey literature was justified by its analytical relevance to environmental justice, regulatory critique, and the invisibilization of chronic harm in official surveillance systems.

Search terms were combined using Boolean operators and adapted to the indexing language of each database. The core structure of the strategy articulated descriptors related to agribusiness and fruit production, pesticides and agrochemicals, occupational and environmental health, and the semiarid territory. Terms such as agribusiness, fruit culture, pesticides, agrochemicals, occupational health, environmental impact, semi-arid, São Francisco Valley, Petrolina, and Juazeiro were used in different combinations. The search strategy was refined iteratively in order to avoid overrepresentation of generic agronomic studies that did not address exposure, health, or territorial effects.

A total of 216 records were initially identified across the selected sources. After retrieval, the records underwent successive screening procedures involving duplicate removal, preliminary relevance assessment based on titles and abstracts, and full-text evaluation according to the eligibility criteria established for this review. The objective was not merely to gather publications on irrigation or regional economy, but to identify studies capable of contributing substantively to the proposed analytical model, especially those addressing the health impacts of

pesticide exposure, socio-spatial inequalities of agrarian modernization, and contamination pathways involving water, soil, and vulnerable populations.

2.3 Inclusion and exclusion criteria

Eligibility criteria were established prior to the screening process in order to preserve analytical consistency and avoid arbitrary selection. These criteria were based on the guiding question of the review and on the theoretical commitment to integrate biochemical, socioeconomic, and geoenvironmental dimensions of the problem.

Inclusion criteria:

- Studies published in Portuguese, English, or Spanish.
- Studies retrieved between October 2025 and March 2026 through the selected databases and grey literature sources.
- Empirical studies, theoretical analyses, theses, dissertations, and institutional documents with direct relevance to the research problem.
- Publications focusing on the Brazilian semiarid, the São Francisco Valley, or specifically the Petrolina-Juazeiro pole.
- Studies addressing at least one of the following dimensions: pesticide exposure, occupational health, environmental contamination, water use and circulation, territorial restructuring, labor vulnerability, agrarian inequalities, or public policy related to irrigated agriculture.
- Studies whose findings contributed to one or more of the three analytical axes defined for synthesis: biochemical-clinical, socioeconomic, and geoenvironmental.

Exclusion criteria:

- Publications centered exclusively on agricultural productivity, crop management, or market performance without any connection to exposure, health, environment, labor, or territory.
- Studies conducted in regions with no analytical relation to semiarid irrigated agribusiness or to the São Francisco context.
- Editorials, opinion texts, conference abstracts, or brief communications lacking sufficient methodological or analytical substance.
- Duplicated records indexed in more than one database.
- Texts unavailable in full after database retrieval and institutional repository searches.
- Studies whose thematic focus was too distant from the review objective, even when they included generic references to agriculture, irrigation, or development.

The screening process was conducted in three stages. First, duplicate references were removed. Second, titles and abstracts were read to exclude manifestly irrelevant studies. Third, full texts were examined to assess conceptual adherence, geographic pertinence, and contribution to the analytical framework. Only studies that demonstrated effective relevance to the central problem of this review were retained for interpretive synthesis.

2.4 Analytical framework

The analytical framework was developed to move beyond a fragmented reading of the literature and to support a critical synthesis capable of linking exposure, territory, and development. The selected studies were therefore analyzed according to a three-axis model specifically designed for this review. This model was not used merely as a classificatory device, but as a means of identifying convergences, tensions, and explanatory gaps across heterogeneous bodies of evidence.

The first axis, biochemical-clinical, encompassed studies addressing direct or indirect health effects associated with pesticide exposure, including toxicological effects, genotoxicity, endocrine disruption, neurological damage, chronic illness, and risk perception in exposed populations. This axis was essential for identifying how bodily harm is documented, recognized, or obscured in the literature.

The second axis, socioeconomic, included studies focused on labor relations, gendered precariousness, agrarian dualities, governance structures, public policy, and the unequal distribution of risks and benefits produced by irrigated agribusiness. This dimension allowed the review to examine exposure not as an isolated biological event, but as a socially organized condition embedded in regional development dynamics.

The third axis, geoenvironmental, comprised studies dealing with water valuation, hydrological dependence, riparian degradation, contaminant circulation, virtual water trade, and environmental transformations linked to irrigated agriculture in the semi-arid. This axis was central to understanding how ecological processes mediate the spatial diffusion of risk and connect local exposure to broader territorial and hydrosocial systems.

After classification within these axes, the studies were subjected to an interpretive synthesis aimed at identifying recurrent patterns, complementarities, and silences in the literature. Particular attention was given to intersections among the three dimensions, since the central hypothesis of this article is that chronic harm in the Petrolina-Juazeiro pole cannot be fully understood through isolated categories. Rather, it emerges from the interaction between chemical exposure, water-mediated circulation, climatic adversity, and unequal territorial organization. It is from this analytical convergence that the concepts of chemical-hydric exposome and sacrifice zones are developed in the subsequent sections.

Table 1 systematizes the core elements of the PRISMA-adapted strategy adopted in this integrative review, organizing the search process into five key components: databases, grey literature, search strategy, inclusion criteria, and exclusion criteria. This structure enhances transparency by explicitly linking each methodological decision to its operationalization and analytical purpose. Rather than merely listing procedural steps, the table clarifies how each component contributed to constructing a coherent and targeted corpus aligned with the research objectives. The inclusion of both indexed databases and grey literature reflects the dual commitment to scientific rigor and critical comprehensiveness, particularly in relation to environmental justice and underreported health impacts.

Table 1. PRISMA-adapted search strategy and eligibility criteria

Component	Description	Operationalization	Purpose in Review
Databases	International and regional indexed sources	PubMed/MEDLINE, Scopus, Web of Science, Embase; SciELO, LILACS	Ensure broad coverage and inclusion of global and Latin American evidence
Grey Literature	Institutional and non-indexed sources	ABRASCO dossier and related public health documents	Capture critical perspectives and underreported socio-environmental issues
Search Strategy	Boolean combinations of descriptors	(Agribusiness OR “Fruit culture”) AND (Pesticides OR Agrochemicals) AND (“Occupational health” OR “Environmental impact”) AND (“Semi-arid” OR “São Francisco Valley” OR Petrolina OR Juazeiro)	Identify studies linking production, exposure, health, and territory
Inclusion Criteria	Eligibility parameters for study selection	Geographic relevance; exposure-health-environment nexus; empirical or theoretical contribution; languages (EN/PT/ES)	Maintain analytical coherence and relevance to research problem
Exclusion Criteria	Parameters for removing irrelevant studies	Purely agronomic or economic focus; lack of exposure or health linkage; duplicates; unavailable full texts	Avoid dilution of analytical focus and ensure conceptual consistency

Source: Prepared by the authors.

The configuration presented in Table 1 reveals a deliberate balance between sensitivity and specificity in the search strategy. The combination of international databases with regional repositories reduces epistemic bias by incorporating Global South perspectives often absent from mainstream indexed literature. At the same time, the structured Boolean strategy ensures that retrieved studies are not restricted to agronomic productivity but instead intersect with health, environmental, and territorial dimensions.

The inclusion and exclusion criteria function as epistemological filters, preventing the fragmentation of the analysis and reinforcing the integrative logic of the review. This methodological architecture is fundamental for supporting the subsequent synthesis, as it ensures that the selected corpus is not only extensive but also conceptually aligned with the proposed framework of the chemical-hydric exposome and the identification of sacrifice zones.

3 RESULTS

The selected studies were analyzed based on their contribution to an integrated understanding of the impacts of irrigated fruit production in the Petrolina–Juazeiro hub, considering biochemical-clinical, socioeconomic, and geoenvironmental dimensions. The final corpus included scientific articles, dissertations, theses, and institutional documents, published predominantly between 2006 and 2025, with a predominance of studies conducted in the Brazilian semiarid region, particularly in the São Francisco Valley.

In general, the studies address populations directly or indirectly exposed to pesticides, including rural workers, family farmers, and riverside communities. The evidence converges toward characterizing exposure as chronic, cumulative, and mediated by environmental, climatic, and social factors, highlighting the complexity of contamination processes and their effects on health and territory.

Table 2 presents a synthesis of the main studies included in the review, highlighting their methodological characteristics and key findings.

Table 2 – Synthesis of analyzed studies

Study title	Authors (year)	Location / context	Target population	Main conclusions
Pesticide exposure and health effects in agricultural workers	Rigotto et al. (2020)	Brazil (rural contexts)	Agricultural workers	Shows association between chronic exposure and genotoxic, endocrine, and neurological effects
Spatial distribution of pesticide use in Brazil	Pignati et al. (2017)	Brazil	Rural population	Intensive pesticide use correlates with agricultural regions and higher exposure risk
Health risk perception of pesticide use in Petrolina/Juazeiro	Silvério et al. (2025)	Petrolina–Juazeiro	Rural workers	Low perception of chronic risks despite recognition of acute hazards
Risks to the environment and to the health of family farmers	Souza, Silva, & Pinheiro (2022)	Brazil (family farming)	Family farmers	Continuous exposure represents a persistent risk to health and the environment
ABRASCO Dossier: Impacts of pesticides on health	Carneiro et al. (2015)	Brazil	General population	Chronic exposure is diffuse, cumulative, and underreported in surveillance systems
Local representations of riparian forest change	Silva et al. (2014)	São Francisco River	Local communities	Environmental degradation reduces the capacity to buffer contaminants
The impact of global change on water value	Alcoforado de Moraes et al. (2018)	São Francisco Basin	Irrigation systems	Economic valuation of water neglects environmental externalities

Source: Prepared by the authors.

The synthesis presented in Table 2 shows that pesticide exposure in the Brazilian semiarid does not constitute an isolated event, but rather a systemic, cumulative, and multiscale process. The studies converge in demonstrating that health effects extend beyond acute intoxication, manifesting through genotoxic, endocrine, and neurological alterations that are often underreported or rendered invisible in surveillance systems (Nogueira, Szwarcwald & Damacena, 2020; Carneiro et al., 2015). This condition is aggravated by the wide spatial distribution of pesticide use, associated with regions of intensive agriculture, which expands the potential for exposure beyond directly involved workers, affecting communities and ecosystems (Pignati et al., 2017; Souza, Silva & Pinheiro, 2022).

Moreover, the studies indicate that exposure is deeply embedded in territorial and environmental dynamics, particularly mediated by water and ecological systems. The degradation of riparian zones and the intensification of water use in irrigated systems reduce the capacity to buffer contaminants and favor their

dispersion across multiple scales (Silva *et al.*, 2014; Alcoforado de Moraes *et al.*, 2018). At the same time, social factors such as low risk perception among workers and precarious labor conditions contribute to the normalization of chronic exposure and the reproduction of socioenvironmental inequalities (Silvério *et al.*, 2025; Gomes, 2019). Taken together, these findings reinforce the need for integrated approaches, such as the concept of the chemical-hydric exposome, capable of articulating biological, environmental, and structural dimensions in understanding risks in semiarid territories.

3.1 Biochemical and health impacts of chronic pesticide exposure

The literature consistently demonstrates that pesticide exposure in agricultural systems extends far beyond acute intoxication, manifesting as a chronic and cumulative process with measurable biological consequences. Studies conducted in Brazilian rural contexts indicate associations between prolonged exposure and genotoxic damage, endocrine disruption, and neurological alterations, often occurring at subclinical levels and remaining underdiagnosed (Nogueira, Szwarcwald & Damacena, 2020; Souza *et al.*, 2022).

Rigotto *et al.* (2020) report that agricultural workers exposed to pesticide mixtures present biomarkers indicative of DNA damage and oxidative stress, reinforcing the hypothesis of cumulative toxic effects. Similarly, Souza *et al.* (2022) identify increased risks associated with chronic exposure among family farmers, highlighting that “the continuous use of pesticides represents a persistent source of risk to both human health and the environment” (Souza *et al.*, 2022, p. 5). These findings align with broader national patterns, where the spatial distribution of pesticide use correlates with regions of intensive agricultural production and elevated exposure potential (Pignati *et al.*, 2017).

The endocrine-disrupting potential of agrochemicals further increases the complexity of the exposure scenario, particularly under semiarid conditions, where high temperatures may intensify processes such as volatilization and dermal absorption, thereby amplifying the biological effects of chronic exposure (Nogueira, Szwarcwald & Damacena, 2020; Carneiro *et al.*, 2015; Milhorance *et al.*, 2020; Souza, Silva, & Pinheiro, 2022).. According to the Dossiê ABRASCO, “the effects of chronic exposure are diffuse, cumulative and often invisible to official surveillance systems” (Carneiro *et al.*, 2015, p. 45). This invisibility is not merely a technical limitation but reflects structural gaps in monitoring and reporting mechanisms, which tend to prioritize acute poisoning events while neglecting long-term health outcomes.

Risk perception studies reveal an additional layer of complexity. In the Petrolina–Juazeiro context, Silvério *et al.* (2025) demonstrate that workers frequently underestimate the long-term risks associated with pesticide use, despite recognizing immediate hazards. This dissonance between perceived and actual risk is reinforced by informational asymmetries, economic pressures, and normalization of exposure within the labor process. Londres (2011) had already warned that “the widespread use of agrochemicals in Brazil is accompanied by insufficient information and weak protective measures” (Londres, 2011, p. 32), contributing to a scenario in which exposure becomes both routine and socially tolerated.

Taken together, the evidence indicates that pesticide exposure in the semiarid cannot be understood as an isolated occupational hazard. Rather, it constitutes a systemic condition of chronic exposure, mediated by

environmental, climatic, and social factors, and marked by significant gaps between biological impact and institutional recognition.

3.2 Socioeconomic structure and labor vulnerability

The expansion of irrigated agribusiness in the Petrolina–Juazeiro pole has been accompanied by profound transformations in labor relations, often characterized by precarious employment conditions and structural inequalities. The literature reveals that these dynamics disproportionately affect vulnerable groups, particularly women and smallholder farmers, who are frequently positioned at the margins of formal labor protections and exposed to heightened environmental risks (Oliveira & Castro, 2021; Guedes *et al.*, 2024).

Oliveira and Castro (2021) highlight that labor in the fruit production sector is marked by informality, low wages, and limited access to occupational safety measures. Women, in particular, occupy precarious roles within the production chain, often combining agricultural labor with domestic responsibilities, which intensifies their exposure to both chemical and social stressors. This condition reflects broader patterns of gender inequality within agro-export systems, where economic growth does not translate into equitable labor conditions.

Guedes *et al.* (2024) further demonstrate that economic opportunities generated by irrigated agriculture are unevenly distributed, with entrepreneurial initiatives often constrained by structural barriers such as access to credit, land, and technical assistance. These findings suggest that the benefits of agribusiness expansion are selectively appropriated, reinforcing existing hierarchies rather than promoting inclusive development.

From a territorial perspective, Santos *et al.* (2019) emphasize the struggles of traditional communities to maintain land rights and cultural practices in the face of expanding agribusiness frontiers. The pressure exerted by large-scale irrigation projects contributes to processes of displacement, land concentration, and erosion of local livelihoods. This dynamic is consistent with the dual agrarian structure identified by Brandão *et al.* (2020), in which irrigated agribusiness coexists with marginalized subsistence systems, producing a landscape marked by economic asymmetry and differentiated exposure to environmental risks.

These findings indicate that exposure is not evenly distributed across the population. Instead, it is structured by socioeconomic position, gender, and territorial belonging, reinforcing the argument that health risks in the semiarid are socially produced and politically mediated.

3.3 Geoenvironmental contamination pathways

The geoenvironmental dimension of pesticide exposure in the Petrolina–Juazeiro hub reveals the existence of multiple contamination pathways involving soil, water, and ecological systems. Irrigated agriculture intensifies the mobilization of chemical inputs, increasing the likelihood of surface runoff, leaching, and the accumulation of residues in both surface and groundwater (Pignati *et al.*, 2017; Nogueira, Szwarcwald & Damacena, 2020; Souza, Silva, & Pinheiro, 2022). These processes expand the spatial reach of contamination, transforming localized practices into diffuse environmental risks, particularly in contexts characterized by ecological degradation and intensive water use (Silva *et al.*, 2014; Alcoforado de Moraes *et al.*, 2018; França, 2006).

Silva *et al.* (2014) document changes in riparian ecosystems along the São Francisco River, indicating that

land-use transformations associated with agriculture have contributed to the degradation of riverine vegetation and ecological functions. Such changes reduce the capacity of these systems to buffer contaminant flows, facilitating the spread of agrochemical residues across aquatic environments.

The economic valuation of water within irrigation schemes further complicates this scenario. Alcoforado de Moraes *et al.* (2018) demonstrate that water use in the São Francisco Basin is increasingly driven by productivity considerations, often neglecting environmental externalities. França (2006) had previously shown that the economic value attributed to water in irrigated agriculture does not adequately incorporate the costs associated with contamination and ecosystem degradation.

The concept of virtual water trade adds an additional layer of analysis. Nascimento and Becker (2009) argue that the export of agricultural products from the region entails the transfer of embedded environmental degradation, including water depletion and pollution. In this sense, contamination is not only a local phenomenon but part of a broader system of ecological exchange linked to global markets.

These findings indicate that contamination pathways are multi-scalar and interconnected. Soil, water, and ecological systems operate as vectors that amplify and redistribute exposure, challenging the notion that risks can be confined to specific sites or populations.

Table 3 synthesizes the main findings of the integrative review by articulating evidence across the three analytical axes adopted in this study: biochemical-clinical, socioeconomic, and geoenvironmental. Rather than presenting results in isolation, the table integrates exposure types, associated health outcomes, environmental pathways, and underlying social determinants into a unified framework. This structure allows for a multidimensional visualization of how pesticide exposure operates simultaneously at biological, ecological, and social levels. By organizing the evidence in this manner, the table facilitates the identification of recurring patterns and interactions that are not immediately apparent when studies are analyzed separately.

Table 3. Integrated synthesis of evidence across biochemical, socioeconomic, and geoenvironmental axes

Exposure Type	Health Outcomes	Environmental Pathways	Social Determinants
Chronic pesticide exposure	Genotoxicity, endocrine disruption, neurological effects	Dermal absorption, inhalation, food contamination	Occupational exposure, low risk perception, limited access to protection
Acute and cumulative exposure	Underreported chronic diseases, subclinical toxicity	Direct handling, spraying drift, volatilization under high temperatures	Informality, lack of surveillance, weak regulatory enforcement
Water-mediated contamination	Indirect exposure through drinking water and irrigation	Runoff, leaching, contamination of surface and groundwater	Rural and riverside communities, dependence on local water sources
Soil and ecosystem contamination	Long-term exposure through food chains and ecological degradation	Soil accumulation, loss of riparian buffering capacity	Territorial marginalization, proximity to irrigated perimeters
Agrarian	Unequal exposure burden	Expansion of irrigated areas,	Gender inequality, land concentration, dual agrarian

restructuring	across populations	intensification of input use	structure
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Source: Prepared by the authors.

The integrated structure of Table 3 reveals that exposure in the Petrolina–Juazeiro pole is not a singular event but a systemic condition shaped by the convergence of multiple pathways and determinants. Chronic pesticide exposure emerges as a central axis linking biological damage to environmental dispersion and labor conditions (Nogueira, Szwarcwald & Damacena, 2020; Souza *et al.*, 2022; Pignati *et al.*, 2017). Notably, the table highlights the disjunction between measurable health outcomes and their recognition within institutional frameworks, reinforcing the problem of underreporting identified in the literature (Carneiro *et al.*, 2015; Silvério *et al.*, 2025).

Water-mediated contamination and soil accumulation expand the spatial scale of exposure, demonstrating that risks are not confined to workers directly involved in pesticide application but extend to broader populations through diffuse environmental processes (Alcoforado de Moraes *et al.*, 2018; França, 2006; Nascimento & Becker, 2009). At the same time, social determinants such as labor precariousness, gender inequality, and land concentration structure the distribution of exposure, indicating that vulnerability is socially produced rather than randomly distributed (Oliveira & Castro, 2021; Guedes *et al.*, 2024; Santos *et al.*, 2019; Brandão *et al.*, 2020).

This synthesis supports the central argument of the study: that the interaction between chemical exposure, hydrological systems, and socioeconomic inequalities produces a complex exposure regime that cannot be adequately understood through isolated analytical categories. Instead, the evidence points toward the emergence of a chemically and hydrologically mediated exposome embedded within a territorially unequal development model (Gomes, 2019; Bombardi, 2017), laying the empirical foundation for the conceptual advances explored in the Discussion section.

3.4 Agribusiness expansion and territorial restructuring

The consolidation of the Petrolina–Juazeiro pole as a leading agro-export region is closely linked to processes of territorial restructuring driven by irrigation infrastructure, institutional arrangements, and global market integration. This transformation is not merely economic but involves the redefinition of land use, governance structures, and social relations.

Baiardi and Ribeiro (2023) emphasize that the management of irrigated agriculture in the region is marked by efficiency gains that favor large-scale production systems. However, these gains are unevenly distributed and often come at the cost of increased environmental pressure and social inequality. Sobel (2011) highlights that the governance of the fruit production chain is shaped by transaction cost dynamics that prioritize coordination among large actors, reinforcing barriers to entry for smaller producers.

The spatial organization of the region reflects these dynamics. Silva (2012) describes a pattern of economic concentration and territorial specialization, in which irrigated perimeters become nodes of high productivity surrounded by areas of limited access to resources and infrastructure. This configuration reinforces the dual agrarian structure identified by Brandão and Rist (2020), where irrigated agribusiness and traditional agriculture

coexist in conditions of marked asymmetry.

From a critical standpoint, these processes reveal that territorial restructuring is not neutral. It actively produces differentiated exposure landscapes, in which certain populations are systematically more vulnerable to environmental and health risks. The expansion of agribusiness thus operates as both a driver of economic growth and a mechanism for the redistribution of risk, contributing to the formation of territorially embedded inequalities that underpin the concept of sacrifice zones developed in this study.

4 DISCUSSION

4.1 The emergence of “sacrifice zones” in the semiarid

The evidence synthesized in this review supports the interpretation of the Petrolina–Juazeiro pole as an emerging sacrifice zone, where economic productivity is sustained through the systematic externalization of environmental and health costs. This process is not incidental but structurally embedded in the agro-export model, which prioritizes yield, standardization, and global competitiveness over territorial equity and long-term sustainability. Agribusiness expansion is accompanied by “processes that generate illness and environmental degradation as structural outcomes of development” (Gomes, 2019, p. 3), revealing that harm is not a deviation but a constitutive feature of the system.

The geography of pesticide use in Brazil reinforces this interpretation. Bombardi (2017) demonstrates that regions with high agricultural productivity concentrate the highest volumes of agrochemical consumption, establishing a direct relationship between export-oriented agriculture and exposure intensity. This spatial concentration of toxicity aligns with the findings presented in the results section, where exposure pathways extend beyond occupational settings into broader ecological and social systems. In this sense, the Petrolina–Juazeiro pole exemplifies a territorial configuration in which economic success is inseparable from the production of vulnerability.

The Dossiê ABRASCO further highlights the structural nature of this process by emphasizing that “the use of pesticides in Brazil is intrinsically linked to a model of development that produces illness and death” (Carneiro *et al.*, 2015, p. 21). Such a statement underscores the need to move beyond technical risk assessments toward a political-ecological interpretation of exposure. The concept of sacrifice zones thus provides a critical lens to understand how certain territories and populations are systematically designated as expendable within global food systems.

4.2 The chemical-hydric exposome: a new conceptual model

The articulation of the chemical-hydric exposome emerges from the recognition that exposure in the semiarid is shaped by the interaction between chemical agents, hydrological systems, and climatic stressors. Unlike traditional exposure models that isolate individual pathways, this framework emphasizes synergy, accumulation, and context dependency.

Climatic conditions play a central role in this interaction. Milhorange *et al.* (2020) demonstrate that the Brazilian semiarid is characterized by increasing temperature variability and water scarcity, conditions that intensify

environmental vulnerability and complicate adaptation strategies. These dynamics directly influence exposure patterns by increasing volatilization rates of pesticides and altering their environmental persistence. At the same time, the economic centrality of water in irrigated agriculture amplifies the circulation of contaminants. Alcoforado de Moraes *et al.* (2018) show that irrigation schemes significantly increase water demand and economic value, yet fail to adequately account for contamination externalities.

From a health perspective, Rigotto *et al.* (2020) provide evidence that chronic exposure is not only a function of chemical intensity but also of environmental conditions that facilitate absorption and bioaccumulation. The convergence of heat, water-mediated transport, and chemical use creates a compounded exposure regime that cannot be reduced to isolated variables. The chemical-hydric exposome thus represents a conceptual advance by integrating these dimensions into a unified analytical model, capable of capturing the complexity of exposure in semiarid agro-export territories.

4.3 Statistical invisibility and underreporting of chronic diseases

A central finding of this review concerns the persistent invisibility of chronic health outcomes associated with pesticide exposure. Despite extensive evidence of biological effects, official data systems remain largely focused on acute intoxication, resulting in systematic underreporting of long-term conditions. Pignati *et al.* (2017) demonstrate that pesticide use is widespread and spatially concentrated in regions of intensive agriculture, yet this distribution is not matched by equivalent visibility in health surveillance data.

This discrepancy is further reinforced by recent findings on risk perception. Silvério *et al.* (2025) show that exposed populations often recognize immediate risks but fail to associate chronic symptoms with pesticide exposure, which contributes to underdiagnosis and delayed reporting. As noted by the authors, “risk perception does not necessarily translate into protective behavior or recognition of long-term effects” (Silvério *et al.*, 2025, p. 9). This gap between exposure, perception, and institutional recognition reveals a structural failure in health monitoring systems.

The problem is not merely technical but epistemological. Chronic diseases linked to environmental exposure often lack clear causal attribution within biomedical frameworks, leading to their marginalization in official statistics. This invisibility reinforces the normalization of exposure and obscures the cumulative burden of disease in affected populations, particularly in regions such as the Petrolina–Juazeiro pole.

4.4 Necropolitics of agribusiness and global food systems

The unequal distribution of risks and benefits identified in this study can be interpreted through the lens of necropolitics, in which certain populations are systematically exposed to conditions that compromise their health and well-being. In the context of global agribusiness, this dynamic is mediated by supply chains that prioritize aesthetic and quality standards for export markets while externalizing environmental and health costs to producing regions.

Porto *et al.* (2019) argue that the current model of agricultural development operates through the “production of invisibility and inequality in the distribution of risks” (Gomes, 2019, p. 5). This observation aligns

with the spatial patterns identified by Bombardi (2017), who shows that countries in the Global South often receive agrochemicals banned or restricted in the Global North, reinforcing asymmetrical regulatory regimes.

Within this framework, the Petrolina–Juazeiro pole can be understood as a site where global consumption patterns intersect with local exposure realities. The production of export-quality fruit is contingent upon intensive chemical use and labor conditions that expose workers and communities to cumulative risks. The benefits of this system are largely externalized, while the burdens are territorially concentrated, reinforcing the characterization of the region as a sacrifice zone.

4.5 Climate amplification of toxicity in semiarid environments

Climatic conditions in the semiarid region not only shape agricultural practices but also amplify the toxicity of agrochemical exposure. High temperatures increase the volatilization of pesticides, enhancing inhalation risks, while prolonged drought conditions intensify reliance on irrigation, thereby facilitating the transport of contaminants through water systems (Milhorance *et al.*, 2020).

In addition, thermal stress contributes to increased dermal absorption. As workers operate under high temperatures, sweating and reduced use of protective equipment enhance the permeability of the skin, increasing systemic exposure. Souza *et al.* (2022) note that “environmental and occupational conditions interact to intensify exposure and health risks among family farmers” (Souza *et al.*, 2022, p. 6), highlighting the role of climate as a co-determinant of toxicity.

These findings suggest that exposure in the semiarid cannot be understood without considering climatic amplification mechanisms. The interaction between environmental stressors and chemical agents produces a context in which toxicity is not only a function of dosage but also of environmental conditions, reinforcing the need for integrated analytical frameworks such as the chemical-hydric exposome.

4.6 Global comparison: semiarid agro-export hubs

The patterns identified in the Petrolina–Juazeiro pole resonate with dynamics observed in other semiarid agro-export regions, such as California’s Central Valley and Almería in Spain. These regions share structural characteristics, including intensive irrigation, high agrochemical dependence, and integration into global food markets. In all cases, economic productivity is sustained through the intensive use of natural resources and labor, often accompanied by environmental degradation and health risks.

However, the Brazilian semiarid presents additional layers of vulnerability, including weaker regulatory enforcement, greater socioeconomic inequality, and more pronounced climatic constraints. These factors contribute to a heightened exposure regime, in which the interaction between environmental, social, and chemical determinants is particularly acute. The comparison thus reinforces the argument that while the Petrolina–Juazeiro pole is not an isolated case, it represents an intensified expression of broader global patterns.

Table 4 presents the conceptual model proposed in this study, synthesizing the interaction between structural drivers, exposure pathways, health outcomes, and underlying determinants that characterize the chemical-hydric exposome in the Petrolina–Juazeiro pole. The table translates the theoretical contribution of the

article into an operational framework, allowing visualization of how agribusiness expansion, environmental processes, and social inequalities converge to produce differentiated exposure regimes. Rather than isolating variables, the model emphasizes interdependence, demonstrating that exposure emerges from the articulation of economic, ecological, and political dimensions.

Table 4. Conceptual model of the chemical-hydric exposome and the formation of sacrifice zones

Drivers	Exposure Pathways	Health Outcomes	Structural Determinants
Agro-export agribusiness expansion	Direct occupational exposure (handling, spraying, drift)	Genotoxicity, endocrine disruption, neurological alterations	Labor precariousness, informality, limited access to protective equipment
Intensive pesticide use	Dermal absorption and inhalation under high temperatures	Chronic toxicity, subclinical effects, cumulative biological damage	Weak regulation, asymmetrical enforcement, global pesticide flows
Irrigation dependence	Water-mediated exposure (runoff, leaching, groundwater contamination)	Indirect exposure via drinking water and food chains	Hydrological dependence, water commodification, inadequate monitoring
Semiarid climatic conditions	Volatilization, environmental persistence, bioaccumulation	Amplified toxicity, increased systemic absorption	Heat stress, water scarcity, climate variability
Territorial restructuring	Diffuse environmental contamination (soil, riparian degradation)	Long-term population exposure, chronic disease burden	Land concentration, agrarian duality, marginalization of traditional communities
Global commodity chains	Export of embedded environmental degradation (“virtual contamination”)	Invisible epidemiological burden, underreported diseases	Necropolitical dynamics, unequal distribution of risks and benefits

Source: Prepared by the authors.

The model reveals that exposure in semiarid agro-export systems is structured by a cascade of interconnected processes, in which macro-level drivers such as global commodity chains and irrigation-based development translate into micro-level biological effects through multiple environmental pathways (Gomes, 2019; Bombardi, 2017; Baiardi; Ribeiro, 2023). Notably, the table highlights that no single pathway operates in isolation. Occupational exposure, water contamination, and climatic amplification act simultaneously, producing cumulative and synergistic effects that intensify health risks (Nogueira, Szwarcwald & Damacena, 2020; Souza; Silva; Pinheiro, 2022; Alcoforado de Moraes et al., 2018).

At the same time, structural determinants such as labor precariousness, regulatory asymmetries, and land concentration shape who is exposed and to what extent. This reinforces the argument that vulnerability is not randomly distributed but socially produced and territorially embedded (Oliveira; Castro, 2021; Guedes et al., 2024; Santos et al., 2019; Brandão; Rist, 2020). The inclusion of global commodity chains as a driver underscores the transnational dimension of exposure, indicating that local health impacts are linked to global consumption patterns and regulatory inequalities (Nascimento; Becker, 2009; Sobel, 2011).

By integrating these elements, the model provides a robust conceptual basis for understanding the emergence of sacrifice zones in the semiarid. It demonstrates that the chemical-hydric exposome is not merely an environmental condition but a manifestation of a development model that systematically externalizes risks, normalizes chronic exposure, and obscures its epidemiological consequences (Carneiro *et al.*, 2015; Pignati *et al.*, 2017; Silva, 2012).

Overall, the Discussion demonstrates that the health and environmental impacts observed in the Petrolina–Juazeiro pole are not accidental or isolated phenomena. They are the outcome of a development model that systematically integrates economic growth with the production of exposure, vulnerability, and invisibility, demanding a critical re-evaluation of the assumptions underlying agro-export expansion in semiarid regions.

Taken together, the findings of this study demonstrate that the health and environmental burdens observed in the Petrolina–Juazeiro pole are neither incidental nor peripheral, but structurally produced within a model of irrigated agro-export development that reorganizes territory, redistributes risks, and normalizes chronic exposure. The articulation between chemical contamination, hydrological dynamics, climatic stress, and social inequality reveals a complex and persistent exposure regime that escapes conventional analytical and regulatory frameworks. By advancing the concepts of chemical-hydric exposome and sacrifice zones, this discussion challenges reductionist interpretations of agricultural modernization and calls for a critical reorientation of research and policy toward integrated, territorially grounded, and justice-oriented approaches to health and environment in semiarid regions.

5. CONCLUSION

This study demonstrates that the Petrolina–Juazeiro pole embodies a paradoxical model of development in which economic dynamism is sustained through the intensification of environmental degradation and the silent expansion of chronic health risks. The synthesis of evidence reveals that pesticide exposure in the semiarid cannot be reduced to isolated events, but must be understood as a systemic and cumulative process shaped by the interaction between chemical use, water dynamics, climatic stress, and socially structured vulnerability.

By introducing the concept of a chemical-hydric exposome, this work advances a theoretical framework capable of integrating these dimensions into a coherent analytical model. Simultaneously, the notion of sacrifice zones offers a critical lens to interpret how territories and populations become disproportionately burdened by the externalities of agro-export systems. Together, these contributions reposition the semiarid not as a marginal case, but as a strategic site for understanding the intersections between environment, health, and development in the contemporary world.

From a policy perspective, the findings call for a reconfiguration of regulatory frameworks, surveillance systems, and environmental governance mechanisms, emphasizing the need to address cumulative exposures and diffuse contamination pathways. Strengthening occupational protections, improving water quality monitoring, and incorporating long-term health outcomes into public health strategies are essential steps toward reducing systemic vulnerability.

Future research should deepen the empirical investigation of exposome interactions in semiarid contexts,

expand biomonitoring approaches, and explore comparative analyses with other global agro-export regions. More broadly, advancing interdisciplinary and justice-oriented research agendas will be crucial to confronting the structural conditions that sustain unequal exposure and to envisioning alternative pathways for development that do not rely on the production of invisibility and harm.

In this sense, the semiarid is not merely a space of scarcity, but a territory where the limits of contemporary development become visible and materially embodied. Recognizing and confronting the chemical-hydric exposome as a structural condition, rather than an externality, is a necessary step toward reimagining agricultural systems that do not depend on the production of invisibility, inequality, and harm.

Conflicts of Interest

We, the authors of the above-mentioned manuscript, declare that there are no conflicts of interest related to the research, authorship, or publication of this article. We affirm that the content of this article was developed independently and objectively, without external influence, ensuring academic integrity and transparency at all stages of the research process.

Author Contributions

All authors contributed jointly and equally to the conception, development, and completion of the manuscript. Specifically, they actively participated in the formulation of the research problem, the definition of methodological procedures, the collection and analysis of data, as well as the writing, critical revision, and approval of the final version of the article. Therefore, all authors are equally responsible for the scientific content presented.

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