



JOSÉ CHEREM

**EXPANSION OF DENGUE AND OTHER ARBOVIRAL
DISEASES ACROSS THE AMERICAS**

LAVRAS – MG

2025

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Thesis submitted to the Federal University of Lavras, as part of the requirements of the Graduate Program in Veterinary Sciences, concentration area in Animal Health and Public Health, Epidemiology and One Health Applied to Disease Control and Health Promotion, for obtaining the title of Doctor.

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DAS AMÉRICAS**

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To Luciana, Thiago, Lucas, Luiz, Bint and Jade,
in each and all of you I recognize the divine
presence that inhabits, illuminates, protects, and
gives meaning to my journey. To each of you and
to all of you, I dedicate this arduous and
delightful achievement, with love and gratitude!

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From the love won is born unconditional love, the same I received from my parents, now offered to our children. My unconditional loves are Thiago, Lucas, and Luiz. To my beloved, Luciana, who gave me unconditional love, I offer my heartfelt thanks. Thank you very much.

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I equally thank the Health Departments of the municipalities in the microregion, whose collaboration in responding to the questionnaire was essential to give this work its

unique and conclusive character, allowing the correlation of effective measures that have reached the Brazilian population.

This thesis represents the feeling of a researcher who believes in the extension of scientific knowledge as a bridge between the university and society, wishing that its results transcend academic walls and reach the homes of all, especially the most vulnerable.

“A toast to life!!! A tribute of gratitude for its many opportunities, which made it possible to live not just one, but several inspiring journeys. This is one of them: the journey of knowledge.”(CHEREM, 2025)

RESUMO

Nas últimas décadas, o continente americano tem vivenciado a expansão contínua das arboviroses, especialmente dengue, zika, chikungunya e febre do Oropouche. A combinação entre mudanças climáticas, urbanização desordenada, desigualdade social e manejo inadequado de resíduos sólidos, em particular plásticos descartáveis, tem favorecido a proliferação de vetores como *Aedes aegypti*, *A. albopictus* e *Culicoides paraensis*. Essa conjuntura evidencia uma crise de governança e integração entre políticas de saúde, meio ambiente e saneamento, exigindo abordagens interdisciplinares sob a ótica da Saúde Única. Ante o exposto, o presente estudo teve como objetivo geral compreender os determinantes ambientais, sociais e tecnológicos associados à expansão das arboviroses nas Américas, com ênfase na análise aplicada à microrregião de Lavras (MG). Para tal, combinou-se uma revisão integrativa de literatura e estudo de campo com abordagem mista (quantitativa e qualitativa). A revisão buscou compreender as evidências sobre resíduos plásticos e ecologia vetorial. O estudo de campo foi conduzido em nove municípios da microrregião de Lavras (MG), utilizando questionário estruturado baseado nos eixos do Plano Nacional de Contingência para Dengue, Chikungunya e Zika. Os resultados demonstraram que 100% dos municípios possuem planos de contingência, porém apenas 44,4% utilizam ovitrampas e 55,6% mantêm salas de situação. O monitoramento epidemiológico depende majoritariamente de esforço humano, com baixo uso de inteligência de dados e ferramentas preditivas. Embora 88,9% dos municípios realizem vigilância sorológica e 77,8% mantenham fluxo com o LACEN, a vigilância genômica ainda é incipiente. A análise revelou o paradoxo da “reatividade estruturada”: sistemas tecnicamente capazes, mas operacionalmente fragmentados. Além disso, verificou-se forte relação entre o descarte inadequado de resíduos plásticos e a persistência de criadouros de *A. aegypti*, indicando que o acúmulo desses materiais é um vetor ambiental determinante para a manutenção das arboviroses. A pesquisa reforça que o desafio brasileiro não é a falta de recursos, mas a ausência de integração entre esferas institucionais e políticas públicas, o déficit de governança regional e a subutilização de tecnologias emergentes, como inteligência artificial e vigilância digital. A expansão das arboviroses nas Américas reflete uma crise intersetorial de saúde e meio ambiente.

Palavras-chave: *Aedes aegypti*; Oropouche; Resíduos plásticos; Saúde Única; Vigilância epidemiológica.

ABSTRACT

In recent decades, the American continent has experienced the continuous expansion of arboviral diseases, particularly dengue, Zika, chikungunya, and Oropouche fever. The combination of climate change, unplanned urbanization, social inequality, and improper solid waste management, especially of disposable plastics, has favored the proliferation of vectors such as *Aedes aegypti*, *A. albopictus*, and *Culicoides paraensis*. This scenario reveals a crisis of governance and integration among health, environmental, and sanitation policies, demanding interdisciplinary approaches under the One Health framework. Therefore, this study aimed to understand the environmental, social, and technological determinants associated with the expansion of arboviruses in the Americas, with emphasis on an applied analysis in the microregion of Lavras, Minas Gerais, Brazil. To this end, an integrative literature review and a field study with a mixed (quantitative and qualitative) approach were combined. The review sought to consolidate evidence regarding plastic waste and vector ecology. The field study was conducted in nine municipalities of the Lavras microregion using a structured questionnaire based on the axes of the National Contingency Plan for Dengue, Chikungunya, and Zika. The results showed that 100% of the municipalities have contingency plans, but only 44.4% use ovitraps and 55.6% maintain situation rooms. Epidemiological monitoring still relies heavily on human effort, with limited use of data intelligence and predictive tools. Although 88.9% of the municipalities conduct serological surveillance and 77.8% maintain a diagnostic flow with the state reference laboratory (LACEN), genomic surveillance remains incipient. The analysis revealed the paradox of “structured reactivity”: systems that are technically capable but operationally fragmented. In addition, a strong relationship was observed between the improper disposal of plastic waste and the persistence of *A. aegypti* breeding sites, indicating that the accumulation of such materials acts as a key environmental driver for maintaining arboviral transmission. The findings reinforce that Brazil’s main challenge is not the lack of financial resources but rather the absence of integration among institutional levels and public policies, regional governance deficits, and the underutilization of emerging technologies such as artificial intelligence and digital surveillance. The expansion of arboviruses across the Americas therefore, reflects an intersectoral crisis involving both health and environmental dimensions.

Keywords: *Aedes aegypti*; Oropouche; Plastic waste; One Health; Epidemiological surveillance.

INDICADORES DE IMPACTO

O desenvolvimento desta tese contribui de forma significativa para o entendimento da expansão das arboviroses nas Américas sob as dimensões científicas, sociais, tecnológicas, econômicas e ambientais. Ao evidenciar o papel do descarte inadequado de resíduos plásticos como fator agravante no ciclo epidemiológico das arboviroses, o estudo reforça a necessidade de políticas públicas voltadas à gestão de resíduos e ao estímulo à reciclagem, associando saúde pública, sustentabilidade e governança ambiental. Os resultados publicados em artigos científicos, incluindo um que alerta para o crescimento silencioso da febre do Oropouche e sua disseminação por todos os estados brasileiros, revelam o potencial transformador da integração entre ciência, inovação e políticas públicas. A realização de uma audiência pública sobre doenças negligenciadas, com ampla participação de gestores, profissionais e cidadãos, traduziu os resultados técnicos em linguagem acessível e demonstrou o alcance social da pesquisa, extrapolando o ambiente acadêmico. Adicionalmente, foram promovidos eventos de capacitação e treinamento de profissionais da saúde e ações de orientação de estudantes de graduação e ensino médio, fortalecendo o caráter educativo e multiplicador da tese. A pesquisa está alinhada aos Objetivos de Desenvolvimento Sustentável, com destaque para o ODS 3, ao fortalecer a vigilância em saúde e a resposta a emergências sanitárias; o ODS 4, ao contribuir com a formação de estudantes; o ODS 6, ao relacionar saneamento básico e eliminação de criadouros vetoriais; o ODS 9, ao propor o uso de inteligência artificial e infraestrutura tecnológica para vigilância digital; o ODS 11, ao promover cidades resilientes por meio da vigilância urbana integrada; o ODS 12, ao estimular o consumo e a produção responsáveis e a economia circular; o ODS 13, ao incorporar variáveis climáticas aos modelos preditivos; e o ODS 17, ao consolidar redes interinstitucionais e consórcios regionais de vigilância. A abordagem interdisciplinar também se reflete nas áreas temáticas da Política Nacional de Extensão, abrangendo Comunicação, Direitos Humanos e Justiça, Educação, Meio Ambiente, Saúde, Trabalho e Cultura. O trabalho fortalece a comunicação científica e institucional, amplia o acesso ao conhecimento técnico em linguagem acessível e promove o direito à saúde e à justiça ambiental, ao reconhecer as desigualdades regionais e a vulnerabilidade de populações expostas às doenças negligenciadas, traduzindo o conhecimento científico em ações de impacto social, tecnológico e ambiental, contribuindo para a efetivação dos direitos humanos, a inovação em saúde.

IMPACT INDICATORS

The development of this thesis contributes significantly to understanding the expansion of arboviruses in the Americas across scientific, social, technological, economic, and environmental dimensions. By highlighting the role of inadequate plastic waste disposal as an aggravating factor in the epidemiological cycle of arboviruses, the study reinforces the need for public policies aimed at waste management and recycling incentives, linking public health, sustainability, and environmental governance. The results published in scientific articles, including one that warns about the silent rise of Oropouche fever and its spread across all Brazilian states, reveal the transformative potential of integrating science, innovation, and public policy. The organization of a public hearing on neglected diseases, with broad participation of managers, professionals, and citizens, translated technical results into an accessible language and demonstrated the social reach of the research, extending beyond the academic environment. In addition, training events for health professionals and guidance activities for undergraduate and high school students were promoted, strengthening the educational and multiplier character of the thesis. The research is aligned with the Sustainable Development Goals (SDGs), notably SDG 3 by strengthening health surveillance and response to health emergencies; SDG 4 by contributing to student training; SDG 6 by relating basic sanitation to the elimination of vector breeding sites; SDG 9 by proposing the use of artificial intelligence and technological infrastructure for digital surveillance; SDG 11 by promoting resilient cities through integrated urban surveillance; SDG 12 by encouraging responsible consumption, sustainable production, and circular economy; SDG 13 by incorporating climatic variables into predictive models; and SDG 17 by consolidating interinstitutional networks and regional surveillance consortia. The interdisciplinary approach is also reflected in the thematic areas of the National Extension Policy, encompassing Communication, Human Rights and Justice, Education, Environment, Health, Labor, and Culture. The work strengthens scientific and institutional communication, broadens access to technical knowledge in an accessible language, and promotes the right to health and environmental justice by recognizing regional inequalities and the vulnerability of populations exposed to neglected diseases, translating scientific knowledge into actions with social, technological, and environmental impact, and contributing to the realization of human rights and innovation in public health.

LIST OF ACRONYMS

AI - Artificial Intelligence

APS – Atenção Primária à Saúde

CDC – Centers for Disease Control and Prevention

CGICI – Coordenação-Geral de Incorporação Científica e Imunização

CHIKV – Chikungunya virus

DENV – Dengue virus

DNA – Deoxyribonucleic Acid

DPNI – Departamento do Programa Nacional de Imunizações

NTDs – Neglected Tropical Diseases

FIOCRUZ – Fundação Oswaldo Cruz

LACEN – Laboratórios Centrais de Saúde Pública

MG – Minas Gerais

PAHO - Pan American Health Organization

PLANSAB - Plano Nacional de Saneamento Básico

PPGCV - Programa de Pós-Graduação em Ciências Veterinárias

SDGs – Sustainable Development Goals

SIH – Sistema de Informações Hospitalares

Kdr - knockdown resistance

MAYV – Mayaro virus

MS – Ministério da Saúde

DME – Departamento de Medicina

IHMT – Instituto de Higiene e Medicina Tropical

IOC - Instituto Oswaldo Cruz

OROV – Oropouche vírus

RT-PCR - Reverse Transcription Polymerase Chain Reaction

SUS – Sistema Único de Saúde

SINAN – Sistema de Informação de Agravos de Notificação

SIPNI – Sistema de Informações do Programa Nacional de Imunizações

UFLA – Universidade Federal de Lavras

USP – Universidade de São Paulo

SVSA – Secretaria de Vigilância em Saúde

TAK-003 – Tetravalent dengue vaccine from Takeda, known as Qdenga®.

WHO - World Health Organization

ZIKV – Zika virus

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FIRST PART

1. INTRODUCTION

Over the past four decades, we have witnessed an exponential increase in the incidence of arboviruses in the Americas, especially Dengue, Zika, Chikungunya and, more recently, Oropouche fever. Traditionally associated with tropical regions, these diseases have overflowed their original geographical boundaries and begun to pose emerging challenges in areas once considered safe, driven by environmental, social, and economic factors.

In Brazil, the scenario is particularly concerning. In 2024, the country recorded the largest Dengue epidemic in its history, with more than 10 million probable cases and more than 6 thousand confirmed deaths, reflecting not only the high ecological plasticity of the vectors, but also the persistence of social determinants of health, such as poor sanitation, unplanned urbanization, and socioeconomic inequalities. The emergence of the Oropouche virus, with an increase of approximately 1000% in reported cases between 2023 and 2024, reinforces the need for expanded and integrated surveillance capable of anticipating new outbreaks and containing their spread.

The complexity of these epidemics highlights the phenomenon of syndemia, in which biological, social, and environmental factors interact synergistically, worsening the impacts of the diseases on vulnerable populations. Thus, arboviruses cannot be analyzed solely from the perspective of vector transmission, but also as an expression of a context marked by poverty, food insecurity, unplanned migration, and climate change.

From the vector standpoint, *Aedes aegypti* and *A. albopictus* have established themselves as species of high epidemiological relevance, transmitting not only the four serotypes of the Dengue virus, but also Zika, Chikungunya, yellow fever, and Mayaro. Their ability to adapt to urban environments, combined with increasing resistance to insecticides, compromises the effectiveness of conventional control strategies.

In parallel, *Culicoides paraensis*, the primary vector of the virus that causes Oropouche fever, has expanded its distribution in areas of high population density, widening the spectrum of emerging threats.

In this context, it becomes evident that models centered exclusively on the use of insecticides or punctual campaigns are insufficient to contain the expansion of arboviruses. It is necessary to adopt a One Health paradigm, which recognizes the interdependence between human, animal, and environmental health, and promotes the integration of entomological, genomic, and epidemiological surveillance. The introduction of emerging technologies, such as the use of mosquitoes infected with *Wolbachia*, “big data” platforms for identifying

hotspots, and selective vaccination strategies, stands as a promising path for reducing morbidity and mortality.

Thus, given the need to understand not only the global and national dimensions of arboviruses but also their regional and operational expressions, the present research incorporated a situational analysis applied to the microregion of Lavras (MG). This region was chosen for representing a microcosm of Brazilian epidemiological dynamics: small and medium-sized municipalities located in the state that historically presents the highest numbers of Dengue cases in the country, strong reliance on the Unified Health System, and the presence of intermunicipal consortia that reflect, on a reduced scale, the national federative structure. This connection between theory and reality sought not only to map system weaknesses but also to identify successful experiences that can guide new regional strategies for addressing the issue and be extrapolated to the national scenario.

The results of this evaluation therefore represent the practical synthesis of the theoretical foundations discussed throughout the thesis. They show that structural limitations, institutional fragmentation, and the reactivity of public policies, described on national and continental scales, are reproduced at the local level, confirming that the arbovirus crisis is also a crisis of governance, communication, and technological modernization. At the same time, the study reveals transformation potentials, anchored in local initiatives of molecular surveillance, the gradual incorporation of diagnostic technologies, and the resilient work of health agents and professionals. This final stage of the research thus presents an investigative cycle, articulating the macro-environmental and sociopolitical analysis of arboviruses with the concrete reality of municipal services, and reinforces that overcoming the current fragmented model depends on technical integration, territorial intelligence, and continuous innovation from a One Health perspective.

2. THEORETICAL FRAMEWORK

2.1 History and Context of Arboviruses in the Americas

Arboviruses, notably Dengue, Chikungunya, Zika and, more recently, Oropouche fever, stand among the main public health challenges in the Americas in recent decades. Transmitted predominantly by the mosquito *Aedes aegypti* and, in the case of the Oropouche virus, also by *Culicoides paraensis* and *Culex* mosquitoes, these diseases present a high burden of morbidity, hospitalizations, and mortality, in addition to significant social and economic impacts on health systems and affected communities (Teixeira *et al.*, 2024).

Dengue, considered the urban arbovirus of greatest epidemiological relevance on the continent, has demonstrated continuous geographic expansion and a progressive increase in the number of cases. This phenomenon is related to multiple factors, such as accelerated and unplanned urbanization, vector adaptation to anthropic environments, and climate change that favors its proliferation. The introduction of the Chikungunya virus, the emergence of the Zika virus—associated with neurological and congenital complications such as microcephaly—and the growing dissemination of the Oropouche virus, responsible for outbreaks outside the urban and peri-urban areas of the Amazon, reinforce the complexity of this scenario and impose the need for continuous surveillance and integrated response strategies (PAHO/WHO, 2025; Brazil, 2025; Sousa *et al.*, 2023).

This panorama, however, is not restricted to national borders. As discussed by Barçante and Cherem (2024), the mosquito “does not recognize borders,” and the expansion of arboviruses in the Americas reflects both the effects of global warming and disordered urbanization and the absence of coordinated regional policies for surveillance and control. Neighboring countries, sharing similar climatic and socioeconomic conditions, become interdependent in mitigating risk, and the inertia of one territory directly affects the others, highlighting the urgent need for integrated and supranational strategies for addressing the issue (Barçante; Cherem, 2024).

The simultaneous increase in incidence and territorial range of these arboviruses has resulted in frequent records of viral co-circulation in several countries of the Americas. This epidemiological overlap represents an additional challenge for clinical diagnosis, since initial signs and symptoms are often similar and nonspecific, requiring specific laboratory tests for confirmation. Furthermore, the expansion of arboviruses encounters health systems frequently

overloaded and vector control programs with limited effectiveness, which intensifies population vulnerability and increases the risks of large epidemics (Cruz *et al.*, 2023; Ministério da Saúde, 2025).

The recurrent epidemics of arboviruses reveal, besides a biological phenomenon, the expression of a deeply unbalanced social and environmental context. The persistence of these diseases is closely linked to disordered urbanization, deficient sanitation, poor solid waste management, and the socioeconomic inequality that permeates Latin American cities. The ability of these viruses to adapt to new geographical areas is challenging. This set of factors creates environments favorable to vector proliferation and exposes the inability of public systems to anticipate outbreaks and act in an integrated and preventive manner. Thus, arboviruses constitute not only an infectious challenge but also a reflection of the structural failures of urban, environmental, and health policies, requiring articulated strategies under the One Health approach (Almeida *et al.*, 2020; Donalisio; Freitas; Von ZubenO, 2017).

2.2 Characteristics of the Dengue Virus and Other Prevalent Arboviruses

The Dengue virus (DENV) belongs to the genus *Flavivirus*, family *Flaviviridae*, and has four antigenically distinct serotypes responsible for epidemics in the Americas region (DENV-1, DENV-2, DENV-3, and DENV-4). Each serotype is capable of causing clinical presentations ranging from mild cases to severe forms, including hemorrhagic forms and Dengue shock syndrome, which can be fatal. Infection by one serotype confers long-lasting immunity only against that type, not protecting against the others. On the contrary, subsequent infections by different serotypes are associated with an increased risk of severe outcomes due to immunopathological mechanisms such as antibody-dependent enhancement (Guzman; Harris, 2010; PAHO/WHO, 2025).

In addition to DENV, other arboviruses of growing importance in the region include the Chikungunya virus (CHIKV), the Zika virus (ZIKV), and the Oropouche virus (OROV). CHIKV, an alphavirus of the family *Togaviridae*, is characterized by causing high fever and intense, often incapacitating polyarthralgia, with the possibility of chronic joint sequelae. ZIKV, also of the genus *Flavivirus*, gained global prominence due to its association with neurological complications such as Guillain-Barré syndrome and severe congenital malformations, especially when infection occurs during pregnancy. OROV, an orthobunyavirus of the family *Peribunyaviridae*, has been responsible for recurrent outbreaks

in the Brazilian Amazon and neighboring countries, with clinical manifestations similar to Dengue—fever, headache, myalgia, and arthralgia—which further complicates differential diagnosis (Barçante; Cherem, 2024; Sousa *et al.*, 2023; Ministério da Saúde, 2025).

The four viruses share important epidemiological characteristics, such as a high capacity for geographic expansion and vector adaptation. This context reinforces the need for integrated and multisectoral control strategies, encompassing both epidemiological and laboratory surveillance and innovative vector management measures.

2.3 Social Determinants of Health and the Persistence of Arboviral Diseases

Arboviruses do not spread solely due to their biological dynamics, but primarily through structural factors that shape the health–disease process. Poor sanitation, accelerated urbanization, and social inequality create environments favorable to vector reproduction and human–vector contact (Queiroz; Silva; Heller, *et al.*, 2020). In Brazil, data from the Plano Nacional de Saneamento Básico (PLANSAB) show that more than 49 million people still do not have access to a sewage collection network, revealing profound regional inequalities in access to sanitation infrastructure. This heterogeneous distribution reflects a historical pattern of structural exclusion, in which the North and Northeast regions concentrate the greatest coverage deficits, while the South and Southeast present more advanced indicators. Such disparity reinforces that the absence and poor distribution of basic infrastructure remain central determinants in the persistence and reemergence of arboviruses in the country (Brazil, 2024).

These deficiencies, however, are not evenly distributed across the national territory. According to PLANSAB, the Southeast region has the highest coverage of sanitation services, with about 91.3% of households served by a sewage network or septic tank. In contrast, the North reaches only 37.4%, and the Northeast 58.3%, highlighting a persistent pattern of inequality among the macro-regions. A similar situation is observed in solid waste management: while the South and Southeast show coverage above 95% in household collection, the North still records rates close to 80%, with inadequate waste disposal in vacant lots, riverbanks, and areas of urban forest, which worsens sanitary and environmental risks (brazil, 2024).

Inequalities are also evident in the final destination of solid waste. In 2023, 54.8% of municipalities in the North and 47.1% of those in the Northeast still used open dumps, in

contrast to 4.2% in the South and 2.7% in the Southeast (Brazil, 2024). This discrepancy shows that low-income populations, largely living in peripheral and rural areas of these regions, experience greater exposure to vectors.

Such regional inequalities reinforce that the risk of arboviruses in Brazil is strongly mediated by social and environmental determinants: the absence of sanitation infrastructure and the inadequate disposal of waste are concentrated precisely in areas where the State is least present and social vulnerability is most intense, creating true “hotspots” of vector reproduction and viral circulation.

The theory of Neglected Tropical Diseases (NTDs) reinforces this understanding by showing that the distribution of these illnesses is not random, but strongly shaped by structural factors. Like leishmaniasis and Chagas disease, arboviruses such as Dengue and Oropouche concentrate in socially marginalized populations marked by poverty, urban precariousness, and restricted access to health services, diagnosis, and treatment. From this perspective, the persistence of arboviruses must be understood as an expression of structural neglect, in which inequality and social exclusion act as invisible vectors of transmission. Added to this is a disintegrated and outdated epidemiological system that permeates practically all tropical countries (Hotez *et al.*, 2020; Barçante; Cherem, 2025).

2.4 Climate Change and Unplanned Urbanization

The role of climate change in the expansion of vectors is increasingly documented. Rising global average temperatures have increased the vector capacity of *A. aegypti*, accelerating the viral cycle and expanding risk areas into latitudes previously considered safe. Models project that the increase in average temperatures may intensify Dengue transmission in regions of Europe and the Americas by the end of the 21st century (Liu-Helmersson *et al.*, 2016). Complementarily, recent studies reinforce that global warming and unplanned urbanization favor the overlap of habitats of urban and sylvatic mosquito vectors, expanding the potential geographic distribution of diseases such as Dengue and yellow fever (Aliaga-Saménez *et al.*, 2024).

However, it would be reductionist to attribute the emergence of arboviroses solely to climatic variations. Local factors such as unplanned urban growth, housing deficits, and the accumulation of solid waste exert an immediate and direct effect on the formation of breeding sites and the maintenance of vectors. The overlap between socioeconomic vulnerabilities and

global environmental changes constitutes a syndemic framework, in which biological, social, and ecological factors interact to potentiate the severity and frequency of outbreaks. This concept of syndemic, formulated by Singer and collaborators, reinforces that diseases should not be understood in isolation, but as expressions of the same context of inequality and environmental degradation (Singer *et al.*, 2017).

2.5 Vector Resistance and Ecological Plasticity

Insecticide resistance is one of the greatest contemporary challenges in vector control. Studies conducted in different regions of Brazil demonstrate that *Aedes aegypti* presents mutations associated with resistance to pyrethroids, compromising the effectiveness of control programs based on chemical spraying. In populations from Rio de Janeiro, the presence of *kdr* alleles has been associated not only with loss of sensitivity to pyrethroids, but also with changes in fitness and susceptibility to Zika virus (Santos *et al.*, 2020). On a broader scale, recent meta-analyses indicate a growing and heterogeneous pattern of resistance in various Latin American populations, reflecting the selective pressure imposed by the continuous use of insecticides (Guedes *et al.*, 2020).

In addition, the ecological plasticity of the vector, including the ability of eggs to survive in dry environments for up to 450 days, increases its resilience in adverse urban scenarios (IOC/FIOCRUZ, 2024). Recent evidence reinforces that quiescent *Aedes* eggs persist during the dry season, impacting the planning of vector control (Ávila; Fernandes-Sala, 2024). Experiments conducted in a controlled environment demonstrated that desiccated *Aedes aegypti* eggs maintain high viability, with a significant percentage hatching within the first four hours after contact with rainwater accumulated on plastic surfaces, highlighting the role of this waste as persistent micro-breeding sites in the urban environment (Cherem; Barçante, 2024).

Recent literature reinforces that the effectiveness of insecticides against *A. aegypti* depends on rational management strategies. Despite increasing resistance to pyrethroids, malathion still maintains high mortality levels in mosquito populations. This evidence suggests that alternating between different chemical classes may delay the selection of resistant mutations, reducing continuous selective pressure on a single mechanism. The rotational use of insecticides, associated with locally based entomological monitoring, is an essential tool to maintain the effectiveness of fogging programs. Thus, the study reinforces

that integrated management should replace repetitive campaigns centered on the same molecule, which historically accelerated the loss of efficacy (Mendis *et al.*, 2024).

In the field of molecular biology, recent advances highlight the role of mutations known as *Kdr* (from the English “knockdown resistance”), which affect the voltage-gated sodium channel gene in *Aedes aegypti*. These genetic alterations, naturally selected in populations repeatedly exposed to pyrethroids, reduce the sensitivity of these channels to the neurotoxic action of insecticides and may increase resistance to levels ranging from dozens to hundreds of times. Among the most relevant variants, V1016I, F1534C, and S989P show synergistic effects when combined, resulting in highly resistant phenotypes, especially in urban areas with high density and intensive chemical use. Given this scenario, continuous genetic monitoring of *kdr* mutations becomes indispensable to anticipate control failures and support the rational rotation of insecticides, ensuring the effectiveness of public health actions and the sustainable use of pyrethroids (Uemura *et al.*, 2024).

Complementing empirical and molecular findings, the World Health Organization (WHO) published guidelines consolidating the challenges and recommendations for the rational use of insecticides in the control of *A. aegypti*. The report emphasizes the need for standardized resistance monitoring, with harmonized protocols among countries, in order to enable regional comparisons and joint planning. It also recommends that national programs incorporate complementary tools, such as biological control and improvements in sanitation, reducing exclusive dependence on insecticides. One of the central points of the document is that irrational use—characterized by indiscriminate applications without prior resistance analysis—results in wasted resources and accelerates the loss of effectiveness of available compounds. Thus, the WHO highlights that only integrated management, based on continuous entomological surveillance, can ensure sustainability in the medium and long term (WHO, 2023).

It is important to emphasize that, for rational resistance management, it is necessary to introduce insecticides with new modes of action and also incorporate non-chemical methods (biological control, environmental management, sanitation) to reduce exclusive dependence on chemical insecticides (WHO, 2023).

Regarding the urban cycle of OROV, it is sustained primarily by the ceratopogonid *Culicoides paraensis*, widely recognized as the primary vector of the disease. This insect,

with crepuscular and nocturnal habits, presents high vector competence and is directly associated with most outbreaks recorded in the Amazon region (Travassos da Rosa *et al.*, 2017).

More recent studies on the ecological plasticity of *C. paraensis* indicate that this species has shown adaptability to urban and peri-urban environments, favored by land-use changes, urbanization, and expansion of anthropogenic corridors. For example, recent reviews and mapping studies indicate that the OROV virus is expanding beyond its traditional foci, with implications for the vector *C. paraensis* in urban environments (Barçante; Cherem, 2025). A systematic review of vector competence confirms that *C. paraensis* and *C. sonorensis* are the *Culicoides* species with the best experimental performance (~30% transmission) for OROV, whereas conventional mosquitoes show much lower rates (<20%) (Gallichotte *et al.*, 2025).

These findings reinforce that, although the sylvatic cycle (with animal reservoirs) persists, the urban cycle is effectively structured around *C. paraensis* in human environments, which demands attention to entomological surveillance, vector control practices adapted to urban settings, and the recognition of the plasticity of this vector as a key element in the dynamics of OROV expansion in Brazil and other countries of the Americas.

International organizations such as the CDC (Centers for Disease Control and Prevention) and the Pan American Health Organization (PAHO) classify *C. quinquefasciatus* only as a potential vector, maintaining *C. paraensis* as the main urban vector of OROV. International guidelines also recognize that some mosquitoes may be involved in an accessory manner, but with no conclusive evidence to date (CDC, 2024; PAHO, 2024).

2.6 Control and Response Experiences

The international response to arboviruses demonstrates that institutional integration is decisive for success. The West Nile virus outbreak in New York (1999) is a paradigmatic example: the rapid coordination among veterinary, environmental, and human surveillance, combined with efficient intersectoral communication, made it possible to contain the epidemic and avoid catastrophic outcomes (Nash *et al.*, 2001).

In contrast, Brazil's fragmented response to the emergence of Oropouche since 2023 exposed failures in coordination among different surveillance spheres, which contributed to the abrupt increase in cases in 2024 (Barçante; Cherem, 2024b). These contrasts highlight that

the operational implementation of One Health remains incipient in many Latin American countries.

The trajectory of Dengue illustrates, in a striking manner, the consequences of a fragmented model. In the 1980s, Brazil recorded a few thousand cases annually; four decades later, the country reached unprecedented levels. In terms of incidence, for example, there was an increase from ≈ 8.14 to 67.16 cases per 100,000 inhabitants between 2000 and 2019, a growth exceeding 700%, approaching an order of magnitude (Barçante; Cherem, 2024). In the post-pandemic period, the pace accelerates: according to the alert issued by the Pan American Health Organization (2025), the Region of the Americas recorded more than 13 million cases in 2024, with Brazil accounting for approximately 10.2 million ($\approx 10,232,872$) of these cases. Recent studies on spatiotemporal dynamics in the Brazilian Amazon also indicate patterns of continuous expansion in vulnerable regions (Hage *et al.*, 2025). Furthermore, prediction models based on climatic and spatial variables reveal that Dengue incidence in Brazil is increasingly subject to environmental shocks and complex post-pandemic interactions (Chen; Moraga, 2025).

This acceleration indicates that, without integrated action among human, environmental, and entomological surveillance—that is, without implementing the “One Health” paradigm—the challenge posed by Dengue becomes even more urgent and complex.

This explosive growth was directly associated with reactive and episodic responses, lacking institutional continuity, in which the absence of an integrated strategy across municipal, state, regional, and federal levels favored territorial expansion and the consolidation of *A. aegypti* in densely populated urban areas.

More recently, international organizations have warned that the persistence of responses based on reactive and centralized models, without intergovernmental and territorial integration, constitutes one of the main factors perpetuating the epidemic cycle of arboviruses in the Americas and hindering the consolidation of sustainable strategies for integrated surveillance. The most recent report from the Pan American Health Organization (PAHO, 2025) reinforces this diagnosis by indicating that, even after the 2024 epidemic peak, regional incidence remains high, with more than 3.9 million suspected Dengue cases reported up to Epidemiological Week 39 of 2025, demonstrating that viral circulation remains intense and requires coordinated and continuous vector control actions.

Currently, this pattern is spreading on a continental and global scale. Dengue is no longer restricted to tropical regions; recent epidemics in Europe and North America demonstrate that the absence of effective coordination among health, environmental, and urban planning policies favors vector adaptation and the spread of the disease into new territories. This expansion should not be understood merely as a biological phenomenon, but as a reflection of persistent failures in interinstitutional governance, reinforcing the urgency of a sustainable One Health model capable of anticipating outbreaks, strengthening surveillance, and reducing the social and economic burden of emerging diseases (WHO, 2022).

In line with this perspective, it is important to highlight that the regional response to arboviruses, especially Dengue, requires coordinated actions that transcend national borders, since the vector “does not recognize borders.” The article emphasizes that effective disease control depends on the integration between epidemiological surveillance, environmental management, and coordinated public policies, particularly in the post-pandemic context in which health vulnerabilities have worsened. This analysis reinforces the understanding that isolated solutions, restricted to the biomedical field, are insufficient in the face of the complexity of arboviruses, demanding responses supported by scientific and institutional cooperation on a global scale (Barçante; Cherem, 2024).

However, no institutional governance will be sufficient without individual and community understanding of the problem. The fight against arboviruses depends on simple daily practices, such as eliminating breeding sites inside homes, yards, vacant lots, and public roads, as well as ensuring the proper disposal of solid waste, especially disposable plastic containers that become artificial breeding sites. Several studies indicate that the persistence of household and peridomestic foci does not result only from structural sanitation failures, but also from low community adherence to preventive practices, showing that the sustainability of vector control is directly linked to collective behavior and the population’s risk perception. Keeping the APS (Atenção Primária à Saúde) as the first level of contact with the population is a point of emphasis, but its effectiveness still needs to be measured (Brazil, 2022). In this sense, the success of confronting arboviruses requires not only robust surveillance systems and integration among sectors, but also the co-responsibility of the population, without which any institutional model will be destined for insufficiency (PAHO, 2023).

PAHO (2024) highlights that the control of these urban diseases strongly depends on the direct action of individuals, families, and communities. According to the material, the

elimination of domestic breeding sites, such as open lids, plastic containers exposed to rain, and decorative plants with standing water, as well as the proper disposal of solid waste, must be essential daily habits. In addition, the document emphasizes that changes in human behavior, combined with the dissemination of simple messages adapted to the local context, strengthen risk perception and encourage community cooperation practices. Ultimately, PAHO states that without this social engagement, transformed into community surveillance routines, even the most robust health systems and the most well-articulated vector-control policies remain vulnerable to the emergence or reemergence of arbovirus outbreaks (PAHO, 2025).

2.7 Emerging Technologies and New Perspectives

2.7.1 Breeding Site Control: Community-Based and Environmental Solutions

Mechanical and environmental control of breeding sites constitutes the most traditional and, at the same time, the most effective axis of strategies for confronting arboviruses. Simple measures such as eliminating artificial water containers, sealing water tanks, and the proper disposal of solid waste present high effectiveness and low operational cost, making them accessible even in contexts with limited resources. In tropical and densely populated regions, environmental control substantially reduces vector density, especially when there is continuity and community participation. Maintaining these efforts requires constant surveillance, adequate urban planning, and integration among the health, environment, and education sectors.

In addition to the direct impacts on reducing breeding sites, social involvement plays a decisive role in consolidating a culture of co-responsibility and prevention. Intersectoral actions, such as community clean-up efforts, educational campaigns, and school programs, strengthen the bond between the community and public authorities, expanding adherence to preventive practices. Successful experiences in tropical and developing countries demonstrate that collective engagement, combined with adequate waste management and continuous mobilization, is capable of sustaining long-term results in the prevention of Dengue and other arboviruses (Quintero *et al.*, 2020; Banerjee; Aditya; Saha, 2015).

2.7.2 Entomology and Resistance Profiles

Traditional entomological monitoring, based on larval and Breteau indices, has provided valuable but limited information for planning vector control. Contemporary urban

dynamics, with heterogeneous microenvironments and increasingly dispersed artificial water sources, require tools capable of integrating large volumes of environmental data in real time. In this context, digital technologies have been transforming the field of entomological surveillance, allowing the association of high-resolution images, sensors, and automatic breeding-site recognition algorithms with georeferenced systems (Knoblauch *et al.*, 2024).

In a paradigmatic study, Knoblauch *et al.* (2024) demonstrated that the integration of satellite and “street view” images with machine learning algorithms enables the precise mapping of critical reproduction points of *A. aegypti* in tropical urban areas. The system identified disposable containers, roofs, gutters, and open garbage bins as elements strongly correlated with immature density, revealing that the simple adequacy of containers and the covering of urban waste can significantly reduce the presence of the vector. This is a machine-assisted approach, in which artificial intelligence complements human observation and expands the predictive capacity of surveillance actions (Knoblauch *et al.*, 2024).

Regions that implemented standardized and lidded garbage bins showed a significant decrease in the density of breeding sites, reinforcing the relevance of environmental management combined with urban infrastructure. Automated image analysis made it possible to identify spatial and temporal patterns of risk, assisting public managers in prioritizing neighborhoods and intervention routes. This capacity for territorial predictive analysis, mediated by artificial intelligence, represents a strategic advance for control programs in tropical and developing countries, especially in contexts with budget constraints (Knoblauch *et al.*, 2024).

In parallel, Souza *et al.* (2023) demonstrated that modern entomological surveillance must incorporate the genetic and molecular characterization of *A. aegypti* populations. Monitoring *kdr* mutations along highway corridors and urban centers in the Amazon revealed dispersal patterns associated with pyrethroid resistance, demonstrating that environmental factors and human flows contribute to the spread of resistant genotypes. Thus, the use of georeferencing and real-time genotyping technologies is essential to redirect control measures according to local susceptibility profiles (Souza *et al.*, 2023).

In agreement, the review conducted by Uemura *et al.* (2024) synthesizes recent advances on *kdr* resistance mechanisms, highlighting that mutations at positions 1016 and 1534 of the voltage-gated sodium channel are now predominant in tropical populations. These

alterations reduce the effectiveness of routinely used insecticides, reinforcing the need to integrate technological and molecular approaches into surveillance (Uemura *et al.*, 2024).

The consolidation of this intelligent surveillance requires public policies that encourage interoperability among health, environment, and urban planning databases, as well as the training of multidisciplinary teams. Machine-assisted tools can transform raw data into risk maps accessible to local managers, directing educational campaigns and urban cleaning interventions in a targeted manner. In this way, contemporary entomological control moves from a reactive logic to a proactive and predictive approach, articulating technological innovation, population genetics, and social co-responsibility (Knoblauch *et al.*, 2024; Souza *et al.*, 2023; Uemura *et al.*, 2024).

2.7.3 *Wolbachia pipientis*–Infected Mosquitoes: A Temporally Consolidated Innovation in Vector Control

The introduction of the bacterium *Wolbachia pipientis* into natural populations of *A. aegypti* represents one of the most transformative biotechnological strategies in the fight against arboviruses. In 2011, Hoffmann *et al.* demonstrated for the first time, in the city of Cairns, Australia, the successful stable introduction of the wMel strain into field mosquitoes, proving that the bacterium was capable of persisting in subsequent generations and reducing the mosquito's vector competence for the Dengue virus (Hoffmann *et al.*, 2011). From this pioneering experience, the principle was established that interventions based on *Wolbachia* could offer a sustainable alternative to the use of chemical insecticides.

In the following years, the persistence and stability of the infection were confirmed in multiple locations, indicating that *Wolbachia* not only remained at high population frequency but also did not cause perceptible ecological imbalance. In a subsequent study conducted in Australia, it was verified that wMel infection remained stable for several years after the initial release, with no negative effects on other species or on the environment, reinforcing the safety of the technique (Hoffman *et al.*, 2014).

From this consolidated scientific foundation, the method was adapted and scaled in tropical countries with a high burden of Dengue. In Brazil, the World Mosquito Program, in partnership with Fiocruz, initiated in Niterói and Rio de Janeiro a series of releases of mosquitoes with *Wolbachia*, accompanied by rigorous entomological and epidemiological surveillance. Studies published between 2021 and 2022 demonstrated significant reductions in

the incidence of Dengue, Zika, and Chikungunya in areas with established bacterial presence, confirming the positive impact on public health. The same success has occurred in several cities, such as in Yogyakarta, Indonesia (Tantowijoyo *et al.*, 2020; dos Santos *et al.*, 2022).

In addition to epidemiological effectiveness, the Brazilian experience demonstrated the environmental and social safety of this intervention: no genetically modified organisms are introduced, *Wolbachia* is naturally present in several insects and does not infect vertebrates, and community engagement proved essential for program acceptance and sustainability. Thus, more than a decade after the initial milestone in Australia, the *Wolbachia* strategy has become a paradigmatic example of innovative, safe, and sustainable technology in integrated vector control.

2.7.4 Genomic Surveillance for the Identification of Serotypes and Lineages

Latin America presents a complex scenario of simultaneous circulation of multiple arboviruses, including DENV, ZIKV, CHIKV, Mayaro virus (MAYV), and OROV. These agents share similar clinical manifestations, fever, myalgia, arthralgia, headache, and rash, which complicate clinical and laboratory differentiation, especially in contexts of cocirculation. This overlap of symptoms generates challenges for timely diagnosis and adequate case management, requiring more precise and integrated laboratory surveillance (PAHO, 2024).

In the specific case of Dengue, Brazil currently faces the concurrent circulation of the four viral serotypes (DENV-1 to DENV-4), which increases the risk of more severe and recurrent outbreaks. Shifts in serotype predominance modify the population's immunological profile and increase the likelihood of severe clinical forms in reinfections. This situation reinforces the importance of serotype identification and continuous monitoring of circulating genetic variants, enabling faster responses tailored to the local epidemiological reality (PAHO, 2024).

The “Laboratório Central de Saúde Pública” (LACENs) play a fundamental role in this process. In Brazil, they constitute the main diagnostic and laboratory surveillance network for arboviruses, operating in molecular detection, serotyping, and sample submission for genetic sequencing. Strengthening these laboratories is essential to ensure screening and differentiation among cocirculating arboviruses, as well as enabling genomic tracking and confirming recent viral introductions in areas previously not endemic (PAHO, 2024).

The incorporation of large-scale genomic sequencing technologies, widely accelerated during the COVID-19 pandemic, has proven strategic for arbovirus surveillance. This approach enables real-time identification of Dengue serotypes and viral lineages of OROV and MAYV, in addition to detecting mutations or recombination events with potential impact on transmission and virulence. Genomic surveillance therefore becomes an indispensable tool for modern public health, guiding vector control measures, vaccination policies, and targeted preventive actions (Patiño *et al.*, 2024).

The speed of infectious disease spread remains, and will continue to be, one of the main concerns of contemporary public health. In this scenario, although conventional serological and molecular methods such as RT-PCR (Reverse Transcription Polymerase Chain Reaction) remain indispensable for rapid diagnosis and case confirmation, they present limitations in understanding genetic diversity, viral evolution, and pathogen dissemination routes. In contrast, genomic sequencing emerges as an advanced surveillance tool capable of tracing the geographic origin of strains, identifying viral reintroductions, and monitoring genetic recombinations or lineage replacements that may alter transmissibility, virulence, and consequently the epidemiological behavior of infections (Patiño *et al.*, 2024).

The integration between classical laboratory surveillance and genomic surveillance, supported by the work of the LACENs, is essential to respond to the current epidemiological complexity of arboviruses in Brazil. This convergence of efforts strengthens early detection capacity, reduces response time, and improves the integrated management of arboviruses.

2.7.5 Rational Use of Vaccination

The incorporation of tetravalent Dengue vaccines represents an important advance in the arsenal for combating the disease in high-transmission regions. According to the World Health Organization (WHO, 2025), the Qdenga® (TAK-003) vaccine is recommended for children aged 6 to 16 years living in areas with high transmission intensity, administered in a two-dose schedule with a minimum interval of three months. This recommendation highlights the need for rational and segmented use of this tool, prioritizing groups in which the benefit outweighs the risks.

In Brazil, the “Ministério da Saúde” (Brazil, 2025a) published Technical Note No. 24/2025 (CGICI/DPNI/SVSA/MS), which guides the administration of the Dengue vaccine in specific contexts, especially when doses near expiration are available, as a temporary strategy

to expand protection in vulnerable populations. The document reinforces that vaccination must comply with local epidemiological criteria and prioritize municipalities with high disease prevalence, optimizing available resources and reducing morbidity and mortality.

The safety of Dengue vaccines has been continuously monitored by international organizations and national health authorities. According to the World Health Organization (2025), although efficacy is higher in high-transmission settings and among individuals previously exposed to the virus, caution is recommended regarding use in seronegative populations due to the risk of disease enhancement when administered outside ideal conditions. Thus, immunization should not be viewed as an isolated measure, but as part of an integrated prevention strategy associated with vector control and epidemiological surveillance.

A study conducted by Ghedzi *et al.* (2025) in Dourados, Mato Grosso do Sul, proposes a methodological model to evaluate the real-world effectiveness of the tetravalent vaccine TAK-003 (Qdenga®) in reducing the incidence and severity of Dengue in Brazil. This is a pioneering study that integrates data from SINAN, SIPNI, and SIH/SUS, allowing measurement of the impact of vaccination under real-world conditions. The relevance of this study lies in providing solid scientific evidence on the protection conferred by the vaccine in hyperendemic areas, serving as a national reference to guide the safe and evidence-based expansion of Dengue immunization campaigns (Ghedzi *et al.*, 2025).

From a strategic standpoint, Dengue vaccination becomes part of the set of innovative public health tools, alongside genomic surveillance, serotype typing, and environmental management actions, contributing to reducing severe cases and hospitalizations. The rational adoption of the vaccine, based on local epidemiological data and coordinated among federal, state, and municipal levels, is consolidated as one of the most promising policies to mitigate the impact of Dengue in Brazil (Brazil, 2025a; WHO, 2025).

2.7.6 Data Integration and Artificial Intelligence for Hotspot Identification

The main technological innovation in the field of public health lies in the ability to rapidly integrate the multiple data generated by the previous stages: entomological surveillance, genetic resistance, genomic sequencing, epidemiological records, and vaccine coverage.

Despite the high prevalence of arboviruses such as Dengue, Zika, and Chikungunya, the use of artificial intelligence technologies in this field is still limited. Most studies employ traditional machine learning algorithms aimed at binary case classification, whereas more advanced approaches remain underexplored. Only one identified study used “deep learning” techniques, highlighting an important gap in leveraging the potential of these tools to improve the diagnosis and surveillance of neglected tropical diseases (da Silva Neto *et al.*, 2022).

The incorporation of AI and “big data” technologies has been transforming the paradigm of global epidemiological surveillance. Modern platforms allow the integration, in near real time, of genomic, entomological, environmental, climatic, and epidemiological data, forming intelligent networks capable of identifying dissemination patterns and risk factors with unprecedented precision. This technological convergence has expanded the response capacity of health authorities, gradually replacing reactive control models—based on containment after the outbreak—with proactive and predictive models guided by the integrated analysis of large volumes of data (Sarn; Singh, 2024).

A notable example of this advancement is the study by Ming *et al.* (2025), which developed an AI and knowledge graph platform for global arbovirus analysis. The system integrates genetic, geospatial, and epidemiological data from multiple international databases, allowing the tracking of viral mutations, dispersion routes, and environmental conditions associated with vector expansion. This approach not only improves the monitoring of endemic diseases such as Dengue, but also enables the prediction of emerging epidemics or pandemics by detecting anomalies or behavioral changes in transmission patterns before case surges occur.

The combined use of AI, data science, and machine learning inaugurates a new frontier in the management of NTDs and arboviruses. Through dynamic dashboards and predictive algorithms, it becomes possible to identify transmission “hotspots” in advance, optimize resources, and direct interventions more effectively. This model of digital public health governance strengthens integrated surveillance and contributes to building more resilient health systems capable of anticipating and mitigating global risks in a scientific and sustainable manner (Ming *et al.*, 2025; Sarn; Singh, 2024).

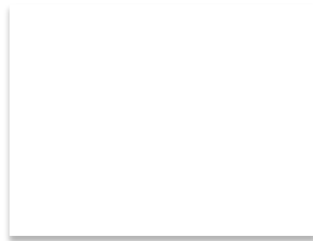
Undoubtedly, the main obstacle to consolidating these technologies will be the universalization of access and the availability of digital infrastructure in the countries located

along the axis of highest disease prevalence and vulnerable populations. The scarcity of datacenters, limited connectivity, and technological dependence still impose significant barriers to the full adoption of artificial intelligence tools and data integration in public health. More than a technical issue, this is an ethical and geopolitical challenge: it is essential that more developed nations and major holders of economic resources understand that promoting health in the territories where epidemics originate is a necessary condition for breaking the historical cycle of suffering and stagnation. Only through international cooperation and equitable investment in innovation will it be possible to transform vulnerability into resilience and promote truly sustainable and solidarity-based development.

SECOND PART - ARTICLES

ARTICLE 1 –

The mosquito knows no borders: Regional challenges for global confrontation in the dengue battle



VIEWPOINTS

The mosquito knows no borders: Regional challenges for global confrontation in the dengue battle

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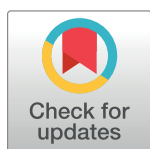
Dengue fever is a neglected disease with a global impact, and its incidence and geographical reach are rapidly expanding. Global warming marked by higher average temperatures, precipitation, and longer periods of drought could prompt a record number of dengue fever infections worldwide, due to the thermal biology of mosquitoes [1]. Additionally, increased movement of people, urbanization, and pressure on water and sanitation have driven the spread of dengue fever [2,3]. The absence of access to tap water leads to an increased reliance on water-storing containers, which can facilitate the breeding of mosquitoes. Similarly, the lack of sanitation can contribute to the formation of small pools of stagnant water, serving as ideal breeding grounds for *Aedes* [3].

While more prevalent in the tropical and subtropical regions, this viral infection, transmitted by *Aedes aegypti* and *Ae. albopictus* mosquitoes, poses a serious public health problem, with outbreaks increasing in number and severity worldwide [4]. In Europe, *Aedes* mosquito vector species are established in about 22 countries, and dengue fever has been reported for over a decade. In addition to the factors mentioned earlier, the increase in mosquito breeding sites has been identified as a determining factor for the rise in the number of cases. As of 2 October 2023, 74 autochthonous/non-travel-associated dengue cases have been reported in Europe from Italy (42), France (31), and Spain (1) [2,5].

Dengue incidence has significantly increased in recent decades, rising from 8.14 cases per 100,000 inhabitants in 2000 to 67.16 cases per 100,000 inhabitants in 2019. Approximately 50 to 100 million infections occur annually in over 100 endemic countries, putting almost half of the world's population at risk [6].

In the Americas, over 3 million cases of dengue have already been reported by the middle of 2023. This signifies that as of now, 2023 holds the position of the second-highest annual disease incidence since 1980, when the Pan American Health Organization (PAHO) began collecting data on case numbers [7]. As an aggravating factor, dengue does not have a specific treatment, and the medications prescribed are only meant to control fever and pain.

In spite of the efforts made by the PAHO, which recommended in January 2023 that member countries intensify preparedness and response measures to counter potential dengue and other arbovirus outbreaks, with the aim of averting fatalities and complications arising from these illnesses, what has transpired is a distressing surge in the count of cases and fatalities. This circumstance has resulted in the resignation of the Peruvian Minister of Health [8] and an escalation in mortality rates among children in Bolivia [4]. Moreover, Argentina and Chile (particularly in their northern and central regions) have declared a state of public health emergency in response to the presence of *A. aegypti* and the epidemiological conditions prevalent



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in neighboring nations [9]. Countries like Argentina, Bolivia, and Peru are currently grappling with one of the most severe dengue outbreaks on record. Although no autochthonous cases of dengue have yet emerged in Continental Chile, concerns are mounting over the potential for local transmission.

In Brazil, the situation is no different. Reported cases until the 18th epidemiological week (EW 18) of 2023 are 13% higher than in the same period of 2022 and 73% higher compared to the average of the last 5 years. During the same period, 387 deaths were reported. From the EW 21, 1,515,460 probable cases of dengue were reported in Brazil, representing 76% of all probable cases in the Americas Region, followed by Bolivia with 126,182 and Peru with 115,949 [10].

What is surprising is that this increase is not an isolated event. Dengue outbreaks have been recurring in Brazil for several decades. Similar to what was observed in 2023, in 2022, by the 19th EW, 855,910 suspected dengue cases were reported (incidence rate of 401.2 cases per 100,000 inhabitants), representing an increase of 181.74% compared to the same period the previous year when there were 303,727 probable cases (incidence rate of 143.4 cases per 100,000 inhabitants).

Brazil's public healthcare system, which represents the sole option for over 75% of Brazilians (165 million people), has been facing saturation since the beginning of the pandemic, impacting both primary care and specialized medical services. We have observed a state of resolute inertia, leading to increased morbidity and mortality from dengue and, consequently, from other diseases. The demand for consultations in primary care centers and emergency units during infectious disease outbreaks leads to a worsening backlog in controlling more prevalent conditions such as hypertension, diabetes, and pulmonary diseases. Longer waiting times for managing various comorbidities result in increased decompensation of these patients, leading to a higher demand for urgent care consultations, more diagnostic tests, and hospitalizations, further burdening an already overwhelmed healthcare system and, consequently, reinforcing this negative cycle that ultimately affects the most socioeconomically vulnerable populations. Neglected diseases like dengue push neglected or socioeconomically vulnerable populations into an even greater abyss, either through the direct effects of the infection or its indirect effects, such as reduced access to public health facilities.

The current dengue emergency may indeed be the result of a combination of favorable climatic conditions resulting from global warming and the vector mosquito's capacity for adaptation, proliferation, and dispersion [11]. However, it is also evident that, in general, public health policies have been more focused on curative approaches rather than strategic preventive actions, especially for diseases considered neglected. This situation has worsened during the pandemic, as efforts were redirected towards combating COVID-19, leading to a further reduction in surveillance in endemic areas. Now, what is observed is the overlap of a new epidemic with a healthcare system that is fatigued and still undergoing restructuring [12].

We must apply the lessons learned from the pandemic. Collective and effective prevention and control measures are essential and need to be intensified, employing a permanent and more efficient epidemiological surveillance system to guide efforts before seasonal or potential outbreaks occur and also to incorporate strategies to quickly identify an outbreak and direct efforts towards its mitigation [13]. Global diseases require global efforts but also an understanding of regional peculiarities. In this unfortunate scenario, it is essential to highlight that the true extent of the disease burden has been underestimated, as limited access to the healthcare system and diagnostic testing is a reality in many underserved regions. To change this situation, objective, integrated, and systematic measures that take into account the local context and reality are necessary. It is crucial to continuously monitor and track health progress, evaluate the application and funding of emerging prevention and control strategies, and inform evidence-based health policies with a focus on prevention.

Above all, it is essential to remember that mosquitoes do not recognize borders; thus, dengue and other vector-borne diseases will continue to expand throughout the region (and the world). As a consequence of climate change and uncoordinated vector control policies, municipalities or countries sharing borders are directly impacted by the inertia of their neighbors. Integrating research on this important neglected disease at every level—municipal, state, federal, and global—is imperative. Fortunately, the dengue scenario brings forth some new points of hope for controlling this and other significant arboviruses. Regarding dengue vaccines, these have prevented the severity of clinical outcomes but have not halted the infection itself [14], which underscores the need for improvements and field application monitoring. Since Ixchiq was approved as the first chikungunya vaccine on November 2023, it is now urgent for the government to enhance health education initiatives to ensure that there is no reduction in community efforts for vector control following the vaccine's introduction, as this could compromise the control of other arboviruses such as Zika, for which vaccines are not yet available.

Several vector-targeted strategies have shown promise, including the shifting of naturally occurring allele frequencies, genetic modification through CRISPR-Cas9 technology, and the release of *Wolbachia*-infected *A. aegypti*. The latter has been successfully implemented in various parts of the world and is one emerging mosquito control approach that might be largely resistant to warming temperatures [15], resulting in a reduction of dengue incidence by 40% to 96%. Particularly with vector control strategies, it is crucial to conduct comprehensive research to understand potential side effects and assess the associated risks. The safety and efficacy of these approaches need to be meticulously considered to mitigate negative impacts on other diseases and the ecosystem as a whole. Despite the apparent success, all approaches must be continually evaluated and monitored across various scenarios and by experts in entomology and ecology be involved in the evaluation and implementation of these strategies. The existence of differing public policies can potentially compromise collective efforts, as previously stated, insects do not adhere to borders.

Author Contributions

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Data curation: Joziana Muniz de Paiva Barçante, José Cherem.

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ARTICLE 2 -

The growing challenge of arboviruses in Latin America: Dengue and Oropouche in focus

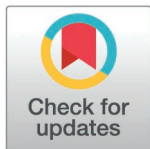
VIEWPOINTS

The growing challenge of arboviruses in Latin America: Dengue and Oropouche in focus

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In recent years, Latin America has emerged as a critical region on the global epidemic landscape due to the exponential rise in arboviral diseases, including yellow fever, chikungunya, Zika, dengue, and more recently, Oropouche fever. The Zika epidemic of 2015, coupled with the unprecedented increase in dengue cases and the yellow fever outbreak earlier this year, foreshadowed even more complex epidemiological challenges. The years 2020 and, particularly, the first half of 2021 (up to epidemiological week 26) in Latin America and the Caribbean were marked by the COVID-19 pandemic, which had severe impacts on public health. This period clearly illustrates a syndemic scenario, characterized by the interaction between the SARS-CoV-2 pandemic and a significant increase in arboviral diseases, with a total of 3,428,831 cases reported by June 2021. This situation highlights the overlap of a global pandemic with an ongoing endemic of arboviral diseases, resulting in additional challenges for the region's healthcare systems, which were already overwhelmed by the health crisis caused by COVID-19 [1]. We are now confronted with the expansion of the Oropouche virus (OROV), an emerging arbovirus in South and Central America with a high potential for widespread dissemination [2]. Given the endemic nature of OROV infection in these areas, the US Centers for Disease Control and Prevention has recently elevated Brazil to a level 1 [Travel Health Alert](#) [3].

Since the first isolation of OROV, >30 outbreaks have been reported in Brazil, Peru, Panama, and Trinidad and Tobago during 1960–2009, with at least half a million persons estimated to have been infected [4]. OROV was described in Brazil in 1960 when it was isolated from a sloth (*Bradypus tridactylus*) captured near a forested area during the construction of the Belem–Brasilia highway and from a pool of *Ochlerotatus* (*Ochlerotatus*) *serratus* mosquitoes, captured near the same site [5]. Nowadays, OROV is primarily transmitted by *Culicoides paraensis*, commonly found in water bodies such as ponds, lakes, and rivers and humid tropical regions, particularly in some areas of different South American countries, and it plays an important role in the transmission dynamics of OROV [3]. Given the potential role of *Culex quinquefasciatus* in the epidemiology of OROV and the broad geographic range of this species, OROV could also be dispersed by this vector into new geographic areas, including Africa, Australia, and Southeast Asia [6]. Several studies suggest that OROV is expanding beyond endemic regions, positioning itself as a potential candidate for large-scale epidemics [7–9].

OROV, an arbovirus of the Orthobunyavirus genus in the Peribunyaviridae family, has become a growing public health concern in several South and Central American countries. Initially restricted to small Amazonian villages, OROV has now spread to large urban centers in Brazil, with 11,695 confirmed cases by December 2024, across all 27 federal units. [10]. The symptoms are similar to dengue, including acute fever, photophobia, joint and muscle pain,

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nausea, vomiting, and, in severe cases, hemorrhagic or neurological complications such as diplopia, nystagmus, and meningoencephalitis [11,12]. Approximately 60% of infected individuals experience relapse episodes about 15 days after the initial symptoms resolve.

The infection is also associated with neurological complications, with OROV genomic RNA detected in the cerebrospinal fluid of patients, suggesting its neuroinvasive potential [13]. In May 2024, Cuba reported its first outbreak of OROV, affecting 74 individuals, of whom 3 (4%) developed a clinical diagnosis of Guillain-Barré Syndrome, a severe neurological complication requiring high-complexity supportive care. Guillain-Barré Syndrome is one of the potential neurological complications associated with OROV infection, as evidenced by these cases. This scenario is reminiscent of the Zika virus epidemic, where similar post-viral neurological disorders were observed, emphasizing the need to strengthen healthcare systems in preparation for potential OROV epidemics. Such measures include scaling up intensive care services and rehabilitation facilities to ensure adequate support for affected patients and to mitigate the burden of this emerging infectious disease [14]. This year Brazil has seen more than 11 times as many cases of the virus than in 2023. A significant challenge for maternal-fetal health is the Brazilian scientists' report indicating that OROV, on the rise in South and Central America, may cause stillbirths and neurological defects in fetuses infected in utero [15,16]. The virus was detected in the umbilical cord blood and tissue samples from several key organs obtained from a stillborn baby, who was 30 weeks into pregnancy, and later tested positive for the virus. These cases evoke memories of similar issues during the Zika outbreaks in the Americas. Over 3,500 cases of infant microcephaly were reported during the major Zika outbreak in Brazil in 2015 and 2016, when it was estimated that 1.5 million people were infected [15].

Another alarming signal was the confirmation of the first deaths related to OROV, marking a significant milestone in the history of this arboviral disease. On July 25, the Brazilian Ministry of Health confirmed the first scientific evidence of deaths caused by OROV: two women in their thirties, without comorbidities, from the state of Bahia, who developed fatal complications following infection. A third case, in the state of Santa Catarina, is still under investigation. These unprecedented mortality records since the identification of OROV in 1955, coupled with the risk of fetal malformations and miscarriages, underscore the urgent need for a national genomic surveillance center to monitor the virus and its mutations, aiming to understand changes in the epidemiological profile of the disease and mitigate future risks.

Like dengue, the OROV exhibits significant genetic diversity, with four distinct genotypes. All four OROV lineages have been found in Brazil, suggesting a plausible origin of the virus or high overlap in the distribution of vectors and virus reservoirs [4]. This fact makes genomic surveillance an indispensable tool for monitoring viral evolution, identifying mutations that may impact transmissibility, virulence, and immune response, and guiding control strategies and vaccine development.

The advancement of the OROV epidemic, alongside recurrent dengue epidemics throughout Latin America, signals significant failures in the control efforts for these diseases. In 2024, dengue reached alarming numbers, with 12,820,082 reported suspected cases throughout the 12 months of the year a historic record according to the Pan American Health Organization. Brazil leads this unfortunate ranking, with 10,099,260 suspected cases and over 5,925 deaths, representing 75.43% of the fatalities in the Americas Region [17]. All four dengue virus serotypes (DENV-1, DENV-2, DENV-3, and DENV-4) are in circulation, increasing the risk of even more severe epidemics due to the possibility of successive infections [17].

The reasons behind the increase in arboviral cases, especially in the Americas, are complex and multifactorial. Climate changes, such as intense heat waves and alterations in rainfall patterns are contributing to the expansion of arboviruses and the populations of the insects

that vector them. Additionally, unplanned urbanization and lack of adequate infrastructure in vulnerable areas hinder control measures, exacerbating the situation [18].

The rise in arboviral diseases in Brazil highlights the urgent need for a robust and integrated epidemiological surveillance system. Furthermore, the increasing number of Oropouche fever cases may be just the tip of the iceberg [19]. It is essential to conduct entomological research to clarify the role of each vector, strategies to control these vectors, and the non-vectorial modes of OROV transmission. Many dengue case reports are based on the clinical–epidemiological criteria due to the lack of confirmatory laboratory diagnosis. Given the symptom similarity between dengue and Oropouche fever, we may be facing hundreds or thousands of cases with misdiagnoses. This underscores the necessity of establishing a national epidemic surveillance center, including genomic surveillance and data integration across all Brazilian states, which is crucial for controlling these diseases and protecting public health. Such a center would enable early detection and rapid response to emerging outbreaks, which is essential given the evident shortcomings in current arboviral surveillance and control efforts. It is imperative that we mobilize global resources and efforts to identify the best approaches to effectively and sustainably combat these threats. As environmental changes create favorable conditions, vector insects expand their geographical distribution, and problems currently concentrated in the Americas may reach global proportions without coordinated international action.

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ARTICLE 3 -

Surge in Oropouche fever: the tip of the iceberg in a new public health challenge in Brazil

Surge in Oropouche fever: the tip of the iceberg in a new public health challenge in Brazil

We read with interest the article published by Ranjit Sah and colleagues¹ in *The Lancet Microbe*. The authors highlighted the Oropouche fever outbreak in the states of Amazonas and Acre of Brazil, emphasising the associated public health risks, including those for travellers. The situation has become more complex in just a little over a month after the original publication. The number of cases in Brazil has surpassed 7930 by August, 2024, which is already ten-fold of 773 cases reported throughout 2023.

Furthermore, the Oropouche virus, which was first detected in the 1950s, presents new challenges for the global health system. At least two miscarriages have been reported in women infected during pregnancy; viral genetic material was found in the umbilical cord and various organs and tissues of the stillborns.^{2,3} Furthermore, at least eight cases of fetal malformations are under investigation by Instituto Evandro Chagas. Notably, for the first time, two deaths with a direct correlation to the viral infection have been confirmed by the Brazilian Ministry of Health; two young women without comorbidities were diagnosed with Oropouche virus infection, which progressed rapidly to a fatal outcome.

Two points raised by Sah and colleagues warrant immediate attention. The first is that the 500 000 cases of Oropouche virus infection recorded in the Americas since 1955 could be an underestimate. The second is the importance of enhancing awareness, preventive measures, and surveillance among populations living in the endemic areas and travellers visiting the affected areas. We believe that these speculations proposed by the authors are, in fact, certainties. The absence of specific diagnostic tests and nascent

genomic surveillance for acute febrile illnesses further underscore the need for renewed efforts concentrated in these two areas.

The experience with COVID-19 has established that genomic surveillance should go hand in hand with epidemiological surveillance. Based on the lessons learnt, promoting widespread testing and genetic sequencing of viruses in circulation will help to direct the focus towards prevention rather than cure. In the wake of the COVID-19 pandemic that caused immeasurable harm to humanity, followed by the largest dengue epidemic in the history of the Americas in 2024 and the latest Oropouche virus infection challenging the health systems once again, enhanced surveillance is warranted.

We declare no competing interests.

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- 1 Sah R, Srivastava S, Kumar S, et al. Oropouche fever outbreak in Brazil: an emerging concern in Latin America. *Lancet Microbe* 2024; 5: 100904.
- 2 Taylor L. Oropouche fever: Latin America on high alert for virus that can cause 141 stillbirths. *BMJ* 2024; 386: q1667.
- 3 Moutinho S. Little-known virus surging in Latin America may harm fetuses. *Science* 2024; 385: 355.



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ARTICLE 4 -**Addressing the escalating burden of dengue in the Americas amid**



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Letter to the Editor

Addressing the escalating burden of dengue in the Americas amid global challenges



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Dear Editor,

In the article by Pareek et al. [1], entitled "*The unprecedented surge of dengue in the Americas: Strategies for effective response*", published in the *Journal of Infection and Public Health*, the authors highlight that, in 2024, the Americas reported 12.2 million suspected dengue cases up to epidemiological week 43, with 6.4 million of these confirmed. Brazil accounted for most of these cases, reflecting a 209% increase compared to 2023. The authors emphasize the limitations of currently available vaccines such as Dengvaxia® and Qdenga®, noting their geographic restrictions. Although a promising new tetravalent vaccine developed by the Butantan Institute is nearing approval, key questions remain, particularly regarding the growing recirculation of the DENV-3 serotype since 2024 [2].

This analysis aligns with the short film *Treating a Feverish Planet: The Dengue Alliance* by the Drugs for Neglected Diseases initiative (DNDi), underscoring the urgent need for coordinated action against dengue amidst climate change [3]. Dengue's global impact is intensifying, disproportionately affecting vulnerable populations and exposing critical gaps in prevention, surveillance, and treatment. Climate change, unplanned urbanization, increased international travel, and insecticide resistance collectively expand *Aedes* mosquito habitats. These factors intensify dengue transmission by creating favorable environmental conditions, facilitating the spread to new regions, and undermining traditional vector control strategies, posing significant global public health challenges [4]. According to the Pan American Health Organization (PAHO), 22 of 44 countries in the Americas reported significant case increases in 2024 compared to 2023 [5]. Alarming, this trend extends globally: dengue cases in the United States surged from 156 in 2023 to over 3011 in 2024, while Europe reported an increase in autochthonous cases from 130 to 304, notably in Italy, Spain, and France [5,6]. Of the more than 14

million dengue cases reported worldwide in 2024, over 85% occurred in the Americas, highlighting the disproportionate impact of this epidemic on the region [7].

Despite decades of vector control efforts as the cornerstone of dengue prevention, the exponential rise in cases reveals a stark reality: current strategies are failing. Innovative measures, such as Wolbachia-infected mosquitoes, offer promise [8] but still face logistical, production, and monitoring challenges, including potential biological risks.

Compounding these issues, the urgency of controlling emerging arboviruses extends beyond dengue. The resurgence of the Oropouche virus (OROV) in 2024 highlights the need to expand genomic surveillance and improve differential diagnoses [4]. Many OROV cases have been misdiagnosed as dengue based on epidemiological criteria, potentially distorting the true burden of dengue and undermining effective public health interventions. Moreover, OROV infection can lead to severe complications, including Guillain-Barré syndrome, fetal malformations, and pregnancy losses, underscoring the critical importance of accurate diagnostics to inform targeted strategies and improve responses to this emerging threat [9].

As a neglected disease, dengue reflects systemic failures in global health priorities. In 2024, \$1.1 billion was spent on patient medical assistance, whereas Brazil's Ministry of Health invested only \$25 million in dengue research from 2004 to 2020, less than 0.15% of treatment costs. These figures underscore the urgent need for systemic change and sustained investment [10].

Addressing these challenges requires equitable access to interventions, strengthened public health policies, and enhanced international collaboration. Governments, research institutions, and global organizations must prioritize integrated, evidence-based

strategies to mitigate the devastating impact of dengue and other neglected diseases on vulnerable populations.

List of Abbreviations

DNDi – Drugs for Neglected Diseases initiative
 DENV-3 – Dengue Virus Serotype 3
 MOH – Ministry of Health
 OROV – Oropouche Virus
 PAHO – Pan American Health Organization
 WHO – World Health Organization

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ARTICLE 5 -

Sob os efeitos das alterações ambientais e à sombra da pandemia: o epidêmico avanço das arboviroses nas Américas



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SOB OS EFEITOS DAS ALTERAÇÕES AMBIENTAIS E À SOMBRA DA PANDEMIA: O EPIDÊMICO AVANÇO DAS ARBOVIROSES NAS AMÉRICAS

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1. INTRODUÇÃO

A intersecção entre as alterações ambientais e a pandemia de COVID-19 tem suscitado uma crescente preocupação quanto ao surgimento e propagação das arboviroses no mundo. As doenças epidêmicas e, potencialmente pandêmicas, configuram uma ameaça permanente para a segurança em saúde. A pandemia de COVID-19 expôs a fragilidade dos sistemas de vigilância em nível global e os inúmeros desafios para manutenção dos programas de controle de outras doenças endêmicas, como as arboviroses, que aumentaram em escala exponencial durante a pandemia (ELNAIEM et al., 2023).

A medida que o mundo enfrenta os desafios da crise sanitária global, as mudanças climáticas e a alterações de paisagens têm criado um ambiente propício para a disseminação de doenças transmitidas por vetores, principalmente para os países em desenvolvimento. Como exemplo, a Dengue persiste como a arbovirose de maior prevalência nas Américas, além de outros arbovírus, como o Chikungunya e Zika, que têm aumentado os números de casos e expandido em distribuição (SEGURA et al., 2021). Apesar do compromisso dos países em implementar progressivamente o manejo integrado de vetores, o controle dos mosquitos transmissores do gênero *Aedes*, sobretudo *Ae. aegypti* ainda constitui um grande desafio a ser superado (SEGURA et al., 2021).

Por sua vez, o surgimento e disseminação dos arbovírus depende da presença e abundância de vetores, estão relacionadas a diversos fatores sociais, econômicos e ambientais, em escala regional e mundial. Este fenômeno complexo e interligado coloca em evidência a necessidade de abordar não apenas a emergência de doenças infecciosas, mas também as condições mais amplas e sistêmicas que as impulsionam (WHO 2017). Alterações globais, como as mudanças climáticas constituem um fator importante na transmissão de vários arbovírus. Os modelos de preditivos prevêem uma expansão da distribuição de vetores e patógenos em todos os cenários de alterações climáticas (MOJAHED et al., 2022). O aumento das temperaturas, a mudança nos padrões das chuvas e umidade, são fatores que associados à biologia térmica e à plasticidade genética de mosquitos do gênero *Aedes* facilitam a expansão contínua e a dispersão desse inseto, até mesmo para áreas antes consideradas livres. Digno de nota, a resistência aos inseticidas, observada em diversas partes do mundo, contribui para o aumento, a persistência e a dispersão das populações de vetores (MA et al., 2021).

Por fim, tornando esse cenário ainda mais intrincado, no Brasil o controle vacinal das arboviroses se encontra limitado à febre amarela e à dengue. Essa situação nada animadora, ainda mais grave à sombra da pandemia, constitui um importante problema de saúde pública, resultando em um aumento na carga de doenças, hospitalizações e até mortes. Isso coloca pressão adicional nos sistemas de saúde e nos recursos destinados ao controle de vetores (BAKER et al., 2022).

Torna-se, então, imperativa a implementação de medidas sustentáveis como estratégia integrada de enfrentamento e controle das arboviroses (WHO, 2017). Isso envolve impedir a proliferação dos mosquitos transmissores, garantir um diagnóstico clínico preciso, fortalecer a vigilância epidemiológica em conjunto com o diagnóstico laboratorial e envolver ativamente a sociedade na eliminação dos criadouros de mosquitos. Para alcançar esse

objetivos, a educação em saúde desempenha um papel crucial. Além disso, é imperativo fortalecer a pesquisa em saúde para identificar os aspectos críticos na pesquisa básica e clínica, nos serviços de saúde, nos sistemas de saúde e na saúde pública. Estabelecer prioridades e coordenar esforços em torno desses aspectos é essencial para gerar conhecimento científico valioso, que embase a tomada de decisões e a implementação eficaz de ações e programas de prevenção e controle. Isso deve ser complementado por iniciativas de extensão que promovam o envolvimento consciente e informado da sociedade (WHO, 2017; WHO, 2022).

2. REVISÃO DE LITERATURA

2.1. ANÁLISE DA SITUAÇÃO DAS PRINCIPAIS ARBOVIROSES URBANAS

2.1.1. Dengue

Dengue é uma enfermidade emergente e globalmente negligenciada, causada pelo vírus dengue (DENV1, DENV2, DENV3 e DENV4) transmitido por meio da picada de fêmeas dos mosquitos *Ae. aegypti* e *Ae. albopictus*.

Considerada uma “doença antiga”, diversos surtos foram relatados mundialmente. Desde seu primeiro registro em 992 a.C. (HOTTA, 1952; NOBUCHI, 1979; MCSHERRY, 1982; GUBLER, 2002), nas últimas décadas, observa-se uma tendência crescente em termos de frequência e gravidade em nível global (GUBLER, 2002; OPAS, 2015; OMS, 2023).

A incidência da Dengue apresentou um aumento notável, registrando um salto de 500.000 casos em 2000 para 5,2 milhões de casos em 2019. Essa trajetória ascendente não mostra sinais de desaceleração (BHATT et al., 2013; OMS, 2023). A doença é endêmica em 100 países nas regiões da África, Américas, Mediterrâneo Oriental, Sudeste Asiático e Pácífico Ocidental e, segundo estimativas, ocorrem cerca de 390 milhões de infecções por DENV, por ano (BRADY et al., 2012; OMS, 2023). Durante o primeiro semestre de 2023, mais de 3 milhões de casos de dengue foram registrados nas Américas, classificando-o como o segundo período anual de maior incidência da doença desde 1980, quando a Organização

Pan-Americana da Saúde (OPAS)/ Organização Mundial da Saúde (OMS) iniciou o registro de dados sobre o número de casos (LENHARO, 2023).

Apesar dos esforços da OPAS/OMS, que em janeiro de 2023 recomendou aos países membros a intensificação das medidas de preparação e resposta para enfrentar possíveis surtos de Dengue e outros arbovírus, com o objetivo de prevenir óbitos e complicações decorrentes dessas doenças, o que se constatou foi um alarmante aumento no número de casos e fatalidades. Essa situação levou à renúncia do Ministro da Saúde do Peru (DANIELS, 2023) e ao aumento das taxas de mortalidade entre crianças na Bolívia (LI et al., 2023). Além disso, Argentina e Chile, particularmente em suas regiões do norte e centro, decretaram estados de emergência em saúde pública devido à presença do *Ae. aegypti* e às condições epidemiológicas predominantes em nações vizinhas (ESTALLO et al., 2023). Países como Argentina, Bolívia e Peru enfrentam atualmente um dos surtos de dengue mais graves já registrados. Embora ainda não tenham ocorrido casos autóctones de Dengue no Chile Continental, a preocupação sobre a possibilidade de transmissão local está em crescimento.

A situação no Brasil segue uma tendência similar. Até a 18ª semana epidemiológica (SE 18) de 2023, os casos notificados são 13% mais elevados em comparação ao mesmo período de 2022 e 73% superiores em relação à média dos últimos 5 anos. Nesse intervalo, foram registradas 387 mortes. A partir da SE 21, o Brasil contabilizou 1.515.460 casos prováveis de dengue, representando 76% do total de casos prováveis na Região das Américas, seguido pela Bolívia com 126.182 e Peru com 115.949 (OPAS/OMS, 2023).

O que chama a atenção é que esse aumento não se trata de um evento isolado. Surtos de Dengue têm ocorrido repetidamente no Brasil por várias décadas cujo impacto se intensifica devido às consequências de um sistema de saúde já sobrecarregado em decorrência da pandemia de COVID-19, afetando tanto a atenção primária quanto os serviços médicos especializados. Semelhante ao que foi observado em 2023, em 2022, até a 19ª semana epidemiológica, foram registrados 855.910 casos suspeitos de dengue (com uma taxa de incidência de 401,2 casos por 100.000 habitantes), representando um aumento de 181,74% em relação ao mesmo período do ano anterior, quando foram registrados 303.727 casos prováveis (com uma taxa de incidência de 143,4 casos por 100.000 habitantes).

Duas vacinas contra a dengue foram aprovadas para uso comercial no Brasil: (1) Dengvaxia (Sanofi Pasteur) e Qdenga (Takeda Pharma), mas nenhuma está incorporada ao Sistema Único de Saúde (SUS). As vacinas disponíveis têm evitado a gravidade dos



desfechos clínicos, mas não interromperam a infecção em si (RAMAKRISHNAN, 2023), o que destaca a necessidade de melhorias e monitoramento na aplicação em campo.

2.1.2. Chikungunya

O vírus Chikungunya (CHIKV) também é transmitido por picadas de fêmeas de mosquitos *Ae. aegypti* e *Ae. albopictus* contudo, caracteriza-se por uma poliartralgia febril aguda, artrite inflamatória, erupções cutâneas agudas e outras manifestações sistêmicas, com sintomas que podem perdurar de meses a anos (MINER et al., 2017) e com desfecho fatal, em casos mais graves (ROLLÉ et al., 2016).

A infecção pelo CHIKV foi descrita pela primeira vez durante um surto no sul da Tanzânia em 1952. Em 2013, foi introduzida no continente americano, desencadeando uma significativa onda epidêmica em diversos países da América Central e ilhas do Caribe, com mais de um milhão de casos detectados no primeiro ano após sua introdução (OPAS, 2023). No segundo semestre de 2014, o Brasil confirmou, por métodos laboratoriais, a presença da doença nos Estados do Amapá e Bahia, e atualmente, todos os Estados relatam transmissão desse arbovírus (BRASIL, 2023).

Nos últimos anos, na Região das Américas tem-se observado um aumento expressivo no número de casos e mortes por Chikungunya. Houve um aumento de 97,8% no número de casos notificados de 2021 a 2022 e um aumento de 34,7% em todo o ano de 2022 até a semana epidemiológica 40 de 2023, além de um aumento nos óbitos de 308,1% no mesmo período.

Em abril de 2023, o Chile declarou emergência de saúde pública em resposta à presença do *Ae. aegypti* e à situação epidemiológica de países vizinhos. Argentina e Uruguai também relataram os primeiros casos de transmissão local de Chikungunya. Na Argentina, foram identificados 1.993 casos de Chikungunya (SE 52/2022 a 20/2023), com 1.336 casos autóctones, enquanto o Uruguai notificou 73 casos de Chikungunya (52 autóctones). O Paraguai também enfrentou epidemias de arbovírus em grande escala em 2023, atingindo uma incidência cumulativa de 1.216 casos por 100 mil habitantes até a semana epidemiológica 23 (ESTALLO et al., 2023). No Brasil, houve um aumento de 35% nos casos de 2020 a 2021, de 100,1% de 2021 a 2022 e de 15% até a semana epidemiológica 40 de 2023, em comparação com o mesmo período de 2022 (OPAS/OMS, 2023).

Atualmente, uma vacina viva atenuada, denominada VLA1553, encontra-se em fase III de estudo, com resultados promissores, embora mais pesquisas em regiões endêmicas e

em populações expandidas sejam essenciais para determinar a eficácia do imunizante na prevenção da Chikungunya (SCHNEIDER et al., 2023).

2.1.3. Zika

O vírus Zika (ZIKV) também possui como vetor fêmeas do gênero *Aedes*, principalmente *A. aegypti*. Apesar de os sintomas geralmente serem leves - erupção cutânea, febre, conjuntivite, dores musculares e articulares, mal-estar e dor de cabeça - a doença ganhou notoriedade por sua associação com casos microcefalia que ocorreram no Brasil, em 2015. Além disso, má formações fetais, distúrbios neurológicos em adultos - como a meningoencefalite e a síndrome de Guillain-Barré – foram associados a infecção viral (PLOURDE; BLOCH, 2016; PAHO/WHO, 2023).

Entre 2015 e 2016, foram notificados 651.470 casos nas Américas, dos quais 273.904 ocorreram no Brasil, representando 42% do total de casos na região (dados da OPAS/OMS). Além disso, outros países, como Canadá, França e Espanha, relataram casos de Zika importados por viajantes provenientes de áreas endêmicas (IMPERATO, 2016). Nos Estados Unidos, foram notificados 36.367 casos por transmissão autóctone em 2016, sendo os Estados mais afetados Texas e Flórida, o que levou o senado a financiar 1.1 bilhões de dólares para investir em medidas de controle da doença (SLACK, 2016; CDC, 2023).

A partir de 2017, houve uma diminuição no número de casos de Zika em todo o mundo. Atualmente, o arbovírus é transmitido de forma autóctone em 89 países, enquanto 61 países e territórios reconhecidos pela ONU com competência do vetor *Ae. aegypti* ainda não documentam a transmissão do ZIKV (WHO, 2019).

Em 2019, foram registrados 35.898 casos de Zika nas Américas, sendo que 30.500 desses casos ocorreram no Brasil, representando 85% do total de casos na região. Em 2020, houve uma redução de 36% no número de casos notificados nas Américas, com uma tendência semelhante no Brasil. No entanto, em 2022, o número de casos notificados de Zika aumentou em cerca de 43% em comparação com a média de casos entre 2020 e 2021, totalizando 40.249 casos nas Américas e 34.176 casos no Brasil. Até setembro de 2023 (SE 39), foram registrados 28.200 casos nas Américas, dos quais 26.659 ocorreram no Brasil (SE 29), representando 94% do total (dados da PAHO/WHO). Esses dados indicam que, apesar da diminuição do número de casos de Zika desde 2017, a doença ainda afeta uma parcela significativa da população nas Américas, com maior incidência no Brasil.



Atualmente, ainda não existem vacinas ou antivirais específicos licenciados para o tratamento e a prevenção da Zika, apesar dos esforços em pesquisa e desenvolvimento nessa área (PIELNAA et al., 2020). Assim, como nas demais arboviroses descritas anteriormente, o principal modo de prevenção relaciona-se ao controle do mosquito vetor e na educação em saúde para mobilização da população no combate e controle da doença.

2.2. O VETOR

O principal vetor das arboviroses urbanas na região das Américas é o inseto *Ae. aegypti*. Esse inseto, originário da África, se espalhou pelo globo durante o período das grandes navegações, tendo chegado ao Brasil durante a colonização (CONSOLI; LOURENÇO-DE-OLIVEIRA, 1994). Atualmente é um mosquito altamente urbanizado e cosmopolita, vivendo de preferência em regiões tropicais e subtropicais. Sua distribuição global vem se expandindo devido, dentre outras razões, ao aquecimento global (KAMAL et al., 2018).

2.2.1. Biologia do vetor e impacto no controle

Aedes aegypti apresenta ciclo de vida do tipo holometábolo sendo constituído dos estágios de ovo, larva (4 estádios), pupa e adulto (macho ou fêmea). Durante a fase larval e de pupa o inseto possui hábito aquático enquanto na fase adulta, terrestre. Tem como condições ideais para seu desenvolvimento, em laboratório, a temperatura de 28°C ($\pm 1^\circ\text{C}$) e umidade relativa de 80% ($\pm 10\%$) concluindo o ciclo de desenvolvimento em aproximadamente 10 dias. Em temperaturas mais altas (ex. verões) o ciclo se conclui de forma mais rápida significando o incremento da população de insetos e na circulação dos arbovírus por eles transmitidos. Dois pontos merecem destaque: i) as fêmeas de *Ae. aegypti* depositam os ovos em múltiplos criadouros, comportamento esse conhecido por “postura em saltos” ou “skip-oviposition” (FAY; PERRY 1965, CHADEE et al., 1990), o que dificulta a eliminação de todos os criadouros e ii) na ausência de condições ambientais favoráveis para eclosão, os ovos são capazes de resistir no ambiente por até um ano através do fenômeno da quiescência, sobrevivendo, dessa forma, as estações secas (CONSOLI; LOURENÇO-DE-OLIVEIRA, 1994), mantendo a população de mosquitos durante todo o ano e, por sua vez, a circulação dos vírus por ele transmitidos.



2.2.2. Controle do Vetor

2.2.2.1. Histórico: eliminação/impossibilidade atual

Em 1947 foi criado pela OPAS/OMS o “Programa de Erradicação do *Ae. aegypti* no Hemisfério Oeste”. Tal iniciativa, ao longo das décadas de 1940 e 1950, se traduziu na eliminação desse mosquito do continente americano à exceção de Cuba, Colômbia, Estados Unidos da América, Haiti, Jamaica, República Dominicana, Suriname e Venezuela (SOPER, 1965). O Brasil estava na lista de países que eliminaram o *Ae. aegypti* datando, tal feito, de 1955. Em 1967, doze anos após a eliminação do *Ae. aegypti* do Brasil, ele foi novamente observado no país (FRANCO, 1976), sendo já descritas nessa época, populações que apresentavam mortalidade reduzida a inseticidas apontando para a resistência, como já se observava em outras partes do mundo (CAMARGO, 1967; FRANCO, 1976). Apesar disso, com a manutenção das atividades de controle químico com novos inseticidas, em 1973 *Ae. aegypti* foi eliminado pela segunda vez do Brasil (FRANCO, 1976) sendo, observado novamente em 1976 (FRANCO, 1976). Ao final dos anos de 1990, foram detectadas as primeiras populações brasileiras de *Ae. aegypti* do Rio de Janeiro (RJ) resistentes aos inseticidas (MACORIS et al., 1999).

2.2.2.2 Resistência

A resistência a um inseticida se traduz em uma diminuição da mortalidade observada na população submetida a um tratamento constante. Trata-se de uma característica que se manifesta com o predomínio de indivíduos que toleram doses letais, sobre indivíduos chamados sensíveis nas primeiras aplicações do produto, ocasionando pressão de seleção nas populações. Este fenômeno tem como base a variabilidade genética das populações naturais a partir da qual, por pressão do inseticida, determinados fenótipos podem ser selecionados e, conseqüentemente, aumentarem em frequência (TABASHNIK; ROUSH 1990). O primeiro relato de resistência de *Ae. aegypti* a inseticidas data de 1956 em Trinidad (Caribe), onde foi observado que as populações de campo apresentaram menor mortalidade ao inseticida DDT (GILKES et al., 1956). Desde então, a frequência dos relatos de resistência vem aumentando no sudeste asiático e na América Latina (RANSON et al., 2010; MOYES et al., 2017). No Brasil, há diversos relatos de populações desse mosquito resistentes - principalmente ao Temefós (razões de resistência 95% -RR₉₅ variando de 1,2 a 254,9) e a



Deltametrina (RR₉₅ de 6,0 a 110,0) (SMITH et al., 2016; MOYES et al., 2017; VALLE et al., 2019).

Frente a um quadro de resistência, em geral tende-se a observar o aumento do uso de inseticidas, traduzindo-se em uma maior contaminação do meio ambiente e a mortandade de espécies não alvo do controle, além de se pressionar ainda mais a população alvo fixando, assim, os genes envolvidos com a resistência. Por consequência, observa-se uma diminuição da disponibilidade de inseticidas que tem efeito sobre as populações, elevando os custos para o controle do inseto. Adicionalmente, não se pode desconsiderar que o desenvolvimento de um novo inseticida, na maioria das vezes, é um processo demorado e oneroso. Portanto, incentiva-se o uso de forma racional dos inseticidas, prolongando a vida útil deles na linha temporal (BRENGUES, 2003; MACORIS et al., 2010; MACORIS et al., 2014; MOYES et al., 2017; BRASIL et al., 2019; VALLE et al., 2019; COSTA, 2020; OMS, 2023).

Considerando ser a resistência aos inseticidas uma realidade, alternativas como o controle biológico têm sido empregadas e avaliadas a exemplo: a bactéria *Bacillus thuringiensis israelensis* (*Bti*), peixes *Betta splendens*, machos estéreis (THOME, 2010; ZHANG, 2015; ATYAME, 2016; GATO, 2021; KLASSEN, 2021) ou machos com gene letal para fêmeas (THORNE, 2010; CARVALHO, 2015; SPINNER, 2022) ou machos infectados com *Wolbachia* (WALKER, 2011; HOFFMAN, 2014; BOURTZIS, 2014; DUTRA, 2015; DORIGATTI et al., 2017, THOMAS et al., 2018).

A *Wolbachia* é uma bactéria intracelular, que se mostrou útil no bloqueio da infecção pelos vírus da Dengue, Zika e Chikungunya em *Ae. aegypti*. Acredita-se que a *Wolbachia*, por ser uma bactéria intracelular, compete com os vírus supracitados por ácidos graxos (ex. colesterol) necessários à replicação viral e regula de forma aumentada as rotas do sistema imune do inseto. Adicionalmente, discute-se a possibilidade dessa bactéria interferir no processo de entrada do vírus dengue na célula do mosquito (THOMAS, 2018). A *Wolbachia* tem transmissão vertical, sendo que as fêmeas transmitem a bactéria para a prole no ovário. Para ajudar a se estabelecer em novas populações, a bactéria também tem a capacidade de gerar incompatibilidade citoplasmática entre machos infectados e fêmeas não infectadas, desta forma somente a prole entre machos infectados e fêmeas infectadas, ou entre machos não infectados e fêmeas infectadas sobreviverá. Trata-se de uma estratégia sustentável que prevê na linha temporal a manutenção de mosquitos com a bactéria na natureza sem necessidade de solturas continuadas (DORIGATTI et al., 2017). Vale destacar que não se trata de uma tecnologia para o controle de *Ae. aegypti*, mas sim das doenças a ele



relacionados uma vez que mosquitos continuarão na natureza, contudo, sem o vírus (WALKER, 2011; HOFFMAN, 2014; BOURTZIS, 2014; DUTRA, 2015).

2.3. ALTERAÇÕES CLIMÁTICAS

2.3.1. Impacto das alterações climáticas nesse cenário

Além da seleção de insetos resistentes aos inseticidas, como citado anteriormente, as mudanças climáticas têm um importante papel no aumento da população de insetos vetores e consequentemente, contribui para a expansão de doenças como as arboviroses.

Causadas principalmente pela atividade humana (MCCARTHY, 2001; STEFFEN et al., 2011), as alterações climáticas têm uma série de consequências para o meio ambiente e sociedade. Fatores como desmatamento, agricultura e pecuária intensiva, atividades industriais, queima de combustíveis fósseis, emissão de gases de efeito estufa, dentre outros, contribuem para as alterações climáticas. Essas ações humanas têm desencadeado uma série de efeitos colaterais significativos, incluindo o aquecimento global, alterações nos padrões de precipitação, derretimento das calotas polares e aumento do nível do mar, geração e acúmulo de resíduos, extinção de espécies, migração forçada de espécies e deslocamento e aglomeração de pessoas. Direta ou indiretamente, todos esses fenômenos afetam a ecologia dos vetores de arbovírus e a expansão da sua faixa geográfica (SEMENZA; MENNE, 2009; BAYLIS, 2017).

Dados meteorológicos confirmam que a temperatura média global aumentou entre 0,8 a 1,2°C, e confirmam a ocorrência de variações extremas nos padrões de chuva (DORE, 2005). Esse cenário tem facilitado a expansão dos habitats de diversos vetores, incluindo os mosquitos e, consequentemente, dos vírus por eles transmitidos. Regiões que antes eram muito frias para sustentar populações de mosquitos podem agora se tornar suscetíveis à propagação destes e com eles os arbovírus. De fato, a transmissão autóctone de arbovírus transmitidos por mosquitos está ocorrendo com mais frequência em regiões subtropicais e temperadas, ocorrendo em altitudes mais elevadas em regiões tropicais e tornando-se cada vez mais intensa em regiões endêmicas, resultando em surtos de maior magnitude (KRAEMER et al., 2019). Além disso, a temperatura também regula a incubação viral no vetor do mosquito, sendo que temperaturas mais quentes são muitas vezes consideradas ótimas por reduzirem o período de incubação do vírus (CHAN; JOHANSSON, 2012).

Recentemente, o *Ae. albopictus* tem ampliado sua área de ocorrência nas Américas, África e Europa. Surtos recentes de Chikungunya e dengue nos Estados Unidos também foram identificados, embora relativamente pequenos e limitados a áreas específicas. No entanto, essas áreas passaram a ser consideradas de risco para o Zika, incluindo os estados da Flórida e Texas e territórios dos Estados Unidos como Porto Rico, Ilhas Virgens Americanas e Guam (CDC, 2023).

Modelos de previsão globais de alterações climáticas indicam que, em todos os cenários de aquecimento, a expansão da distribuição de mosquitos e a transmissão de arbovírus provavelmente continuarão a aumentar (WHITEHORN; YACOUN, 2019). Kamal et al. (2018) demonstraram através de modelos de nicho ecológico (ENMs) que a distribuição potencial prevista de *Ae. aegypti* e *Ae. albopictus* coincide com os dados de distribuição atual. Enquanto o mosquito *Ae. aegypti* é mais amplamente distribuído em regiões tropicais e subtropicais, o *Ae. albopictus* tem um potencial maior em regiões temperadas na Europa e nos Estados Unidos. Além disso, os modelos indicaram que *Ae. albopictus* expandirá sua distribuição para o norte dos Estados Unidos, sul do Canadá e grande parte da Europa em 2050 e 2070. Para o mesmo período, prevê-se que a expansão de *Ae. aegypti* abranja a região sul do leste da Austrália. Recentemente, uma pesquisa realizada no Equador previu identificou que o *Ae. aegypti* aumentará sua área de alcance em direção a altitudes mais elevadas nas encostas dos Andes, podendo impactar uma extensão de aproximadamente 4.215 km² de território adicional e afetar cerca de 12.000 pessoas, especialmente sob o cenário mais extremo de mudanças climáticas considerado até 2050 (LIPPI et al., 2019). Uma comparação da adequação de temperatura entre *Ae. aegypti* e *Ae. albopictus* demonstrou que, em média, o índice de adequação de temperatura para *Ae. albopictus* é cerca de 42 vezes maior do que o de *Ae. aegypti*, evidenciando uma notável superioridade na adaptação de *Ae. albopictus* (WHITEHORN; YACOUN, 2019). É importante salientar que embora a previsão seja de aumento na transmissão global de arbovírus, também é possível que a transmissão destes diminua em regiões tropicais devido ao aumento das temperaturas, que podem se tornar excessivamente quentes para sustentar populações de mosquitos (RYAN et al., 2019). As regiões tropicais e subtropicais são propícias para uma transmissão ao longo do ano, mas a transmissão em áreas temperadas se restringe a, no máximo, três meses por ano, mesmo na presença de vetores. Esses curtos períodos de transmissão diminuem consideravelmente a probabilidade de grandes epidemias após a introdução da doença em regiões temperadas (MORDECAI et al., 2017). Além disso, existe a possibilidade

de que as populações locais de mosquitos evoluam para se adaptar de forma mais eficaz às mudanças nas condições climáticas.

2.3.2. Sazonalidade

A sazonalidade se refere à variação cíclica ou periódica de eventos ou condições ao longo de um determinado período de tempo, muitas vezes seguindo um padrão previsível nas estações do ano. Quando aplicada ao contexto das arboviroses, essa sazonalidade se traduz na tendência de transmissão desses vírus que se intensifica ou diminui em sincronia com as mudanças climáticas sazonais.

Por exemplo, no Brasil e nas Américas, observa-se que a sazonalidade da transmissão da dengue tem se estendido para além do período tradicionalmente considerado como estação de transmissão (WHO, 2023). Os boletins epidemiológicos liberados semanalmente pela Secretaria de Vigilância em Saúde do Ministério da Saúde no Brasil têm registrado essa tendência não apenas no aumento no número de casos dessas doenças, mas também no aumento das epidemias de doenças transmitidas por mosquitos nas últimas décadas, incluindo surtos frequentes de Dengue, Zika e Chikungunya (MINISTÉRIO DA SAÚDE, 2023).

Essa extensão da sazonalidade da transmissão e o aumento na frequência de surtos de doenças transmitidas por mosquitos são preocupantes, pois sobrecarregam os sistemas de saúde e têm um impacto significativo na saúde pública. Portanto, é fundamental ressaltar a importância de medidas de controle contínuo, vigilância epidemiológica, educação pública e pesquisa para enfrentar os desafios decorrentes das mudanças nas condições climáticas e da expansão da atividade dos mosquitos vetores. Compreender esse ciclo sazonal é essencial para antecipar e responder a surtos de arboviroses, permitindo a implementação de medidas preventivas e estratégias de controle em momentos de maior risco.

2.3.3. Eventos climáticos extremos

Eventos climáticos extremos, como secas, incêndios e inundações, podem criar condições propícias para a reprodução de mosquitos. Os relatórios sobre desastres do Banco Mundial e das Nações Unidas (WORLD BANK & UNITED NATIONS, 2010) indicam que na América Latina, no período de 1970 a 2010, os desastres classificados como "naturais" foram predominantemente de natureza hidrológica, representando 45% do total,

sendo principalmente associados a enchentes e deslizamentos causados por chuvas intensas. Em segundo lugar, foram os desastres meteorológicos, com uma proporção de 25%, que englobam eventos como furacões e ciclones. Os eventos climatológicos, incluindo secas e ondas de calor, representaram aproximadamente 8% do total. No Brasil, dentre um total de 31.909 desastres naturais documentados entre 1991 e 2010, os eventos hidrológicos, como inundações repentinas ou graduais, representaram 32,7% de todas as ocorrências e afetaram diretamente mais de 60% das 96 milhões de pessoas envolvidas. Esses eventos resultaram em tristes estatísticas, incluindo 1.567 fatalidades, 309.529 indivíduos feridos ou doentes, 1.812 pessoas desaparecidas, além das 3.566.087 pessoas que precisaram abandonar temporária ou permanentemente suas moradias e outras 610.764 que se viram forçadas a migrar de suas regiões de residência (XAVIER et al., 2014).

No Brasil, as regiões norte e sul têm registrado com maior frequência eventos climáticos extremos. Secas prolongadas no oeste do Estado de Santa Catarina e chuvas torrenciais na região leste apresentaram maior frequência a partir da década de 1990 (CEPED, 2013). Áreas inundadas podem se tornar criadouros ideais para larvas de mosquitos, enquanto períodos de seca podem levar a um acúmulo de água parada em recipientes, que também são locais de reprodução de mosquitos (IBARRA et al., 2013). Um caso ocorrido em São Paulo (Brasil) destaca a conexão entre a crise hídrica que ocorreu em 2014 com a epidemia de dengue que afetou a cidade em 2015. No primeiro bimestre de 2014, foram notificados 11.876 casos de dengue. No mesmo período em 2015, houve um aumento significativo, com 94.623 casos notificados, ou seja, um aumento de 697% (MINISTÉRIO DA SAÚDE, 2015). Devido à falta de informações claras sobre as medidas de racionamento de água, bem como sobre quando e em que quantidade a água seria fornecida, a população passou a armazenar água, frequentemente de maneira inadequada. Acredita-se que uma das consequências desse armazenamento foi o aumento significativo no número de casos notificados de dengue e óbitos relacionados à doença transmitida pelo mosquito *Ae. aegypti*. É evidente que a implementação de planos de emergência deve ser acompanhada por políticas transparentes para enfrentar essas crises cíclicas. Isso é fundamental para evitar o consumo de água de fontes não oficiais e improvisadas, bem como o armazenamento inadequado de água. Essas práticas contribuem, entre outros efeitos adversos, para o aumento do risco de surtos de doenças.

2.3.4. Degradação ambiental

A degradação ambiental, incluindo o desmatamento e a urbanização desordenada, leva à migração e à adaptação das espécies a novos ambientes. No Brasil, houve um aumento na abundância e diversidade de mosquitos, com espécies diferentes circulando em áreas urbanas. Por exemplo, em parques municipais de São Paulo, foram identificadas pelo menos 81 espécies, com *Ae. albopictus* sendo mais comum que *Ae. aegypti* (MEDEIROS-SOUSA et al., 2015; BREVIGLIERI; LORENZ, 2017; CARVALHO et al., 2017; ATAÍDE et al., 2023).

O surto de Febre Amarela no Brasil entre 2016 e 2018, o maior da história do país, foi fortemente influenciado pela degradação ambiental. A devastação da Mata Atlântica, reduzida a menos de 8% de sua extensão original, foi central nesse problema. Minas Gerais foi um dos estados que mais desmataram a Mata Atlântica nos últimos anos (SOS MATA ATLÂNTICA, 2015). O desmatamento levou os vetores da febre amarela silvestre a migrarem para áreas periurbanas, aumentando a proximidade com os humanos (TAIPE-LAGOS; NATAL, 2003).

A Febre Amarela tem duas formas de transmissão: silvestre e urbana. No Brasil, a forma urbana foi erradicada, mas a silvestre continua sendo transmitida por mosquitos como *Haemagogus* e *Sabethes*, com os macacos como principais hospedeiros (MUCCI et al., 2016). A degradação ambiental, resultante do desmatamento, aumenta a densidade populacional de mosquitos vetores. Por sua vez, a escassez de predadores naturais e de animais fonte de alimento forçam os mosquitos a buscarem outras fontes, incluindo os humanos.

A expansão do surto da Febre Amarela das áreas silvestres para áreas urbanas e rurais impôs desafios significativos para a saúde pública. E, seu controle foi possível por meio de uma abordagem abrangente que envolveu a vacinação em massa, o aumento da capacidade de produção da vacina e esforços de conscientização pública. Essas medidas demonstraram a eficácia das ações coordenadas das autoridades de saúde e da sociedade no enfrentamento de doenças transmitidas por vetores. Além disso, esse surto destacou a necessidade contínua de vigilância e adaptação às mudanças nas condições epidemiológicas e climáticas.

2.3.5. Desastres Ambientais

Recentemente, o Brasil testemunhou o desabamento de barragens de mineração que resultou em uma das mais graves catástrofes ambientais do país. Os incidentes envolveram o rompimento das barragens de mineração “Fundão”, ocorrido em Mariana em 2015 e “Córrego do Feijão”, ocorrido em Brumadinho em 2019, e tiveram impactos significativos em termos humanos, ambientais e econômicos. Embora o desabamento de barragens em si não cause diretamente a transmissão de arboviroses, ele pode criar condições ambientais e sociais que favorecem o aumento do risco de transmissão dessas doenças (Watson et al., 2007; Kouadio et al., 2012). Desastres ambientais comumente sobrecarregam os sistemas de saúde locais limitando a capacidade do governo de responder eficazmente a surtos de doenças, incluindo as arboviroses. A falta de acesso a cuidados de saúde adequados pode resultar em casos não diagnosticados ou não tratados. Além disso, o deslocamento de comunidades afetadas por desastres, como desabamentos de barragens, muitas vezes leva a condições precárias de habitação em abrigos temporários, onde a exposição a mosquitos transmissores de arboviroses é maior devido à falta de infraestrutura adequada e ao ambiente propício à proliferação desses mosquitos, aumentando o risco de picadas em pessoas infectadas. A resposta a esses desastres exige recursos significativos do governo, mobilização de equipes de resgate e reabilitação de áreas afetadas. Isso pode sobrecarregar os recursos disponíveis para outras emergências de saúde pública, incluindo a epidemia de COVID-19 e as epidemias de arboviroses.

2.4. SOB A LUZ DA PANDEMIA

Os efeitos prejudiciais da pandemia foram muito além da COVID-19. Vivencia-se hoje uma escassez de profissionais de saúde e leitos hospitalares para lidar com casos graves das arboviroses, em especial com a nova epidemia de dengue, em 2023. Estamos testemunhando um estado de inércia resoluta, que leva ao aumento da morbidade e mortalidade por dengue, bem como por outras doenças.

A busca por consultas nos centros de atenção primária e nas unidades de emergência durante surtos de arboviroses contribui para agravar o atraso no tratamento de condições mais comuns, como hipertensão, diabetes e doenças pulmonares. Tempos de espera mais longos para o tratamento de várias comorbidades levam a uma piora no estado de saúde desses pacientes, resultando em uma demanda crescente por consultas de cuidados



urgentes, testes diagnósticos adicionais e hospitalizações, sobrecarregando ainda mais um sistema de saúde já exaurido. Isso, por sua vez, reforça um ciclo negativo que afeta, em última análise, as populações vulnerabilizadas socioeconomicamente. Doenças negligenciadas como a dengue empurram ainda mais essas populações para o abismo, seja pelos efeitos diretos da infecção ou pelas barreiras ao acesso a instalações de saúde pública.

Devemos aplicar as lições aprendidas com a pandemia. Medidas coletivas e eficazes de prevenção e controle são fundamentais e devem ser reforçadas, incluindo a implementação de um sistema de vigilância epidemiológica permanente e mais eficiente. Esse sistema desempenha um papel crucial na orientação de esforços, permitindo que sejam tomadas ações antes do surgimento de surtos sazonais ou potenciais, bem como facilitando a rápida identificação de surtos para direcionar esforços de mitigação.

Doenças de alcance global requerem esforços globais, mas também demandam uma compreensão das particularidades regionais. Nesse contexto, é importante ressaltar que a verdadeira extensão do ônus da Dengue, por exemplo, pode ter sido subestimada, uma vez que o acesso limitado aos sistemas de saúde e aos testes diagnósticos é uma realidade das populações negligenciadas em muitas regiões carentes. Além disso, a obtenção de resultados diagnósticos confiáveis frequentemente exige esperar de 2 a 3 dias a partir do início dos sintomas.

A fim de transformar essa realidade, é imperativo adotar medidas concretas, abrangentes e organizadas que levem em conta as circunstâncias e peculiaridades locais. Monitorar constantemente e acompanhar o avanço da saúde, avaliar a aplicação e o financiamento de novas estratégias de prevenção e controle, bem como fundamentar as políticas de saúde em evidências com ênfase na prevenção, assume um papel de extrema importância.

A existência de diferentes políticas públicas pode, em potencial, comprometer os esforços coletivos. A segurança e eficácia dessas abordagens precisam ser cuidadosamente avaliadas para mitigar possíveis impactos adversos em outras doenças e no ecossistema como um todo. Portanto, recomenda-se que as autoridades de saúde e os especialistas em entomologia e ecologia estejam envolvidas na avaliação e implementação dessas estratégias.

3. CONSIDERAÇÕES FINAIS

Deixando claro que os patógenos transmitidos por mosquitos não conhecem fronteiras geográficas, a Dengue e outras doenças transmitidas por vetores continuam a se espalhar globalmente. Devido a fatores como a falta de coordenação integrada nas políticas de controle vetorial, o Brasil e seus países vizinhos sofrem ainda mais com a carga e as consequências da expansão das arboviroses. Diante da complexa interação entre as alterações ambientais e a pandemia de COVID-19, que tem catalisado o avanço das arboviroses nas Américas, fica claro que é necessário um esforço multidisciplinar e sustentável para enfrentar esse desafio de saúde pública global.

A atual emergência de arboviroses em áreas antes livres e o aumento da incidência em regiões já endêmicas pode de fato ser o resultado de uma combinação de fatores que inclui, além da ausência de ações integradas e coordenadas, as condições climáticas favoráveis resultantes do aquecimento global e da capacidade de adaptação, proliferação e dispersão do mosquito vetor (OBHOLZ et al., 2022). No entanto, também é evidente que, em geral, as políticas de saúde pública têm se concentrado mais em abordagens curativas do que em ações preventivas estratégicas, especialmente para doenças consideradas negligenciadas. Tornando esse cenário ainda mais grave, durante a pandemia, os esforços foram direcionados para combater a COVID-19, levando a uma redução ainda maior na vigilância em áreas endêmicas. Atualmente o que se observa é a sobreposição de uma nova epidemia com um sistema de saúde fatigado e ainda em reestruturação.

Na tentativa de superar esses obstáculos é crucial integrar as ações de controle e atividades de pesquisa em diferentes esferas - municipal, estadual, federal e mundial. Assim como se observou no enfrentamento à pandemia de COVID-19, colaborações podem facilitar a partilha de recursos entre nações com desafios semelhantes. Essas parcerias têm o potencial de gerar as ferramentas e as evidências necessárias para orientar políticas que protejam a saúde das populações. Assim, o compartilhamento de informações e recursos, o desenvolvimento em conjunto de protocolos, treinamentos e capacitação, resposta a surtos transfronteiriços, pesquisa colaborativa, e as campanhas de conscientização são essenciais. No entanto, é importante que essas diretrizes compartilhadas sejam adaptadas às necessidades específicas de cada localidade. Caso contrário, os programas de controle resultam apenas em resultados de curta duração e, portanto, não são sustentáveis.

A pesquisa colaborativa também compreende a realização de estudos epidemiológicos, o desenvolvimento de vacinas e de tratamentos, e a vigilância da resistência aos medicamentos, de forma conjunta. No que tange às campanhas de conscientização, essas desempenham um papel de extrema importância, uma vez que instruem os indivíduos sobre as medidas de prevenção e o reconhecimento dos sintomas das arboviroses, contribuindo de maneira significativa para o combate eficaz contra essas doenças. Assim, a cooperação entre regiões têm um papel crucial na contenção dos arbovírus, porquanto as enfermidades causadas pela infecção com esses agentes frequentemente atravessam as fronteiras de múltiplos países simultaneamente.

O desafio crítico do controle de arboviroses tem demandando urgentemente estratégias inovadoras de prevenção, controle de vetores e educação em saúde. A vigilância desempenha um papel central, identificando áreas de alta infestação de mosquitos transmissores e direcionando esforços de controle, permitindo a implementação de medidas preventivas e de controle antes que ocorram surtos de doenças. Contudo, diante da complexidade das dinâmicas de transmissão de patógenos, os programas de controle tradicionais têm se mostrado insuficientes. Nesse sentido o engajamento comunitário, bem como a educação em saúde, tem emergido como ações fundamentais para o enfrentamento das arboviroses, já que, comunidades engajadas e informadas têm o potencial de se tornarem agentes ativos na mitigação dos riscos das arboviroses. A conscientização e a educação pública podem atuar na disseminação de práticas preventivas eficazes. Além disso, as ações educativas promovem não apenas o acesso ao conhecimento, mas também a construção de uma sociedade mais preparada e resiliente diante desse desafio de saúde pública. A colaboração entre pesquisadores, profissionais de saúde e a sociedade pode levar soluções inovadoras e mais sustentáveis para evitar o avanço das arboviroses.

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ARTICLE 6 -

From plans to practice: why Brazil struggles to contain arboviruses despite the world's highest dengue burden

FROM PLANS TO PRACTICE: WHY BRAZIL STRUGGLES TO CONTAIN ARBOVIRUSES DESPITE THE WORLD'S HIGHEST DENGUE BURDEN

José Cherem, Ana Paula Peconick, Joziana Muniz de Paiva Barçante

ABSTRACT

Brazil faces the world's highest dengue burden, despite decades of investments in national contingency plans and surveillance systems. This study critically evaluates the operationalization of arbovirus surveillance and control policies in the Lavras microregion, Minas Gerais, Brazil, a representative setting of local heterogeneity and institutional fragmentation. Using a mixed-methods approach, data were collected from all nine municipalities through structured questionnaires addressing contingency plans, epidemiological tools, entomological practices, intermunicipal integration, and innovative technologies. Results revealed that although 100% of municipalities reported formal contingency plans and routine LIRAA implementation, only 44.4% employed ovitraps, 55.6% maintained situation rooms, and less than half used control diagrams. Entomological and epidemiological surveillance remain heavily dependent on human effort rather than data intelligence. While genomic and molecular diagnostic infrastructures advanced during the COVID-19 pandemic, their integration into arbovirus surveillance remains limited. The study underscores the paradox of “structured reactivity”, a technically capable yet operationally fragmented system. Overcoming these limitations requires regionalized governance, integration of Community Health Workers and Endemic Disease Control Agents, adoption of AI-based predictive tools, and intermunicipal coordination consistent with the One Health approach. These findings demonstrate that institutional and technological integration, not resource scarcity, is the main barrier to effective arbovirus control in Brazil.

Keywords: Arboviruses; Dengue; Epidemiological Surveillance; Vector Control; One Health; Public Health Policy; Brazil; *Aedes aegypti*; Genomic Surveillance; Artificial Intelligence.

1 INTRODUCTION

Emerging and re-emerging arboviral diseases such as dengue, chikungunya, Zika, and Oropouche represent one of the major public health challenges of the 21st century, intensified by climate change, unplanned urbanization, and fragile surveillance systems in tropical countries ([1]PAHO, 2025d; [2]Barçante; Cherem, 2025). In 2024, the Americas reported more than 13 million dengue cases, the highest number in recent history. By the 21st epidemiological week of 2025, over 3 million cases had already been recorded across the continent, with Brazil accounting for approximately 1 million infections and 681 confirmed deaths. The state of Minas Gerais ranked among those with the highest dengue burden in the country, reflecting the Southeast region's vulnerability to sustained vector proliferation and viral dissemination. This scenario underscores the structural limitations in containing *Aedes aegypti* and *Aedes albopictus*, highlighting the urgent need to replace fragmented, reactive strategies with integrated One Health approaches based on predictive surveillance and technological incorporation ([3]PAHO, 2025a; [4]PAHO, 2025b; [5]Brasil, 2025).

Globally, dengue virus distribution continues to expand into previously non-endemic areas. However, how the emergence and local dynamics of dengue transmission are shaped by contextual factors remains poorly understood ([6]Gibb *et al.*, 2023). This knowledge gap emphasizes the importance of microrregional analyses that examine how governance structures, public policies, and institutional capacities affect the practical effectiveness of surveillance and control interventions.

Brazil, an endemic country for multiple arboviruses, faces a paradox between scientific progress and operational stagnation. Despite the implementation of robust national plans such as the National Contingency Plan for Dengue, Chikungunya, and Zika ([7]Brasil, 2025b) and the strengthening of genomic surveillance during the COVID-19 pandemic ([8]Brasil, 2022), local responses remain heterogeneous and dependent on municipal technical capacity. In many areas, entomological and epidemiological surveillance still rely more on human effort than on data intelligence, perpetuating the historical cycle of reactivity that has characterized arbovirus control in the country ([9]PAHO, 2023c; [7]Brasil, 2025b). These operational disparities underscore the need to understand how the formal surveillance framework translates, or fails to translate, into effective local action.

The increasing spread of arboviruses results from the adaptation of vectors to climate change, urban growth, and migration, highlighting the interaction of

environmental and social factors. Policy failures, poor coordination across government levels, and environmental neglect, particularly plastic waste accumulation, sustain vector breeding. Strengthening ecological understanding and interinstitutional collaboration is crucial to convert scientific progress into effective epidemiological outcomes ([10]Barçante; Cherem, 2025, [11]Barçante; Cherem, 2024).

Given this context, the present study critically analyzes the operationalization of arbovirus surveillance and control policies in the Lavras microregion of Minas Gerais, Brazil, focusing on technical capacity, regional integration, and the adoption of innovative technologies. This investigation aims to determine the extent to which the formal surveillance framework, supported by plans, protocols, and public campaigns, results in practical efficacy, outlining pathways toward a predictive, integrated, and sustainable surveillance model consistent with the principles of One Health and international vector control recommendations.

2 MATERIALS AND METHODS

This study did not involve the collection of personal data from individuals. It was limited to the analysis of institutional and technical information regarding the organization and functioning of municipal health services, focusing exclusively on surveillance routines, planning, and implementation of arbovirus control actions. All procedures complied with the ethical principles established by the Brazilian National Health Council Resolutions No. 466/2012 and No. 510/2016.

2.1 STUDY AREA

The study was conducted in the microregion of Lavras, located in the southern part of the state of Minas Gerais, Brazil, at approximately 21°14'S and 44°59'W. The microregion comprises nine municipalities: Lavras, Nepomuceno, Carrancas, Ijaci, Ingaí, Itumirim, Itutinga, Luminárias and Ribeirão Vermelho. Lavras is the main urban and administrative center of the region, with an estimated population of 110,682 inhabitants in 2025 ([12]IBGE, 2025). Minas Gerais recorded the second highest incidence rate of dengue in Brazil in 2024 (7,778.1 cases per 100,000 inhabitants), surpassed only by the Federal District (9,316.7 cases per 100,000 inhabitants), according to data from the official Arbovirus Surveillance Dashboard of the Ministry of Health

(<https://www.gov.br/saude/pt-br/assuntos/saude-de-a-a-z/a/aedes-aegypti/monitorament>

[o-das-arboviroses](#)). The Lavras microregion was selected because it represents an important epidemiological setting for analyzing arbovirus control strategies in a state with one of the highest national burdens.

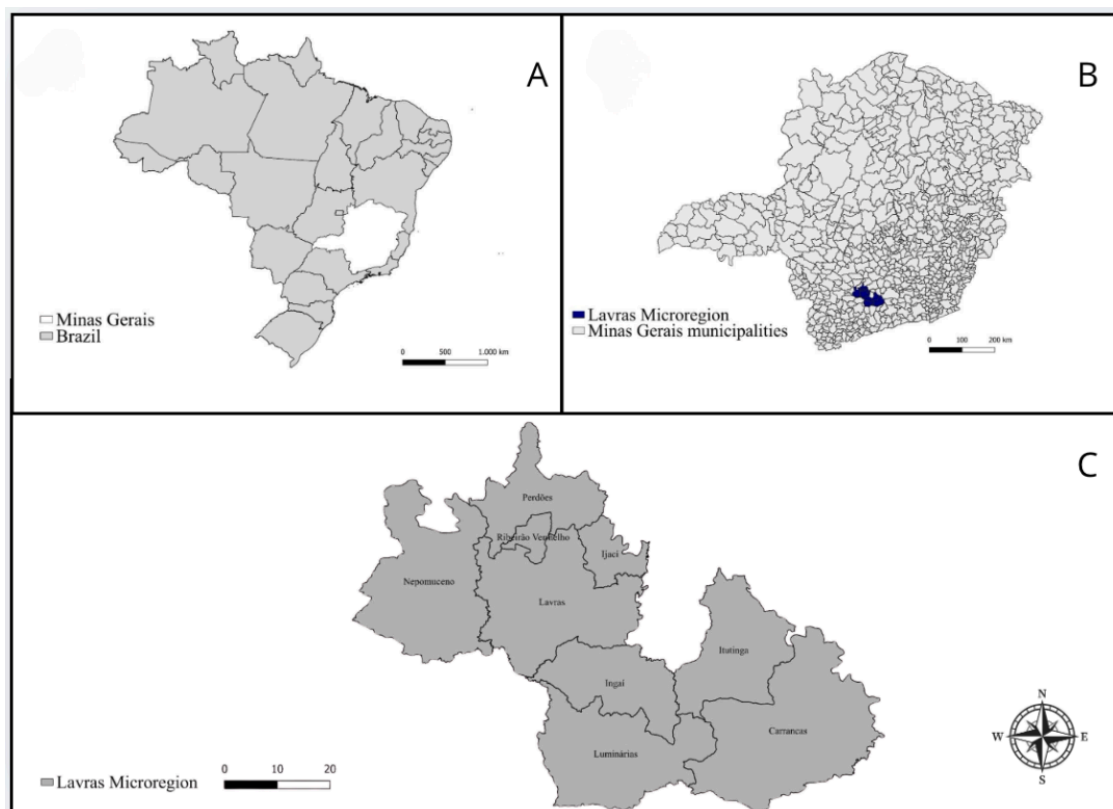


Figure 1. Location of the study area. (A) Map of Brazil highlighting the state of Minas Gerais. (B) Map of Minas Gerais highlighting the Lavras microregion. (C) Map of the Lavras microregion and its nine municipalities. Source: QGIS 3.44.

2.2 STUDY DESIGN

This was a cross-sectional, descriptive and exploratory study that employed a mixed-methods approach combining quantitative and qualitative analyses. Data were collected between September and October 2025.

2.3 POPULATION AND SAMPLING

The study included nine respondents, corresponding to municipal health managers and technical professionals responsible for epidemiological surveillance in the nine municipalities of the Lavras microregion. This represents a 100% response rate.

These professionals were selected because they are directly responsible for implementing prevention, monitoring and control actions for arboviral diseases at the local level, representing the most reliable source of information on the operationalization of the National Contingency Plan for Dengue, Chikungunya and Zika of the Brazilian Ministry of Health ([13]Ministério da Saúde, 2025). Participation was voluntary, and informed consent was implied through completion of the online questionnaire.

2.4 DATA COLLECTION INSTRUMENT

Data were collected using a structured questionnaire developed in Google Forms, based on the strategic axes of the National Contingency Plan for Dengue, Chikungunya and Zika ([7]Brasil, 2025b). The instrument included questions addressing: (i) the existence and publication of municipal contingency plans; (ii) the use of epidemiological monitoring tools; (iii) the implementation of entomological and laboratory surveillance, including RT-PCR and serology testing and partnerships with reference laboratories; (iv) risk communication strategies and countermeasures against health misinformation; and (v) intermunicipal cooperation mechanisms, with emphasis on the role of health consortia.

2.5 DATA ANALYSIS PROCEDURES

Responses were exported to Microsoft Excel (Version 2021, Microsoft Corporation, USA) and processed using descriptive statistics (absolute and relative frequencies). Qualitative responses were examined using thematic content analysis to identify operational patterns and perceptions regarding surveillance and control practices. Data validation included screening for duplicate or incomplete responses and cross-checking for consistency.

Findings were interpreted in light of the official recommendations of the Brazilian Ministry of Health and contextualized within the current epidemiological scenario in Brazil and the Americas, characterized by a sharp increase in dengue incidence and the concurrent emergence of Oropouche virus infections. The analytical framework was informed by the operational axes of the National Contingency Plan and aligned with the World Health Organization Integrated Vector Management (IVM) guidelines ([14]WHO, 2020).

3 RESULTS AND DISCUSSION

It is well established that the distribution of the dengue virus is expanding globally; however, how the emergence and spread of dengue cases are shaped by local determinants remains poorly understood ([6]Gibb *et al.*, 2023). In this context, the Lavras microregion, located in southern Minas Gerais, Brazil, represents a suitable setting for analyzing the dynamics of arbovirus surveillance and control. Comprising nine municipalities of varying sizes, ranging from 2,632 inhabitants in Ingaí to 110,682 in Lavras, the region reflects, on a smaller scale, the same contrasts that characterize the national panorama. Within this microregion, some cities maintain well-established epidemiological surveillance structures, while others remain dependent on sporadic and reactive control actions (Table 1).

This territorial mosaic clearly illustrates how the guidelines established in national contingency plans are reinterpreted and operationalized at the local level, especially under conditions of high epidemiological pressure and limited resources. The observed heterogeneity mirrors Brazil's structural disparities in infrastructure, sanitation, and technical capacity across municipalities ([7]Brasil, 2025b; [15]Brasil, 2025d; [16]Cerqueira-Silva, 2025).

Table 1. Relationship between population size, Community Health Workers (CHW), and Endemic Disease Control Agents (ACE) in the nine municipalities of the Lavras microregion, Minas Gerais, Brazil, 2025.

	Inhabitants *	Inhabitants **	CHW ***	Inhabitants/ CHW	ACE ****	Inhabitants/ ACE
Perdões	21,384	22,075	60	368	11	2,007
Itumirim	6,638	6,876	16	430	6	1,146
Ingaí	2,58	2,632	9	292	3	877
Itutinga	4,217	4,366	10	437	4	1,092
Nepomuceno	25,018	25,757	29	888	14	1,840
Carrancas	4,049	4,161	10	416	3	1,387
Ijací	7,003	7,358	-	-	3	2,453
Ribeirão Vermelho	4,08	4,217	9	469	4	1,054
Lavras	104,761	110,682	112	988	75	1,476
Mean	19,97	20,903	31.9	536	13.7	1,481
SD*****	32,824	34,698	36.8	255.3	23.3	520.7
Minimum	2,58	2,632	9	292	3	877
Maximum	104,761	110,682	112	988	75	2,453

*Data from the 2022 IBGE Census

**IBGE estimate for 2025

***Community Health Workers (CHW)

****Endemic Disease Control Agents (ACE)

*****Standard deviation (SD)

3.1 The existence and publication of municipal contingency plans

All municipalities included in the study reported having an active and formally published contingency plan. However, analysis of the responses revealed substantial heterogeneity in the operationalization of the planned actions, despite the universal existence of such documents. This paradox highlights a disconnection between the

normative framework and practical implementation, indicating that the mere existence of a plan does not ensure its effectiveness. This pattern is recurrent in Brazilian public health, where planning instruments often fulfill a formal requirement but fail to translate into consistent local response strategies ([17]Faria *et al.*, 2023).

3.2 The use of epidemiological monitoring tools

Among the most critical findings was the uneven performance of municipal epidemiological surveillance. Although 88.9% of municipalities reported conducting routine monitoring of epidemic curves (Figure 2), 33.3% did not use the control diagram (Figure 3), an essential tool for early outbreak detection and evidence-based decision-making. The absence of this instrument compromises local analytical capacity and prevents the transformation of raw data into actionable epidemiological information, limiting the timeliness and effectiveness of responses to emerging events ([18]Schuab *et al.*, 2024).

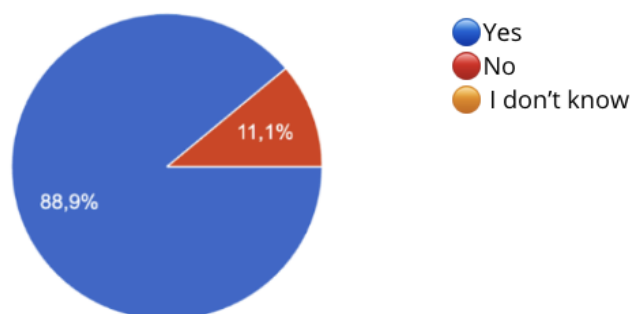


Figure 2. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the routine use of epidemic curves to monitor trends.

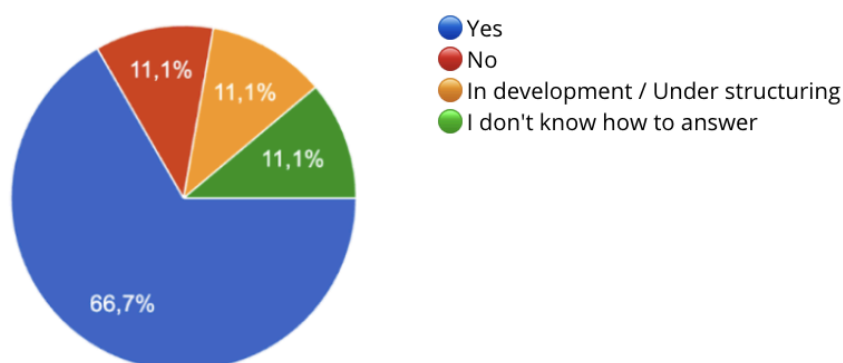


Figure 3. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the use of control diagrams for monitoring arboviral cases.

Another indicator of institutional fragility concerns the existence of situation rooms: only 55.6% of the municipalities reported having such a structure (Figure 4). This absence represents not only a deficit in analytical infrastructure but also an obstacle to the integrated management of information, which is essential in contexts of rapid viral dissemination.

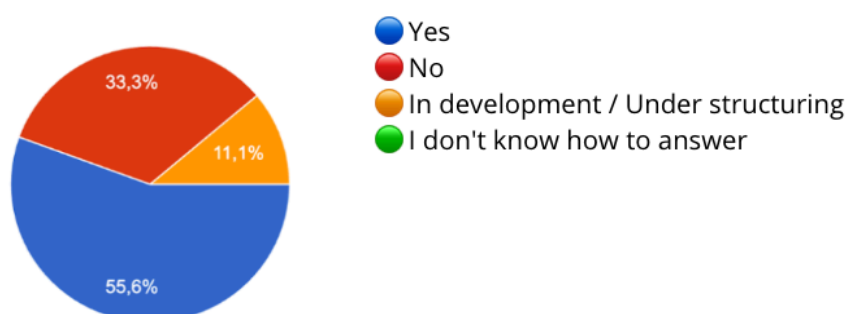


Figure 4. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the existence of a health situation room for arbovirus monitoring.

Qualitative analysis of the responses suggests two non-exclusive hypotheses. First, some managers appear to confuse empirical practices of monitoring case notifications with the standardized use of official surveillance tools. Second, there remains a technical and methodological training gap that results in perceptions not aligned with established practice. This scenario reinforces the existence of fragmented normative knowledge in which managers understand legal and procedural requirements but struggle to apply them operationally.

This condition reveals a key point: municipal health services possess a certain level of theoretical knowledge about surveillance obligations but fail to fully translate it into practice. This statement reinforces that, although national contingency plans are essential as guiding frameworks, they do not guarantee local implementation or the sustainability of actions against arboviruses ([19] Aguilar *et al.*, 2025).

Overall, the results demonstrate that the challenges for implementing the National Contingency Plan for Dengue, Chikungunya and Zika ([7]Brasil, 2025b) go beyond technical barriers and reflect structural and organizational issues within municipal surveillance systems. The consolidation of integrated strategies that combine intelligent monitoring tools, continuous technical training and intermunicipal institutional support emerges as an indispensable condition for the plan to fulfill its role of promoting a coordinated, sustainable and evidence-based response.

3.3 The implementation of entomological and laboratory surveillance, including RT-PCR and serology testing and partnerships with reference laboratories

Data obtained from the questionnaire (Figures 5, 6 and 7) reveal significant advances in the diagnostic infrastructure for arboviruses in the Lavras microregion. According to the results, 77.8% of municipalities reported having an established diagnostic flow with the Central Public Health Laboratory (LACEN), 88.9% perform routine serological surveillance and 77.8% reported some type of partnership or genomic surveillance activity. Although these percentages indicate stronger integration with the state laboratory network, this perception of progress must be analyzed through two complementary dimensions: the expansion of laboratory infrastructure during the COVID-19 pandemic and the still incipient incorporation of molecular surveillance of arboviruses at the municipal level.

During the COVID-19 health emergency, Brazil experienced an unprecedented structural and technological leap. Federal and state financial investments in universities, public laboratories and reference hospitals enabled the widespread dissemination of RT-qPCR platforms, genetic sequencing technologies and bioinformatics tools, strengthening the diagnostic capacity of the Unified Health System (SUS) to an unprecedented level ([20]Barberia *et al.*, 2023). However, this infrastructure has not been fully converted into permanent routines for arbovirus diagnosis, where immunochromatographic and serological tests still predominate. Although these methods are practical and fast, they have limited sensitivity and a reduced capacity for early detection of new serotypes or viral lineages.

Recent studies indicate that, although Brazil has initiated the incorporation of genomic surveillance for arboviruses, this implementation remains incipient and concentrated in reference centers, with limited reach within municipal health networks

([21]Jesus *et al.*, 2024). Therefore, what is observed is a conceptual and perceptual advance greater than a practical one, marking a transitional stage between the recognition of genomics' importance and its effective institutionalization within surveillance processes.

Even so, this movement represents a paradigmatic milestone. The pandemic consolidated the understanding that genomics can and should be integrated into the epidemiological surveillance of emerging and re-emerging viruses, as demonstrated by the creation of cooperative sequencing and bioinformatics networks such as Rede Corona-Ômica BR and Fiocruz Genômica, which enabled real-time tracking of SARS-CoV-2 variants ([22]Sena *et al.*, 2024). This model of integration between science and public service established technical and institutional precedents that can be adapted for monitoring arboviruses, particularly Dengue virus (DENV), Zika virus (ZIKV), Chikungunya virus (CHIKV) and Oropouche virus (OROV).

In this context, the responses of municipal managers should not be interpreted solely as performance indicators but as evidence of a cultural and cognitive shift in health surveillance management. The recognition of genomic surveillance as a strategic tool reflects the institutional and scientific maturity that emerged from the pandemic experience. However, to translate this change into tangible results, it is essential to establish hybrid diagnostic workflows that integrate rapid screening tests, confirmatory RT-qPCR, and sample-based genetic sequencing within a networked and feedback-oriented structure linking local, regional and reference laboratories.

The central challenge, therefore, lies in converting the installed technical potential into sustained and decentralized practice by overcoming barriers related to human resources, funding and interinstitutional coordination. Only through such integration will it be possible to enhance diagnostic accuracy, strengthen viral traceability and enable early detection of outbreaks and emerging mutations of arboviruses in Brazil.

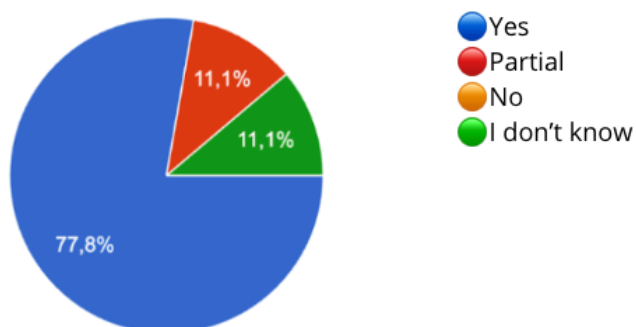


Figure 5. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the existence of a consolidated diagnostic flow with the Central Public Health Laboratory (LACEN) for RT-PCR, serology, and NS1 antigen testing.

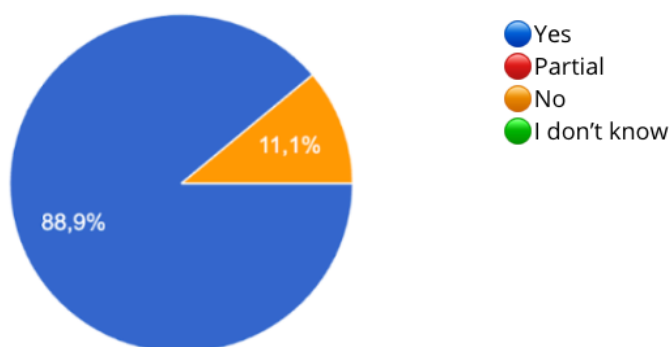


Figure 6. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the use of serological surveillance to monitor viral circulation.

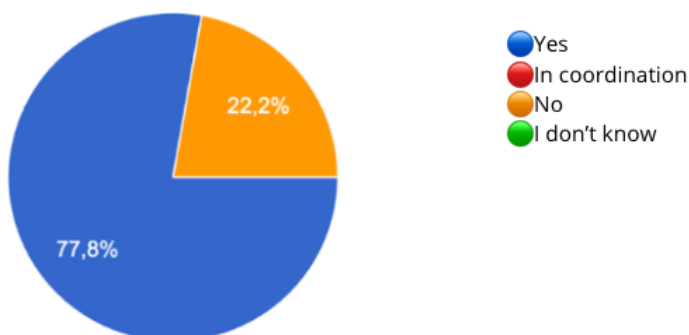


Figure 7. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding genomic surveillance activities (sequencing or partnerships with reference centers).

The questionnaire results indicate that 100% of the municipalities in the microregion regularly conduct the Rapid *A. aegypti* Index Survey (LIRAA/LIA), demonstrating the consolidation of this methodology as a central pillar of vector surveillance. However, only 44.4% reported the use of ovitraps or larvitrap (Figure 8), revealing significant gaps in the adoption of complementary tools for early detection of breeding sites and estimation of the density of ovipositing females, a key variable for predictive action planning and improvement of entomological control strategies.

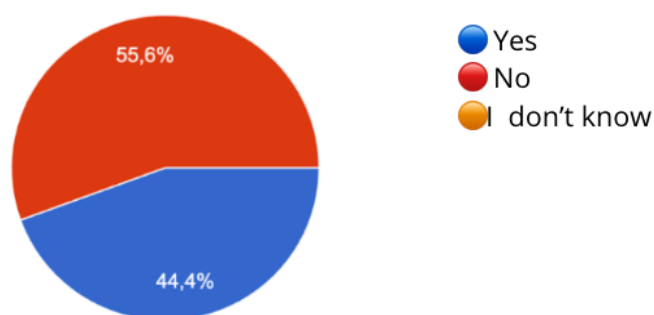


Figure 8. Percentage of municipalities in the Lavras microregion, Minas Gerais, Brazil, that use ovitraps or larvitrap for *Aedes aegypti* surveillance.

Regarding indoor residual spraying (IRS), 44% of the municipalities reported performing this activity, 33.3% stated that it was not applied in special premises (Figure 9), and 22% reported being either unaware of or in the process of implementing it. This scenario highlights the heterogeneity in the adoption of complementary vector control methodologies, reflecting both structural limitations and the diversity of interpretations concerning the applicability and effectiveness of blocking strategies.

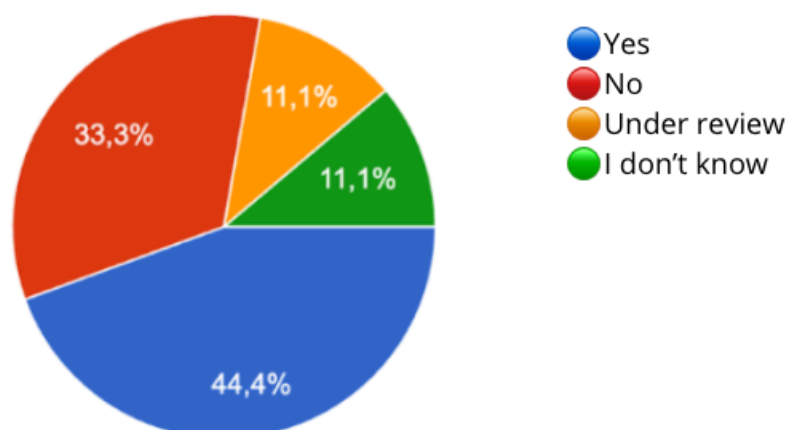


Figure 9. Percentage distribution of responses from municipalities in the Lavras microregion, Minas Gerais, Brazil, regarding the implementation of indoor residual spraying (IRS) and its application in special premises.

In contrast, 100% of the municipalities reported performing control activities in strategic locations such as cemeteries, tire repair shops, and junkyards, which are historically recognized as high-productivity breeding sites of epidemiological relevance for maintaining viral circulation. These results confirm the persistence of traditional practices consolidated over past decades that still represent an indispensable component of vector control ([23]Rodrigues *et al.*, 2023).

Although classical tools such as LIRAA and ovitraps are widely validated in the literature as effective methods for entomological surveillance and outbreak prediction, their effectiveness depends directly on methodological standardization, regular data collection, and qualified technical interpretation of the resulting indices ([24]Vieira *et al.*, 2023). In the analyzed context, the consolidation of LIRAA contrasts with the limited use of ovitraps, which compromises the ability to anticipate increases in infestation levels and, consequently, to implement timely preventive measures.

Open-ended responses from the questionnaire reinforced the presence of structural and operational barriers in the execution of entomological activities. The most frequent statements included “lack of trained personnel,” “shortage of human and financial resources,” “administrative bureaucracy,” and “high service demand with reduced teams” (Source: Questionnaire applied to municipalities of the Lavras microregion, 2025). These reports indicate chronic shortages of personnel and funding,

as well as management bottlenecks that hinder the operationalization of available tools. This finding aligns with national studies identifying insufficiently qualified professionals and low investment in continuous training as persistent barriers to the effectiveness of vector surveillance ([25]Macêdo *et al.*, 2024).

An integrated reading of the results reinforces that confronting arboviruses requires shared responsibility among managers, technical teams, and the community. The questionnaire highlights recurrent challenges such as “lack of information or inaccurate information about dengue and its prevention, generating mistrust regarding vaccination and control measures,” and “low community engagement and difficulties in accessing technologies” (Source: Questionnaire applied to municipalities of the Lavras microregion, 2025). These perceptions indicate that information deficits and the gap between public authorities and communities limit the effectiveness of traditional vector-control actions, emphasizing the need for integrated communication and health education strategies.

Thus, while the role of Endemic Disease Control Agents remains essential, overcoming contemporary challenges requires a more structured and innovative approach. Strengthening entomological surveillance depends not only on increasing personnel but also on incorporating digital technologies, process automation, and continuous technical training to optimize response times and expand field operations. Maintaining models centered exclusively on workforce expansion represents a traditional, low-resolutivity, and unsustainable long-term approach.

In this regard, it is imperative to modernize entomological routines by integrating digital information systems and emerging technologies based on Artificial Intelligence (AI). Predictive models fed by spatial, temporal, climatic, environmental, and sociodemographic data enable more precise forecasting of infestation patterns and epidemiological risk, transforming surveillance from reactive to proactive ([26]Chen; Moraga, 2025). This paradigm shift enhances the analytical robustness of control actions, optimizes resource allocation, and anticipates critical scenarios, thereby strengthening the capacity of municipalities to respond to outbreaks before they reach epidemic proportions.

Analysis presented in Table 1 shows considerable heterogeneity among the nine municipalities of the Lavras microregion, Minas Gerais, regarding the ratio between inhabitants, Community Health Workers (CHW), and Endemic Disease Control Agents (ACE). Only four municipalities, Perdões, Itumirim, Ingaí, and Itutinga, present a

population-to-CHW ratio below 750, thus complying with the maximum limit established by Ordinance No. 2.436/2017 of the Ministry of Health, which recommends coverage of up to 750 people per CHW and 100% population coverage by the Family Health Strategy. In contrast, municipalities such as Nepomuceno (888 inhabitants per CHW) and Lavras (988 inhabitants per CHW) demonstrate an undersupply of professionals, which may negatively affect home visits and the resolution capacity of Primary Health Care. It is noteworthy that the municipality of Ijaci did not report CHW data, indicating a possible gap in population coverage.

Regarding ACEs, the average observed proportion was one agent for every 1,481 inhabitants, with significant variation across municipalities, ranging from 1:877 in Ingaí to 1:2,453 in Ijaci. This disparity underscores the absence of a fixed national standard for determining the number of ACEs, which is defined by local managers based on epidemiological profile, population density and territory, and socioeconomic conditions.

The overall average for the microregion indicates the presence of approximately one CHW for every 536 inhabitants and one ACE for every 1,481 inhabitants. These values generally reflect satisfactory coverage in Primary Health Care but indicate deficiencies in Health Surveillance activities, particularly in municipalities with larger populations.

Such discrepancies suggest the need for more equitable planning in workforce distribution, as well as strategies for integrating CHWs and ACEs. This integration could optimize the available human resources and strengthen territorial surveillance and health promotion activities, particularly in areas at risk for arboviruses and other vector-borne diseases.

Addressing arboviruses, particularly dengue, requires a strategic transition from the traditional vector-control model to an intelligent, integrated, and predictive framework grounded in the principles of One Health. Only through coordinated action among government authorities, the scientific community, and civil society will it be possible to build sustainable and effective responses to the intensification and geographic expansion of arboviruses in Brazil.

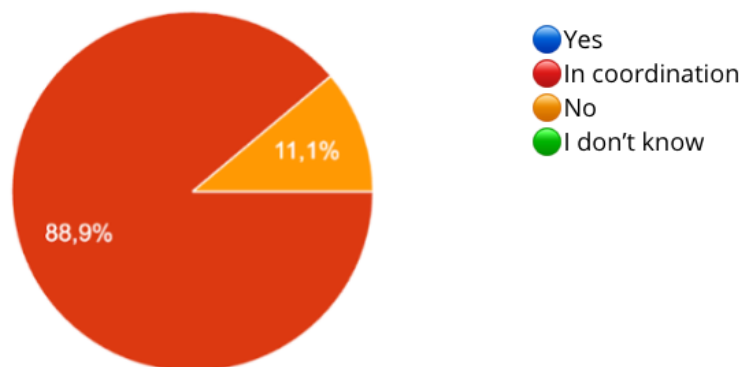


Figure 10. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the use of or partnerships established for the release of *Aedes aegypti* mosquitoes infected with *Wolbachia*.

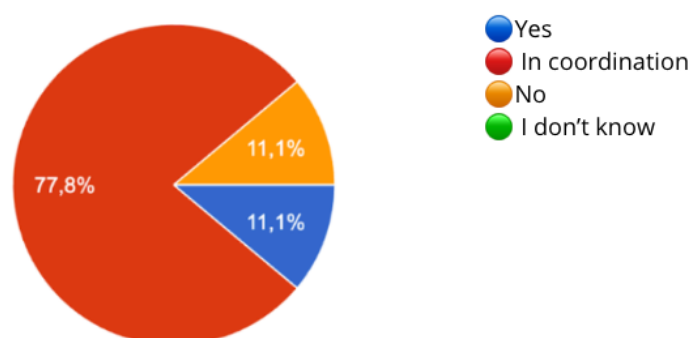


Figure 11. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the implementation or evaluation of the Sterile Insect Technique (SIT) using sterile *Aedes aegypti* mosquitoes.

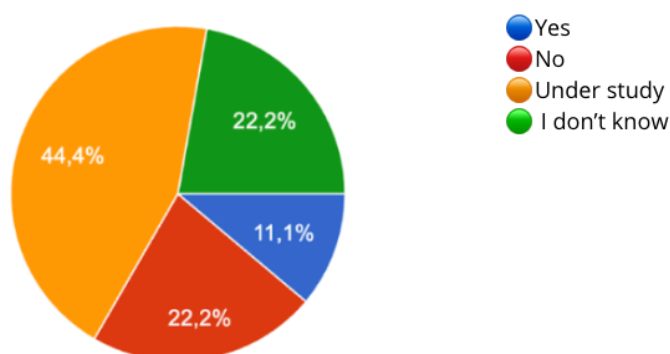


Figure 12. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the implementation or intention to establish larvicide dissemination stations.

This gap reveals the distance between conceptual knowledge and the practical application of innovations, reinforcing the still experimental nature of these strategies at the municipal level. Such a mismatch is not exclusive to this microregion. Recent reviews have noted that although the *Wolbachia* method has demonstrated proven efficacy, its large-scale expansion remains limited by institutional, regulatory, and political barriers that hinder its full incorporation into surveillance programs ([27]Zimmermann *et al.*, 2024; [28]Rahul *et al.*, 2024).

Even in the National Guidelines for the Prevention and Control of Urban Arboviruses: Entomological Surveillance and Vector Control ([15]Brasil, 2025d), the Brazilian Ministry of Health acknowledges that structural and operational adjustments are needed to integrate local experiences, indicating that the problem is not merely technical but systemic. At the local level, initiatives such as those led by the Oswaldo Cruz Foundation (FIOCRUZ), which organized the workshop “Social Sciences in the Face of Arboviruses” in September 2025, highlight that the sustainability of these innovations depends not only on the technology itself but also on governance structures that ensure continuous funding, technical support, and intersectoral coordination ([29]FIOCRUZ, 2025). Therefore, more than disseminating new tools, the contemporary challenge lies in institutionalizing innovation and transforming experimental results into lasting and equitable public policies.

The introduction of *Wolbachia* into *A. aegypti* populations has, in multiple studies, shown reductions exceeding 70% in dengue incidence by limiting viral replication and reducing vector competence ([30]Hoffmann *et al.*, 2011; [31]Ryan *et al.*, 2020). Subsequent studies reinforce this evidence. In Niterói, Brazil, the release of mosquitoes carrying *Wolbachia* was associated with a 69% reduction in reported dengue cases, and recent longitudinal analyses demonstrate sustained epidemiological impacts ([32]Anders *et al.*, 2025). In Townsville, Australia, models indicate a 65% reduction during the release period and over 95% within 24 months afterward ([33]Ogunlade *et al.*, 2023). These results strengthen the robustness of the approach, suggesting that in complex urban environments, *Wolbachia* provides a scalable and durable intervention, provided that it is supported by integrated surveillance and institutional commitment.

However, as revealed by open-ended responses in the questionnaire, the central limitation does not stem from a lack of scientific evidence but from technological and operational barriers to implementation. Respondents highlighted issues such as “lack of information and technical training on new technologies,” “excessive bureaucracy and lack of investment,” “shortage of skilled labor and maintenance resources,” and “difficulty in accessing technologies and obtaining community engagement.” These statements demonstrate that the current challenge is not merely increasing the number of endemic disease control agents but rather qualifying and equipping existing teams with technological tools, continuous training, and institutional support to enable the sustainable adoption of innovative practices.

This finding aligns with recent analyses of the determinants of arbovirus expansion in the Americas. Studies indicate that the proliferation of *A. aegypti* in urban environments results from predominantly reactive and episodic responses, lacking institutional continuity and effective territorial coordination among municipal, state, and federal levels. In addition, environmental factors and the absence of integrated solid waste management amplify vector persistence, creating a context in which innovative policies become ineffective when disconnected from environmental management and basic sanitation ([10]Barçante; Cherem, 2025).

These analyses reinforce that vector control requires intersectoral and executive plans that combine scientific innovation, entomological surveillance, and environmental governance under strengthened and continuous regional coordination, in order to translate technological advances into sustainable and equitable public health outcomes ([11]Barçante; Cherem, 2024).

The interpretative divergence between “absence of a plan” and “existence of a plan that is not executed” is, in reality, an expression of the same phenomenon: the misalignment between normative formulation and practical execution. Although Brazil possesses well-recognized national frameworks, such as the National Dengue Control Program (PNCD) and the National Contingency Plan for Dengue, Chikungunya, and Zika ([7]Brasil, 2025b), their implementation lacks effective regionalization, measurable goals, and intergovernmental coordination. Therefore, what is observed is not an absence of plans but rather a lack of pragmatic, executable, and territorially adapted plans with clear performance indicators and sustained funding streams. The heterogeneity of municipal results, demonstrated by the questionnaire and particularly by Figure 12 concerning larvicide dissemination stations, clearly confirms this gap:

each city adapts its actions according to its own constraints, generating a mosaic of fragmented and inefficient strategies.

Hence, the central problem does not lie in the formal design of public policies but in their operational transposition, often hindered by political, budgetary, and administrative obstacles that limit the continuity and scalability of actions. Overcoming this impasse requires the institutionalization of programmed action plans with regional timelines, defined coverage targets, results-based financing, and technically transparent governance. Only under these conditions will it be possible to convert technological potential into measurable epidemiological impact, breaking the historical cycle of fragmented reactivity and establishing proactive, coordinated, and sustainable entomological surveillance, an indispensable condition to contain the exponential spread of arboviruses in the coming decades.

It is no longer acceptable for the country to remain bound to theoretical and normative plans or for new technologies to appear only in reports and guidelines without effective implementation. The persistent institutional fragmentation, expressed through municipal heterogeneity and discontinuity of actions, translates year after year into the reproduction of a critical and predictable epidemiological scenario in which the absence of integration and operational planning negates the gains achieved in scientific and technological fields.

3.4 Risk communication strategies and countermeasures against health misinformation

The results show that the microregion demonstrates strong formal technical capacity. A total of 66.6% of the municipalities reported holding regular technical update meetings (Figure 13), and 100% confirmed the existence of current clinical and classification protocols. However, this structure reflects a reactive system, one more prepared to respond to crises than to prevent them. This historically consolidated pattern in arbovirus control demonstrates that technical knowledge exists but functions reactively in response to system collapse rather than proactively for prevention.

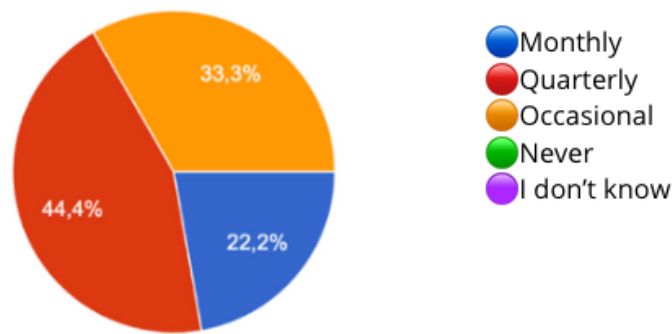


Figure 13. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the frequency of technical meetings on arboviruses held in the previous year (2024).

The direct consequence of this logic is predictive inefficiency. When epidemiological surveillance and primary health care remain anchored in episodic and fragmented responses, they lose the capacity to anticipate outbreaks and contain the escalation of arboviral transmission. The transmission dynamic operates under a continuous feedback model: structural failures in surveillance and control increase vector density, and rising vector density in turn expands the number of infected individuals, perpetuating an active viral cycle ([34]Villela, 2025). This process is reflected in the Lavras microregion, where institutional structures and endemic disease control agents are in place, yet the absence of technical standardization and operational integration prevents the system from translating its formal structure into preventive effectiveness. Breaking this kinetic transmission pattern requires the application of new statistical models ([35]Freitas *et al.*, 2025).

At the environmental level, unplanned urbanization and inadequate solid waste management expand the ecological niche of the vector, reinforcing feedback loops and the permissive nature of entomological conditions. Classical and recent studies have shown that *A. aegypti* readily adapts to domestic and peridomestic microhabitats such as plastic containers, water tanks, and small storage vessels, which explains the persistence of breeding sites even in areas under regular surveillance coverage ([36]Zara *et al.*, 2016). [37]Cherem *et al.* (2024) demonstrated that *A. aegypti* eggs desiccated for eight months and later exposed to natural water stored in plastic containers exhibited larval hatching within only four hours. This finding highlights the epidemiological role of environmental plastic waste as persistent and highly resilient micro-breeding sites

capable of maintaining vector viability even during extended dry periods. These results reinforce the hypothesis that urban plastic pollution acts as an indirect vector in sustaining arbovirus transmission, maintaining viral circulation in environments seemingly unfavorable for mosquito reproduction.

The challenge, therefore, goes beyond the technical dimension of tools and lies in effectively translating knowledge into operational practice. This requires continuous technical training for municipal teams, the consolidation of standardized and interoperable territorial databases, and the institutionalization of integrated predictive surveillance that combines climatic, genomic, and entomological data within an intersectoral framework ([26]Chen; Moraga, 2025). Breaking the historical cycle of reactivity that has characterized arbovirus control in Brazil for decades demands stable interinstitutional planning, independent technical governance, and results-based funding. Only under these conditions will it be possible to transform technological potential into measurable epidemiological impact, replacing delayed reaction with strategic anticipation, the cornerstone of truly integrated surveillance under the One Health paradigm ([4]PAHO, 2025b).

Data indicate that 100% of the municipalities in the Lavras microregion, Minas Gerais, Brazil, have formally established referral and counter-referral flows for managing severe cases, which in principle suggests an organized care network. However, this documentary uniformity does not translate into operational effectiveness. The normative structure exists, but the real capacity to respond to clinical deterioration in patients remains limited.

Figure 14 reinforces this scenario, showing that although 66.7% of municipal representatives reported that PHC teams are fully capable of identifying dengue warning signs, 33.3% stated that this ability is only partial. This gap reveals that even with formalized referral flows, deficiencies persist in team qualification and integration, undermining early case detection and timely action along the continuum of care.

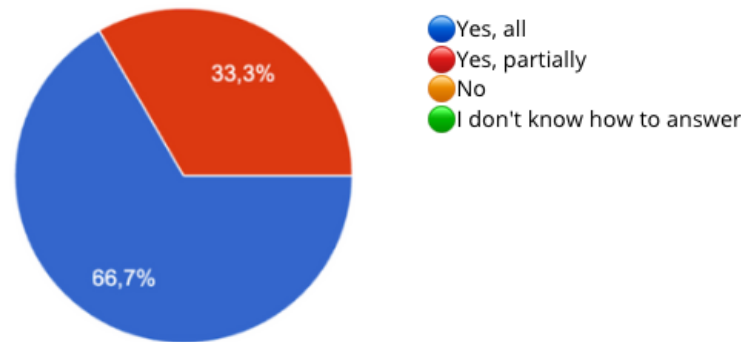


Figure 14. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the capacity of Primary Health Care (PHC) teams to identify warning signs of dengue.

This discrepancy between the formal structure and the practical capacity of local teams highlights that the problem does not lie in the absence of protocols but in insufficient operational support, particularly regarding the availability of intensive care beds and the coordination among primary health care (PHC), epidemiological surveillance, and the hospital network. In contexts of service overload, the influx of severe dengue, Zika, chikungunya, or Oropouche cases often exceeds the installed capacity, exposing the historical deficit in hospital regionalization and the lack of effective contingency planning ([38] Sanabani, 2025; [11] Barçante; Cherem, 2024).

The lack of integration between epidemiological surveillance, PHC, and the hospital network, further aggravated by the emergence of new arboviruses such as Oropouche, reveals the systemic fragility of a care model that still fails to anticipate and mitigate predictable crises, perpetuating inequalities in access and the quality of healthcare responses ([11] Barçante; Cherem, 2024; Castro-Nunes *et al.*, 2024).

Data show that informational campaigns were maintained in 100% of the municipalities in the microregion, and 66.7% still conduct community mobilization activities through schools, churches, and local leaderships (Figures 15 and 16). At first glance, this might indicate a consolidated health communication system. However, longitudinal analysis reveals that despite the persistence of campaigns, their practical impact on reducing vector indices and promoting behavioral change has declined over the years.

During the 1990s and 2000s, educational campaigns such as the emblematic “10 Minutes Against *Aedes*” program had a strong mobilizing effect, driven by a collective sense of urgency and institutional enthusiasm for vector eradication, as

proposed by Brazil's *Aedes aegypti* Eradication Program ([40] Brasil, 2002). These strategies, heavily supported by mass communication, were considered the cornerstone of urban vector control, grounded in the belief that information and community mobilization would suffice to curb dengue expansion. Yet, by 2006, the lack of objective results had already become evident ([41] Barreto *et al.*, 2006).

Health communication campaigns targeting dengue control, traditionally based on repetitive, nationwide messages, have begun to show clear signs of communicational fatigue. The uniformity of content, the repetition of slogans, and the absence of adaptation to regional specificities have reduced community engagement and behavioral change capacity. Recent studies indicate that the public has become desensitized to media discourse, underscoring the need for segmented and territorially contextualized messages that value the social and cultural diversity of exposed populations ([42] Lin *et al.*, 2025).

The weakening of mass campaign impact becomes even more evident amid the heterogeneity of dengue transmission patterns in Brazil. The literature demonstrates that the effectiveness of communication actions strongly depends on local conditions such as the degree of urbanization, population density, sanitation infrastructure, and municipal response capacity. Thus, maintaining generic and decontextualized strategies limits the scope of educational and vector control actions, rendering them insufficient to address the epidemiological particularities of each territory ([43] Almeida *et al.*, 2025; [44] Gurgel-Gonçalves *et al.*, 2024).

Overcoming this limitation requires the incorporation of remote monitoring technologies, georeferencing, and artificial intelligence to link communication with technical outcomes. Only the convergence of transparency, innovation, territorial proximity, and tangible results can restore public trust and consolidate effective social participation in combating arboviral diseases, transforming the community mobilization model from reactive and informative to participatory, integrated, and evidence-based.

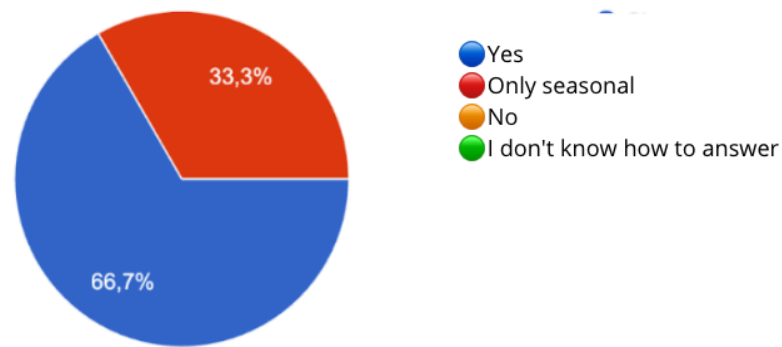


Figure 15. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the implementation of continuous local educational campaigns on arboviruses.

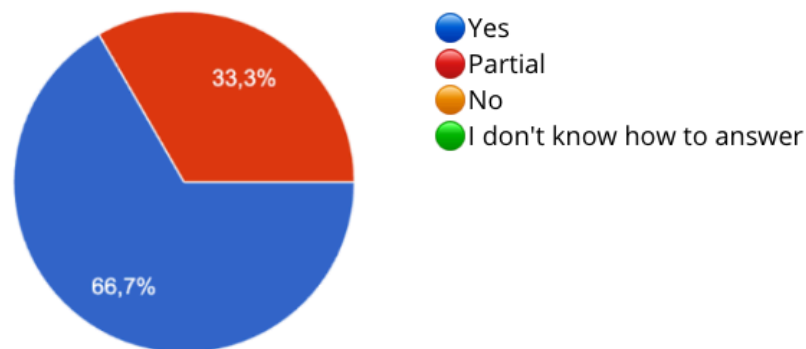


Figure 16. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the development of community mobilization activities through schools, churches, and community Leaders.

3.5 Intermunicipal cooperation mechanisms, with emphasis on the role of health consortia.

All municipalities in the Lavras microregion, Minas Gerais, Brazil, representing 100% of respondents, reported participation in at least one intermunicipal consortium. At first glance, this universal adherence to consortia could suggest a consolidated and cooperative regional arrangement. However, only 44.4% of respondents stated that their consortia are actively involved in arbovirus-related activities (Figure 17), while 11.1% reported that they are not, 11.1% indicated that actions are “under negotiation,” and 33.3% were unable to answer.

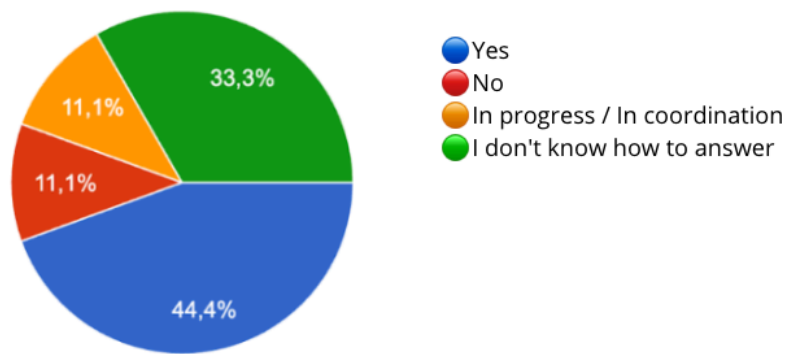


Figure 17. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the involvement of intermunicipal health consortia in arbovirus-related activities.

A similar trend is observed when examining specific actions for the control of dengue, Zika, chikungunya, and Oropouche: only 22.2% confirmed the existence of such initiatives, 33.3% denied them, and 44.4% reported having no information (Figure 18).

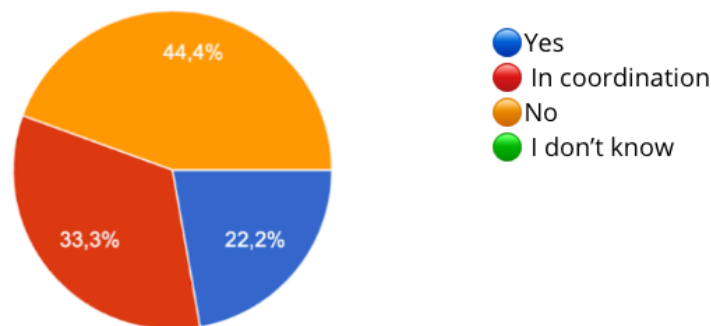


Figure 18. Percentage distribution of responses from representatives of the nine municipalities comprising the Lavras microregion, Minas Gerais, Brazil, regarding the development of specific actions for the control of arboviruses (dengue, Zika, chikungunya, Oropouche).

These results reveal institutional communication fragility and a disconnection between decision-making and operational levels. The consortium structure, originally designed to strengthen collective efforts and optimize resource allocation, has been largely confined to administrative functions, restricted to the purchase of supplies, personal protective equipment, laboratory tests, and medical devices. Although

necessary, these activities remain reactive and poorly coordinated, failing to promote joint and continuous epidemiological surveillance planning. As a result, consortia have assumed a predominantly bureaucratic role, reproducing at the horizontal level the same patterns of fragmentation and verticalization that characterize Brazil's traditional health management structure.

Analysis of the open-ended responses reinforces this diagnosis. Expressions such as “we have no plan,” “I do not know,” and “I have no information” appear repeatedly, indicating the absence of communication flows between regional and local levels and a clear gap in transparency and technical coordination. This reality demonstrates that, despite formal integration on paper, consortium-level decisions rarely translate into effective actions at the municipal level. The cooperation model, therefore, exists in theory but not in the daily practice of surveillance.

This scenario reflects a narrow and essentially reactive vision aligned with national trends, one that treats diseases in isolation while disregarding the broader environmental, social, and ecological factors sustaining vector dynamics. Instead of an integrated surveillance system, what emerges is a sum of fragmented efforts: municipalities repeating similar campaigns with differing schedules and indicators and lacking intermunicipal coordination. The result is resource waste, redundancy of actions, and the persistence of structural vulnerabilities, particularly in rural-urban interface and peri-urban areas where vector circulation intensifies.

An integrated reading of these data reveals that the problem does not lie in the absence of consortia but in their systemic inoperability regarding arbovirus control and the lack of cross-sectoral coordination among involved areas. These consortia lack shared technical structures, joint governance instruments, and permanent monitoring mechanisms capable of ensuring administrative continuity and territorial integration. The absence of intersectoral hubs bringing together health, environment, and sanitation under a unified planning framework prevents the establishment of regional networks for integrated surveillance, maintaining fragmentation across management levels.

This situation has been widely discussed in recent publications, which highlight that One Health governance in Brazil still operates in a compartmentalized manner, with overlapping competencies and the absence of effective collaborative mechanisms. As a result, although the consortium model is institutionally formalized, it reproduces the same fragmentation found at federal and state levels, perpetuating inefficient

poly-management in which different entities act in isolation without generating synergy or territorial continuity ([45]Wakimoto *et al.*, 2025).

Therefore, the collective evidence and analyses demonstrate that the current intermunicipal structure replicates the vertical fragmentation of the national health system at the regional scale. Consortia, conceived as cooperative mechanisms, have become parallel structures limited to procurement and resource transfer management, with little technical coordination capacity. Redundant efforts persist in some municipalities and are absent in others, revealing that integration without convergence produces only the appearance of cooperation.

Data obtained from the questionnaire show that dengue vaccination (Qdenga®) was fully implemented in all municipalities of the Lavras microregion, with 100% adherence to immunization among the priority groups established by the National Immunization Program (PNI). This finding reinforces the organizational capacity of Brazil's Unified Health System (SUS) and the solidity of its decentralized practices in surveillance and prevention, reflecting the effectiveness of vaccination policy as an instrument of collective health.

The wide coverage observed reflects the capillarity of the SUS, built over decades through the structuring of municipal primary care networks and the consolidation of Primary Health Care as the coordinating axis of care. This robust network, present throughout almost the entire national territory, includes more than 38,000 vaccination rooms, ensuring vaccine access even in sparsely populated regions and guaranteeing equity in the distribution of immunobiologicals. Such capillarity is one of the pillars supporting the national response to emerging arboviruses, demonstrating the critical role of public health infrastructure in collective protection and the maintenance of population immunity ([46]Brasil, 2024e).

Therefore, the full implementation of Qdenga® vaccination in the microregion demonstrates not only the logistical and technical efficiency of municipal systems but also the sociopolitical maturity of the SUS and its ability to translate national guidelines into tangible results at the local level.

4. LIMITATIONS OF THE STUDY

This study has some limitations that should be acknowledged. The analysis was based on data obtained from nine municipalities in the Lavras microregion, which,

although representative of regional diversity, restricts the generalization of results to broader contexts. Additionally, the use of self-reported questionnaires may introduce information bias, as responses depend on the accuracy and perception of local managers. Nevertheless, these limitations do not compromise the validity of the findings, as the study provides valuable insights into the operationalization of arbovirus surveillance and control at the municipal level and contributes to the understanding of systemic challenges in decentralized health governance.

5. PRACTICAL RECOMMENDATIONS FOR STRENGTHENING MUNICIPAL ARBOVIRUS SURVEILLANCE

Based on the evidence gathered in this study, the following recommendations are proposed to enhance municipal and regional capacity in arbovirus surveillance and control:

1. **Integration of Workforce:** Promote functional integration between Community Health Workers (CHWs) and Endemic Disease Control Agents (ACEs) to optimize human resources and expand territorial coverage, particularly in peri-urban and high-risk areas.
2. **Consortium Strengthening:** Strengthen intermunicipal health consortia by creating shared technical units for entomological and genomic surveillance, enabling regional data harmonization and coordinated response.
3. **Intelligent Digital Surveillance Systems:** Adopt digital platforms enhanced with artificial intelligence (AI) and machine learning models capable of processing climatic, entomological, and epidemiological data in real time, generating automated alerts and predictive insights that accelerate outbreak detection and guide targeted control interventions.
4. **Continuous Capacity Building:** Institutionalize permanent training programs in predictive epidemiology, vector control technologies, and genomic surveillance for municipal teams.
5. **Community Engagement:** Redefine communication strategies using localized and participatory approaches, integrating schools, community leaders, and civil society organizations into preventive actions.
6. **Sustainable Financing:** Ensure stable funding mechanisms that link resource allocation to performance indicators, fostering accountability and long-term sustainability of control programs.

6. FINAL CONSIDERATIONS

The results indicate that municipalities in the Lavras microregion maintain a consolidated yet predominantly reactive structure, supported by contingency plans, endemic disease teams, and routine prevention campaigns, but with limited predictive capacity. Surveillance remains grounded in retrospective indicators and emergency responses rather than in continuous and analytical monitoring models. The limited use of digital tools such as drones, artificial intelligence systems, and interoperable platforms hampers the conversion of empirical data into actionable epidemiological intelligence, perpetuating the historical cycle of delayed responses to arboviruses.

Despite these constraints, the microregion presents favorable conditions for advancing toward intelligent surveillance. The consolidation of laboratory workflows with LACEN, the expansion of genomic monitoring, and the full implementation of dengue vaccination (Qdenga®) establish a robust technical foundation for modernization. Although still in an early phase, these initiatives represent meaningful progress in confronting a persistent and multifactorial epidemiological challenge. Within this framework, machine learning emerges as a strategic tool to integrate entomological, laboratory, climatic, and social variables, enabling early forecasting and evidence-based decision-making.

The Lavras microregion reflects, on a smaller scale, Brazil's broader structural reality, marked by the coexistence of technologically advanced areas and others still dependent on manual operations. Existing surveillance tools and technologies often function in isolation, without effective interoperability or data exchange, preventing the creation of a coordinated response network. This institutional and technological disconnect reveals that the core challenge lies not in resource scarcity but in the lack of integration across systems, sectors, and management levels. At the national scale, this pattern mirrors Brazil's longstanding difficulty in aligning policies, information, and technologies within a cohesive framework, delaying the consolidation of intelligent and interconnected surveillance.

Consequently, the microregion illustrates, at the local level, the broader national challenge of transforming fragmented initiatives into an integrated and sustainable system for responding to emerging arboviruses. Overcoming this inertia requires shifting from reactive control to proactive intelligence, prioritizing integration, collaboration, and continuous evaluation of effectiveness.

The findings presented here have relevant implications for both policy and academia. Politically, they highlight the urgency of strengthening decentralized governance through intersectoral and intermunicipal cooperation, fostering integrated surveillance networks consistent with the One Health framework. Academically, they emphasize the importance of expanding microrregional empirical research in Brazil and promoting collaboration among universities, health departments, and civil society to co-produce actionable knowledge. By bridging science and public policy, the study provides an evidence base to guide decision-making, stimulate investment in technological innovation, and support the training of a new generation of health professionals skilled in predictive epidemiology and integrated management of arboviral diseases.

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ARTICLE 7 -**Plastic waste and arboviral diseases: a timeline of epidemiological evidence**

PLASTIC WASTE AND ARBOVIRAL DISEASES: A TIMELINE OF EPIDEMIOLOGICAL EVIDENCE

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Joziana Muniz de Paiva Barçante

ABSTRACT

Dengue has become the most widespread arboviral disease in the world, with recurrent epidemics driven by *Aedes aegypti* proliferation in rapidly urbanizing and climate-vulnerable regions. Despite advances in sanitation and vector control, the disease continues to expand across tropical areas, revealing deep environmental and infrastructural determinants. Among these, the rise of plastic pollution has emerged as a neglected yet critical driver of transmission. The massive growth of plastic production and the dominance of single-use packaging have transformed waste streams, generating long-lasting containers that collect rainwater and sustain mosquito breeding. This integrative review synthesized and contextualized epidemiological, entomological, and environmental evidence linking the mismanagement of plastic waste to the expansion of arboviral diseases, particularly dengue, under the One Health framework. Studies published between 1990 and 2025 in Scopus, PubMed, Web of Science, and institutional repositories were analyzed using a chronological and narrative approach. Across Latin America and Asia, disposable plastics consistently appear as dominant breeding habitats for *A. aegypti*. Mechanistic pathways include rainwater retention, thermally stable microhabitats, microbial biofilms that nourish larvae, and the protection of desiccation-resistant eggs. Municipalities with efficient solid waste management exhibit lower entomological indices and reduced dengue incidence, whereas irregular collection and open dumping are correlated with a higher transmission risk. Evidence indicates that the combination of growing plastic consumption, low recycling rates, and inadequate waste services has established persistent urban niches that perpetuate arboviral cycles even during dry seasons. Mismanaged plastic waste thus represents a structural and high-relevance environmental determinant of arboviral persistence. Integrating solid-waste prevention, selective collection, and

circular-economy strategies into public-health surveillance and urban planning is essential to align epidemic control with sustainability and planetary health.

Keywords: plastic waste; *Aedes aegypti*; dengue; arboviruses; urban solid waste management; One Health; vector ecology; circular economy.

1 INTRODUCTION

The advent of synthetic polymeric materials in the twentieth century, particularly from the 1930s onward with the commercial production of polystyrene and, later, polyethylene (PE) after the Second World War, marked one of the greatest industrial transformations in modern history. From the 1950s and 1960s, the packaging industry massively adopted plastics owing to their unmatched combination of lightness, durability, low cost, and molding versatility. This expansion fostered a disposable consumption culture and revolutionized food and pharmaceutical logistics by ensuring hygiene and extending product shelf life ([1]Rhodes, 2018). However, it was from the late 1970s and throughout the 1980s that plastics progressively replaced traditional materials such as paper, glass, and metals, particularly in the packaging sector. As a result, plastics became the dominant market for synthetic polymers, surpassing other materials in total volume of use ([2]Thompson *et al.*, 2009; [3]Chalmin, 2019).

However, the industrial success of plastics has resulted in an environmental crisis of global proportions. Between 1950 and 2015, approximately 6.3 billion tons of plastic waste were generated, of which the vast majority (79%) were sent to landfills or directly discarded into the natural environment, while only 9% were effectively recycled ([4]Geyer *et al.*, 2017). Global plastic production is estimated to exceed 400 million tons annually, with single-use products and packaging accounting for about 40% of this volume ([5]OECD, 2022). This linear production-and-disposal model is driving the contamination of ecosystems, including in Brazil, where recent studies have reported microplastic pollution in seven out of ten coastal beaches ([6]IHU, 2025).

In tropical and developing countries, deficiencies in Solid Urban Waste (SUW) management have created a dangerous synergy between environmental degradation and public-health crises. The improper disposal of plastic packaging and other rigid containers creates ideal and persistent reservoirs for the proliferation of *Aedes aegypti*, the primary vector of arboviruses such as dengue, Zika, and chikungunya ([7]Prasad *et al.*, 2023; [8]Pereira *et al.*, 2024). By collecting rainwater in urban and peri-domestic environments, these plastic residues become efficient breeding sites, sustaining the mosquito's reproductive cycle and consequently increasing the risk of disease transmission ([9]Silva; Scalize, 2023; [10] Barçante; Cherem, 2024).

The association between clusters of irregular waste disposal and the rise in arboviral detection rates has been scientifically documented in major urban centers. Ecological studies in Brazilian cities such as Recife and São Luís demonstrate a positive

and significant correlation between inadequate waste-collection services and the incidence of dengue cases ([11]Sobral; Sobral, 2019; [8]Pereira *et al.*, 2024). In Minas Gerais, between 2007 and 2016, municipalities with adequate solid waste management presented lower dengue incidence rates compared to those still relying on open dumps. Proper disposal in sanitary or controlled landfills was associated with a significant reduction in arboviral transmission. Strengthening local waste-management systems plays an important role in vector control and public-health protection. These findings highlight the need for integrated environmental and health policies in urban planning ([12]Mol *et al.*, 2020).

The problem therefore, transcends the traditional sanitary sphere, demanding an integrated understanding that links the chemistry and industrial production of materials to urban infrastructure and health determinants.

Given the urgent need to mitigate the threat of expanding arboviral diseases, intensified by poor plastic-waste management, this integrative review aims to synthesize and contextualize the available scientific evidence establishing the temporal trajectory and nature of the relationship between the rise of disposable plastic packaging and the epidemiological expansion of arboviruses, under the One Health perspective.

2 MATERIALS AND METHODS

2.1 Study design and review procedures

This study was developed as an integrative review with a narrative and temporal analytical approach, aiming to synthesize and contextualize the scientific evidence available on the relationship between plastic waste and the epidemiological expansion of arboviral diseases. The review integrated results from ecological, entomological, environmental, and epidemiological studies published between 1990 and 2025, retrieved from multidisciplinary sources indexed in Scopus, PubMed, Web of Science, and institutional repositories.

Reference selection prioritized peer-reviewed articles addressing plastic waste as an environmental determinant of vector proliferation and arboviral transmission. The searches included descriptors in Portuguese and English related to *plastic waste*, *solid waste management*, *urbanization*, *Aedes aegypti*, *arboviruses*, *dengue*, *Zika*, *chikungunya*, and *Oropouche*.

The included articles were independently assessed by two researchers to ensure consistency in eligibility criteria and to minimize bias in the selection of evidence.

Discrepancies were resolved by consensus, considering thematic relevance and methodological quality.

The analysis followed a chronological and interpretative line, identifying transformations in scientific understanding and research approaches over the decades, linking socio-environmental determinants, urban infrastructure, waste-management practices, and public-health outcomes.

Although this review does not adhere to a formal systematic protocol such as PRISMA 2020, it incorporates several of its core principles of transparency, reproducibility, and traceability. The present review, therefore, adopts an evidence-based interpretive structure that combines quantitative indicators and qualitative insights, enabling the construction of a comprehensive panorama of the role of plastic pollution as a structural factor in the dynamics of urban vector-borne diseases, within the One Health paradigm.

3 RESULTS AND DISCUSSION

The historical trajectory of dengue in the Americas reveals a complex endemo-epidemic pattern characterized by recurrent outbreaks and expanding vector distribution. Dengue is a viral disease primarily transmitted by *Aedes aegypti* mosquitoes, and records compiled in medical literature and by Pan American Health Organization (PAHO) allow its evolution to be divided into some initial phases. The first phase, from 1600 to 1946, corresponds to the introduction of dengue in the Americas, marked by the earliest epidemic descriptions in Martinique, Guadeloupe, and Panama. The second one, between 1947 and 1970, was defined by the implementation of the continental eradication plan for *A. aegypti*, which successfully eliminated the vector from 18 continental countries by 1962. The third phase, from 1971 to 1999, represents the period of reinfestation that followed the failure to maintain the eradication program, leading to the re-establishment of transmission cycles across tropical and subtropical areas ([13]Dick *et al.*, 2012). Finally, from 1980 to nowadays, we are facing the intense viral circulation and widespread vector dispersion, culminating in more than 13 million dengue cases in 2024 ([14]PAHO, 2024). The historical relationship between dengue transmission, *A. aegypti* dynamics, and the evolution of plastic production is summarized in Figure 1.

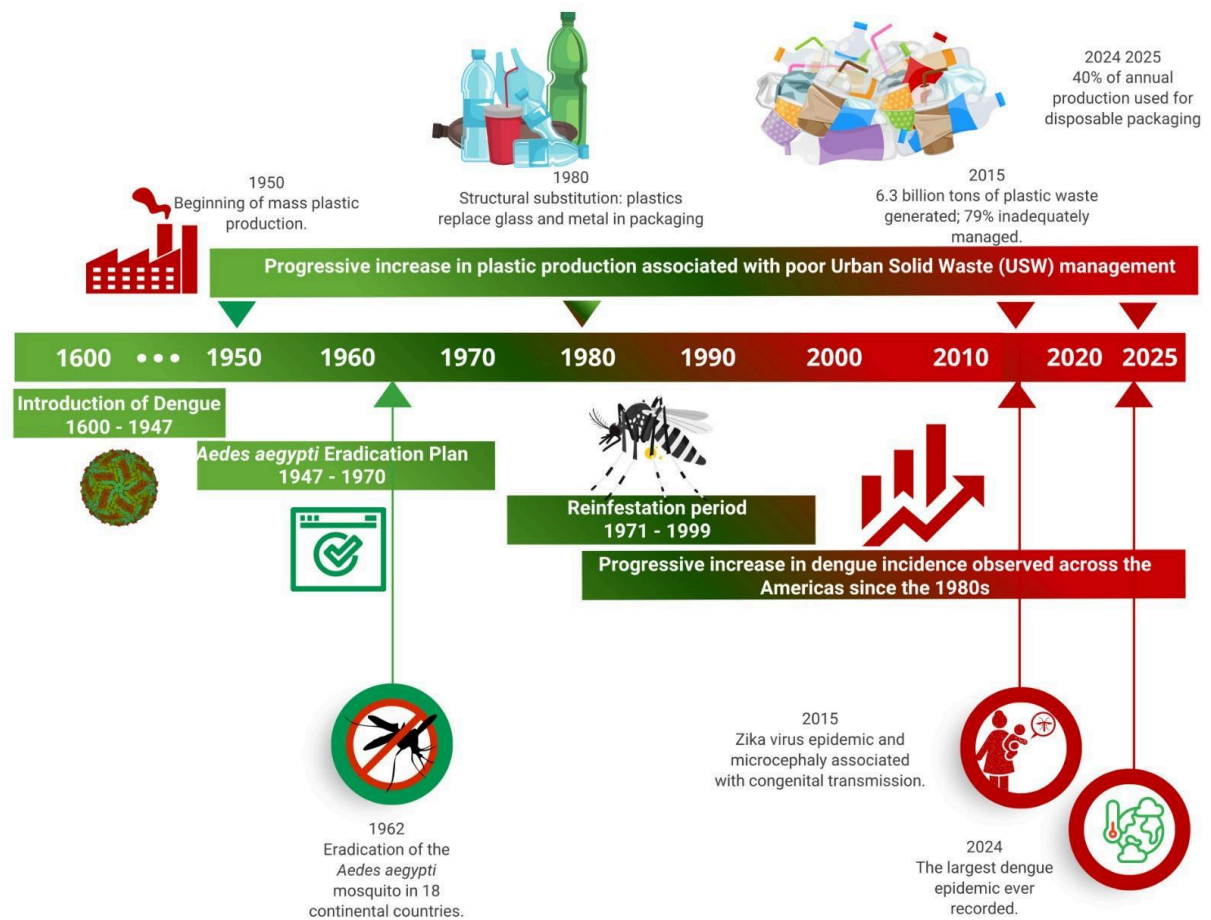


Figure 1. Visual timeline illustrating the relationship between the progressive increase in plastic production, inadequate urban solid waste management, and the expansion of dengue across the Americas. The intensification of plastic production since the 1950s coincided with the rise in dengue incidence from the 1980s onward, following the *Aedes aegypti* reinfestation period. Key events include the mosquito eradication in 1962, its reintroduction and spread between 1971 and 1999, the Zika virus epidemic in 2015, and the largest dengue outbreak ever recorded in 2024.

The link between plastic waste and the proliferation of arboviral diseases, particularly dengue, was documented as early as the 1990s in Brazil. Studies demonstrated that disposable containers such as plastic bottles, cans, and tires served as important breeding sites for *Aedes aegypti* even in cities with regular waste collection,

such as Marília (São Paulo). These investigations revealed the paradox between advances in urban infrastructure and the persistence of environmental conditions favorable to vector reproduction, showing that the problem transcends the absence of public services and involves human behaviors related to improper waste disposal ([15]Mazine *et al.*, 1996).

To strengthen the mechanistic understanding of this association, it is important to highlight that plastic residues influence vector ecology through multiple interconnected pathways. Physically, they accumulate rainwater and create microhabitats with stable humidity and temperature, favoring larval development and adult emergence ([10]Barçante; Cherem, 2024; [16]Cherem *et al.*, 2024; [17]Barçante; Cherem, 2025). Biologically, the rough inner surfaces of disposable containers facilitate the formation of microbial biofilms that serve as a nutrient source for larvae, while the durability of plastics protects desiccated eggs capable of hatching after prolonged dry periods ([18]Hunt *et al.*, 2020). Ecologically, these artificial habitats expand the urban niche of *A. aegypti* and sustain residual viral transmission even during droughts. Together, these processes transform mismanaged plastics from passive waste into active drivers of vector persistence and disease transmission ([19]Flaibani *et al.*, 2020).

Methodological critiques at the time suggested the possibility of bias due to sampling limitations, restricting the extrapolation of results. However, the following decades confirmed this scenario with urban expansion, increased consumption, and the growing disposal of plastics, leading to the formation of permanent artificial environments that favor the proliferation of urban mosquitoes. More recent research has empirically confirmed this trend, showing that plastic waste has become consolidated as entomological hotspots, transforming urban garbage into a structural vector of modern epidemics ([20]Goud *et al.*, 2025).

In the 2000s, evidence accumulated on how accelerated urbanization and growing plastic consumption intensified artificial breeding sites. The focus evolved from a purely entomological to a socio-environmental perspective, recognizing household waste as a central element in vector ecology, particularly in densely populated areas with insufficient collection systems ([21]Banerjee *et al.*, 2015). Plastics, due to their durability, create persistent habitats that extend the reproductive cycle of *Aedes*, increasing risks in tropical contexts. [21]Banerjee *et al.* (2015) also differentiated urban and rural settings, showing that discarded plastics increase vector density and

epidemiological risk, consolidating a direct association between modern waste and the expansion of arboviral diseases.

During the 2010s, dengue epidemiology in Brazil began to incorporate sanitation and waste management variables. Based on data from Recife, it was shown that deficiencies in urban waste collection and disposal are directly associated with an increase in *Aedes aegypti* breeding sites and consequently with higher dengue incidence. In areas with irregular waste collection coverage, the accumulation of solid waste, especially plastic and disposable containers, promotes water retention and vector proliferation. Thus, policies for reduction, segregation, and proper management of urban waste can represent an effective environmental intervention for dengue control by reducing mosquito breeding sites and, therefore, the number of disease cases ([11]Sobral; Sobral, 2019).

A study published in 2020 presented consistent evidence for the state of Minas Gerais, demonstrating that proper solid waste management, particularly selective collection, was associated with a significant reduction in dengue cases, reinforcing the environmental dimension as an independent variable in epidemiological risk models. The study, however, was limited to identifying a positive correlation only with dengue, not observing the same pattern for other arboviral diseases such as chikungunya and zika, and did not include rural areas, which restricts the generalization of the results ([12]Mol *et al.*, 2020).

Irregular disposal of plastics and household waste remains a universal and persistent challenge, affecting both urban and rural zones. In the latter, the absence or low efficiency of selective collection aggravates the formation of potential breeding sites for vectors, increasing the risk of arboviral transmission. Therefore, expanding integrated sanitation and waste management policies represents an essential strategy for sustainably reducing these diseases in territories with precarious infrastructure.

Recent ecological studies have also highlighted the oviposition preference of *A. aegypti* for plastic containers. An analysis of more than 27,000 containers across 3,400 households revealed that plastics concentrate the majority of eggs, characterizing them as passive environmental vectors with predictive potential for outbreaks ([7]Prasad *et al.*, 2023). Another study shows that the distribution of *A. aegypti* breeding sites is closely related to environmental variables and urban patterns, particularly inadequate waste management and the absence of efficient drainage systems. Integrating climatic and environmental data into urban planning is essential to reduce vector density and

prevent outbreaks of dengue, chikungunya, and Zika. These analyses reinforce that continuous monitoring of environmental variables must be incorporated into surveillance and control policies, enabling faster responses to conditions favorable for mosquito proliferation.

It is also important to note that Brazil recycles less than 3% of the plastic waste it produces, according to recent industry estimates, which intensifies the accumulation of disposable containers and favors the multiplication of breeding sites. In this context, integrated waste management and circular economy policies aligned with sustainable city models become central strategies to contain the expansion of arboviral diseases in vulnerable tropical territories ([9]Silva; Scalize, 2023).

Currently, it is estimated that only about 10% of all plastics produced globally are effectively recycled, while the remaining 90% are improperly discarded, accumulating in landfills, waterways, and urban environments. This low reuse rate exacerbates environmental pollution and contributes to the formation of artificial breeding sites for vectors such as *A. aegypti*, intensifying the spread of arboviral diseases. The persistence of plastics in the environment prolongs exposure to pathogens and promotes the creation of micro-ecosystems that sustain infectious disease transmission cycles, reinforcing the urgency of global circular economy policies and source reduction ([22]Maquart *et al.*, 2022).

Figure 2 presents the historical evolution and global projections of the plastic life cycle between 1950 and 2050, according to the study by ([23]Liu *et al.* (2024). It shows exponential growth in production since 1950, with projections exceeding 1,100 million tons by 2050, while recycling, although increasing, remains below total waste generation. The accumulation of residues and inadequate management constitute one of the main contemporary environmental challenges, with direct implications for public health and the spread of arboviral diseases in urban contexts.

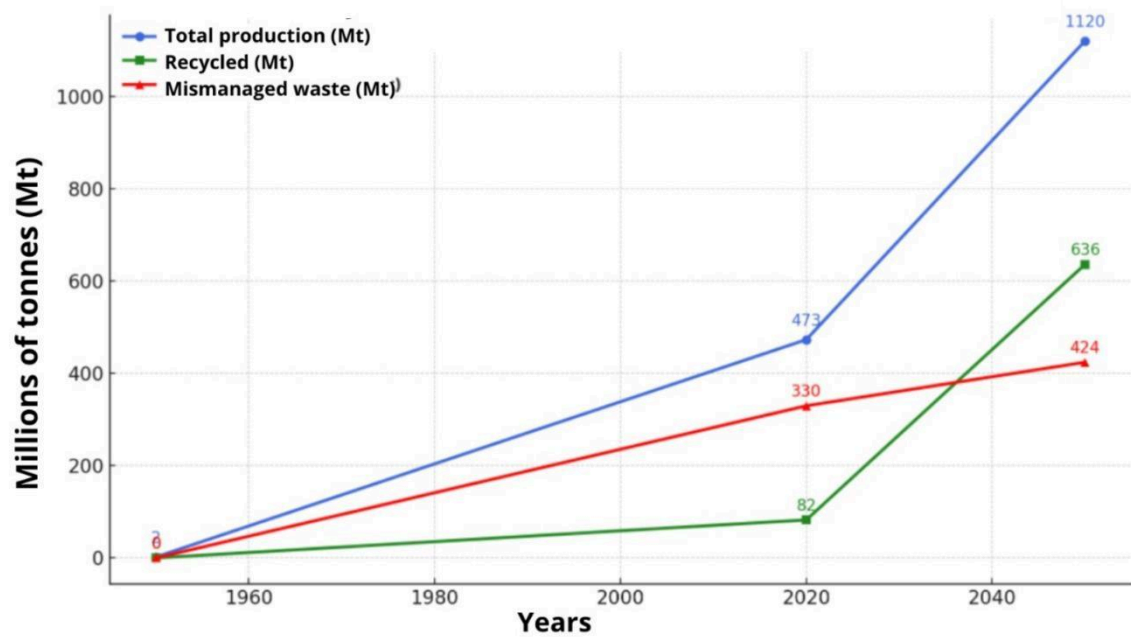


Figure 2. Global trends in plastic production, recycling, and mismanaged waste (1950–2050). The blue line represents total annual plastic production, the green line indicates the recycled volume, and the red line shows the amount of plastic waste that is improperly managed (*mismanaged waste*). Data source:

Despite the establishment of the National Solid Waste Policy (PNRS) in 2010, Brazil's progress in waste management remains limited. Official recycling rates are approximately 4% for solid waste and only 1% for plastics, placing the country significantly behind other nations with comparable economic growth. Although Brazil possesses a comprehensive regulatory framework, its practical implementation is hindered by structural weaknesses, insufficient municipal funding, and the lack of an effective reverse logistics system. Consequently, less than 4% of plastic waste is recycled, far below global averages.

This gap between legislation and practice has led to large volumes of mismanaged plastics accumulating in landfills, waterways, coastal zones, and peri-urban areas. The scarcity of selective collection infrastructure, the informality of sorting activities, and the undervaluation of waste pickers further exacerbate inefficiency and environmental degradation. Beyond ecological impacts, poor waste management directly threatens public health by fostering environments suitable for disease vectors such as *A. aegypti* and promoting the bioaccumulation of micro- and nanoplastics in aquatic and human systems.

Overall, Brazil faces a critical imbalance: industrial plastic production continues to grow while waste treatment remains stagnant. This scenario represents not merely a technical issue but a political and institutional deficit, demanding integrated public policies and a One Health approach that recognizes plastics as a cross-cutting determinant of human, environmental, and animal health ([24]Fraga Filho, 2025).

There is no more time to wait. The health and environmental damages are rapidly escalating in a globalized and plastic-dependent world. The World Health Organization (WHO), through its Intergovernmental Negotiating Committee, warns that health risks are present at every stage of the plastic life cycle, from production to disposal and environmental persistence. The ingestion and inhalation of micro and nanoplastics, combined with exposure to additives and toxic compounds, represent direct threats to environmental balance and human health. In response to this scenario, the WHO advocates for a legally binding international treaty to combat plastic pollution, grounded in the principles of maximum protection of health and the environment, safe management of chemicals, and equitable access to safe and effective health products ([25]WHO, 2024).

In Brazil, mechanical recycling of post-consumer plastics reached 20.6% in 2023, while the specific rate for plastic packaging was 24.3%. This means that 80% of plastics were improperly discarded and remain in the environment. In numerical terms, in 2023 alone, 1,120,000 tons were not recycled (ASSOCIAÇÃO BRASILEIRA DA INDÚSTRIA DO PLÁSTICO, ABIPLAST), a figure that continues to grow with the annual increase in plastic packaging and product consumption ([26]ABIPLAST, 2023). However, the results also show that although there have been advances in the total volume recycled, there remains wide room for improvement in the efficiency of the circular plastic economy. The ABIPLAST study highlights that the drop in virgin resin prices in 2023 negatively affected the competitiveness of recycled raw materials, thereby limiting the growth of recycling rates. The remainder is dispersed across landfills, urban peripheries, rural zones, or directly in nature, as evidenced by the fact that 3.44 million tons of plastic waste are discarded annually into the sea under Brazilian jurisdiction ([27]Lima *et al.*, 2024).

Globally, the picture is no less alarming. The Organization for Economic Cooperation and Development ([5]OECD, 2022) projects that plastic production will triple by 2060 if no structural changes occur, with less than 10% being recycled. These data reinforce that negligence in plastic management, rather than its invention itself,

sustains the growing overlap between environmental pollution, social inequality, and epidemiological risks. Waste projections follow the same troubling trend: the global volume of plastic waste is expected to triple by mid-century, reaching unprecedented levels. Half of this waste will continue to be sent to landfills, while less than 20% will be effectively recycled.

This structural inefficiency reflects both technological limitations and economic and regulatory barriers that hinder the transition to a truly circular economy. Even though the use of recycled plastics, known as secondary plastics, is expected to grow faster than that of primary plastics, their overall share will remain small, reaching only about 12% of total global plastics by 2060. This indicates that fossil-based plastics will continue to dominate production matrices, perpetuating environmental impacts and emissions associated with material life cycles. The environmental dimension of the problem is equally alarming. Plastic leakage into the environment is expected to double, reaching 44 million tons per year, while the accumulation of plastic debris in aquatic ecosystems could more than triple. These residues disrupt ecological chains, harm marine and terrestrial species, and increase human health risks through the bioaccumulation of micro and nanoplastics. Faced with this scenario, the OECD warns that the current model of plastic production and consumption is unsustainable and demands globally coordinated policies for reduction, reuse, and innovation in alternative materials ([5]OECD, 2022).

Analysis of urban infrastructure conditions and the capacity for adequate solid waste management has received increasing attention among researchers, who identify these factors as indirect determinants of *Aedes aegypti* population density. Recent evidence suggests that municipalities with better solid waste management performance tend to have lower entomological indices, indicating that the quality of these services may serve as a predictor of vector infestation. Studies further demonstrate that predictive models should be regionally and individually adapted to achieve greater accuracy, with potential for the use of machine learning techniques in estimating vector density based on urban and environmental variables. However, in Brazil, there remains a lack of comprehensive and standardized public databases on solid waste management, which compromises analytical reliability and hinders integration among public health, sanitation, and urban planning policies ([29]Klafke *et al.*, 2023).

Moreover, molecular entomological investigations have integrated the characterization of larval habitats with genetic analyses of mosquito populations,

revealing that plastic containers such as tires, drums, and storage tanks are predominant in recent dengue outbreaks. Studies conducted in 2023 identified these habitats as key transmission sources, with larvae found in stagnant pools formed by accumulated waste, thereby expanding endemic cycles in urban areas ([7]Prasad *et al.*, 2023). This integration between entomology and molecular epidemiology underscores the role of plastics in maintaining vector genetic diversity, facilitating adaptation to chemical control.

The acceleration of global plastic production, driven by its versatility and low cost, has become one of the major contemporary environmental and health challenges. Estimates indicate that only about 9% of all plastics produced until 2015 were recycled, around 12% were incinerated, and approximately 79% accumulated in landfills or the natural environment, with total global production already reaching 8.3 billion metric tons ([4]Geyer *et al.*, 2017). This massive dispersion has created a persistent landscape of waste whose physical longevity and water retention capacity favor the establishment of microecosystems suitable for the proliferation of vectors such as *Aedes aegypti*, whose aged eggs can hatch upon contact with natural water ([10]Barçante; Cherem, 2024). The continuous increase in global plastic production, projected to double by 2040, tends to expand these risk areas, particularly in tropical countries with deficient sanitation and waste collection infrastructure.

Even more concerning is the structural deficit of knowledge and integrated policies addressing the interface between plastic waste and vector-borne diseases. Despite growing recognition of the problem, the scientific literature still lacks studies that quantify, in a geospatial and longitudinal manner, how urban plastic waste sustains the endemicity of arboviral diseases such as dengue, Zika, and Chikungunya ([22]Maquart *et al.*, 2022; [30]Barçante; Cherem, 2024b). The absence of standardized data on solid waste management, especially in developing countries, exacerbates the environmental surveillance gap and hinders the formulation of effective strategies. Given the intensification of unplanned urbanization and the climate crisis, it will become inevitable to face a scenario in which vector control depends not only on entomological actions but also on the ability to reformulate production, consumption, and disposal models for plastics. Incorporating the environmental and solid waste dimensions into public health programs thus emerges as an urgent and strategic necessity to contain the next wave of infectious diseases associated with urban degradation ([4]Geyer *et al.*, 2017).

The growth of global plastic production and consumption has followed an exponential trajectory over the past seven decades, contrasting sharply with the stagnation of waste management and disposal systems. While annual production increased from 2 million tons in 1950 to more than 470 million tons in 2020, recycling rates have remained below 15%, revealing a structural imbalance between economic growth and environmental responsibility ([4]Geyer *et al.*, 2017; [23]Liu *et al.*, 2024). Industrial prosperity, the incorporation of polymers into vital sectors such as health, technology, and infrastructure, and the developmental optimism of recent decades have shifted managerial focus toward short-term progress metrics, relegating the need for a sustainable use and disposal cycle to the background. As historically occurred with pesticides, once symbols of innovation and later recognized as environmental threats, time exposes the hidden costs of negligence. In this context, integrated plastic waste management under environmental, human, and animal perspectives must cease to be a peripheral agenda and become a central axis of public policy. Only an urgent transformation in plastic disposal and recovery practices will enable the alignment of economic development with sustainability and planetary health.

Studies on emerging plastic waste habitats highlight how discarded plastic bags and packaging become hotspots for urban mosquitoes, co-opting waste structures to stabilize larval environments. Analyses conducted in 2025 identify these materials as facilitators of vector-borne disease transmission, with implications for the ecology of *Aedes* and *Culex*, aggravating the burden of arboviral infections in rapidly urbanizing contexts. The accumulation of such waste has altered vector ecological dynamics, favoring population expansion and resistance. This perspective emphasizes the urgency of waste management policies that consider health impacts, transforming an environmental issue into a priority for epidemic prevention ([20]Goud *et al.*, 2025).

Larval ecology within plastic habitats also reveals specific vector preferences for certain types of waste, such as disposable containers that retain water for long periods. Recent household surveys encompassing thousands of containers confirm that plastics represent the majority of productive breeding sites, with epidemiological implications for oviposition control. This evidence, accumulated in studies conducted in 2023, reinforces the need for educational campaigns focused on disposal behaviors, integrating environmental variables to predict and prevent outbreaks in endemic regions of Brazil ([7]Prasad *et al.*, 2023; [31]Santos *et al.*, 2023).

Recent evidence indicates that plastic waste acts as a structural element in the expansion of dengue in the Americas, establishing strategic breeding sites for *A. aegypti* ([16]Cherem *et al.*, 2024). The adaptive plasticity of *A. aegypti* has been remarkable since its introduction to the Americas, with a colonization potential that has become devastating in recent decades. Among the factors that enhance this resilience, plastic waste plays a central role by serving as a protective cradle for desiccated, resistant eggs capable of remaining viable for months under adverse conditions. This strategic position of plastics in vector ecology resembles hidden landmines on a battlefield, latent hazards that remain invisible at first glance but can trigger epidemic outbreaks once favorable conditions arise. This scenario reveals that plastic waste is not merely an environmental burden but a critical component of arboviral epidemiology, demanding continuous surveillance, data integration, and proactive strategies that anticipate and neutralize these invisible foci of vector proliferation.

The evidence gathered over three decades reveals consistent patterns linking plastic waste accumulation to the persistence of urban arboviral transmission. Studies across Latin America and Asia converge in identifying disposable containers as the dominant breeding habitats for *Aedes aegypti*, particularly in areas with inadequate waste collection ([21]Banerjee *et al.*, 2015; [11]Sobral; Sobral, 2019; [9]Silva; Scalize, 2023). Although dengue remains the most extensively studied arboviral disease, empirical evidence for other viruses such as chikungunya and Zika remains limited, indicating a gap in current surveillance research ([12]Mol *et al.*, 2020). Ecological and urban studies further suggest that plastic residues create thermally stable microhabitats that sustain residual vector populations even during dry seasons, reinforcing the role of waste management as an independent determinant of disease risk ([10]Barçante; Cherem, 2024; [19]Flaibani *et al.*, 2020). Collectively, these findings point toward a persistent and expanding ecological niche for *A. aegypti* that parallels the growth of plastic consumption in rapidly urbanizing regions ([31]Urban *et al.*, 2024; [32]WHO, 2024).

Mitigating the combined impacts of urbanization and climate change requires an integrated governance approach capable of articulating urban planning, environmental conservation, and social equity policies. The concept of co-benefit governance proposes that interventions targeting urban sustainability, such as the creation of green infrastructure, restoration of micro-habitats, and establishment of ecological corridors, yield simultaneous benefits across multiple fronts: reduction of local temperature, flood

control, promotion of biodiversity, and improvement of human health. In tropical and densely populated areas, such solutions can also reduce the proliferation of urban vectors by replacing impermeable surfaces and artificial breeding sites with ecologically functional environments. Therefore, the integration of territorial planning and climate policies becomes an essential axis for transforming cities into resilient spaces capable of mitigating environmental and epidemiological risks in a synergistic way ([31]Urban *et al.*, 2024).

FINAL CONSIDERATIONS

Brazil faces a complex epidemiological and environmental scenario given the multifactorial nature of dengue and other arboviral diseases, influenced by climatic, urban, demographic, and sanitation determinants. High population density, historical deficiencies in basic sanitation and access to safe water, combined with intense internal and cross-border migration flows, create conditions conducive to the persistence and expansion of these diseases.

Added to this scenario is the growing problem of plastic waste, with national recycling rates remaining between 1% and 4% of total production, revealing structural weaknesses in solid waste management. At the same time, the country has become the global epicenter of arboviral infections, concentrating about 80% of the more than 13 million cases recorded worldwide in 2024, according to recent estimates.

There has also been a marked increase in zika, chikungunya, and oropouche infections, emerging tropical diseases that expand the epidemiological burden and impose new challenges for health surveillance. As demonstrated in this study, mismanaged plastic waste constitutes ideal microenvironments for vector proliferation, modifying urban ecology, favoring the selection of insecticide-resistant mosquitoes, and acting as reservoirs for quiescent eggs capable of sustaining viral transmission even during prolonged droughts.

This work adds to a growing body of evidence emphasizing the relevance and urgency of the environmental dimension in arbovirus control. Poorly managed plastic waste represents a high-relevance environmental determinant of epidemiological importance, associated with the intensification of disease transmission that has increased exponentially over the past five decades and reached explosive behavior in recent years. It is therefore essential to design and implement integrated, intersectoral, evidence-based public policies guided by the One Health paradigm, which connects the

human, animal, and environmental axes. Only through such a systemic approach will it be possible to mitigate the impacts of arboviral diseases and promote more sustainable, healthy, and resilient urban ecosystems.

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ARTICLE 8 -**Arbovirus Expansion in a Warming World: From Tropical Endemics to Global Public**

Arbovirus Expansion in a Warming World: From Tropical Endemics to Global Public Health Threats

ABSTRACT

The global expansion of arboviruses such as dengue, Zika, chikungunya, and Oropouche fever is increasingly influenced by climatic, ecological, and social factors. This review explores how environmental change, urbanization, insecticide resistance, and globalization have driven the proliferation of *Aedes* mosquitoes and the pathogens they transmit. Brazil and other countries in the Americas have experienced unprecedented outbreaks, with the 2024 dengue epidemic marking the highest incidence on record. The convergence of warming temperatures, plastic waste accumulation, and socio-spatial vulnerability has fostered ideal breeding conditions for *A. aegypti* and *A. albopictus*, facilitating their geographic expansion, including into temperate regions. We examine the rise of insecticide resistance, limitations of traditional vector control strategies, and advances in biological control, notably the introduction of *Wolbachia*-infected mosquitoes. We argue that arboviral transmission today represents an “epidemiological synergism” in which anthropogenic pressures and biological adaptability create a compounded public health challenge. Addressing this complex scenario requires coordinated surveillance, community engagement, investment in genomic tools, and sustained research toward vaccines and antiviral therapies. Without a globally integrated response, arboviruses may become permanently established in previously unaffected areas, posing a growing threat to planetary health.

Keywords: arboviruses; *Aedes*; vector-borne diseases; climate change; mosquito control.

1 INTRODUCTION

The global risk of mosquito-borne diseases, including dengue, yellow fever, Oropouche fever, chikungunya, and Zika, is rapidly increasing due to the geographic expansion of their vectors [1]. Amid the challenges of a global health crisis, climate change, and land-use alterations, these factors have created favorable environments for vector proliferation. For instance, the year 2024 marked the largest recorded dengue epidemic, along with a significant rise in both the incidence and severity of Oropouche virus infections [2].

Despite international commitments to progressively implement integrated vector management, controlling *Aedes* mosquitoes, particularly *A. aegypti* and *A. albopictus*, remains an immense challenge. Consequently, the number and geographic spread of arboviral diseases such as chikungunya and Zika continue to increase [3].

The emergence and spread of arboviruses are heavily dependent on the presence and abundance of vectors and are closely linked to various social, economic, and environmental factors on regional and global scales. This complex and interconnected phenomenon underscores the urgent need to address not only the immediate rise in infectious diseases but also the broader systemic conditions that drive them [4].

Global change, particularly climatic and microclimatic shifts, plays a central role in the transmission dynamics of several arboviruses. Predictive models forecast an expansion in the distribution of vectors and pathogens under all climate change scenarios [5]. Rising temperatures, shifts in rainfall and humidity patterns, combined with the thermal biology and genetic plasticity of *Aedes* mosquitoes, facilitate the continued spread of these vectors, including into previously unaffected areas [6]. Insecticide resistance, reported in multiple regions worldwide, further contributes to the persistence and dissemination of vector populations [7].

In response to these challenges, it is essential to implement sustainable measures as part of an integrated strategy to combat arboviruses [4]. This includes reducing mosquito proliferation, strengthening epidemiological surveillance alongside entomological and genomic monitoring, and fostering active community involvement in the elimination of breeding sites, particularly considering that over 70 percent of vectors are found in domestic or peri-domestic environments.

In this context, citizen science offers a powerful pathway for active community engagement in prevention efforts. Defined as any activity involving public participation in scientific research, it has the potential to effectively bridge science, policymakers, and society.

Furthermore, strengthening health research is critical to identifying priority areas in basic and clinical research, health services, health systems, and public health. Setting research priorities and coordinating efforts across these domains is vital for generating high-impact scientific knowledge, informing decision-making, and implementing effective prevention and control programs [4,8].

Only through a globally integrated approach, mobilizing citizen science, advancing surveillance systems, and ensuring investment in comprehensive vector control, can we effectively confront the spread of arboviruses in an era of unprecedented environmental transformation.

2. ARBOVIRUSES

2.1 Dengue

Dengue is undeniably an escalating global health threat, with its distribution traditionally concentrated in tropical and subtropical regions. The disease is now endemic in over 100 countries, with the highest incidence rates reported in Southeast Asia, South Asia, and the Americas. Dengue can also lead to severe and potentially fatal outcomes, such as hemorrhagic fever, which significantly contributes to mortality rates [9].

The public health impact of dengue is substantial and is mirrored in its socioeconomic burden. In Brazil, economic losses due to work absenteeism are estimated to exceed 5 billion US dollars [10]. In endemic regions, dengue not only overwhelms healthcare systems but also imposes significant economic losses, largely due to absenteeism and high treatment costs, which often require intensive care interventions [11].

Although dengue outbreaks have traditionally been seasonal, mainly occurring during the rainy season, which favors *Aedes* proliferation, current viral transmission dynamics point to additional complexity. Urbanization increases population density in vector-prone areas, while globalization and international travel expand the geographic range of dengue, carrying the virus beyond its traditional endemic zones [6].

Recent studies highlight an increase in both imported and autochthonous dengue cases in Europe. In Germany, there was a sharp increase in cases among travelers returning from Egypt, with 36 notifications in 2023, exceeding the annual average of zero to eight cases between 2017 and 2022. Over 90% of these cases were linked to stays along the Red Sea coast, particularly in private residences, where mosquito control is more challenging than in hotel areas.

In addition, the northward spread of *A. albopictus* has created favorable conditions for autochthonous transmission, especially in regions such as Baden-Württemberg and North Rhine-Westphalia [12].

France also recorded several episodes of local transmission, particularly in 2022, when 65 cases were reported across nine distinct events, surpassing the cumulative total between 2010 and 2021. This trend continued in 2023, including a cluster of three autochthonous cases in the department of Val-de-Marne, marking the northernmost transmission focus in Europe [13]. By September 2024, the situation had worsened, with 82 cases reported in France, 199 in Italy, and 8 in Spain [14].

The global expansion of dengue appears to be driven by multiple factors, including environmental changes that contribute to global warming. Rising temperatures facilitate the adaptation of *A. aegypti* to new areas and extend mosquito activity periods in cooler, previously non-endemic regions [2].

The main vectors of the dengue virus are *A. aegypti* and *A. albopictus*, both of which play a central role in the dynamics of viral transmission due to their proximity to human environments and their ability to reproduce in artificial containers found in urban settings [15,16]. *A. aegypti* is highly adapted to urban environments, prefers human blood, and breeds in small collections of water. It is an extremely efficient dengue vector, with desiccated eggs remaining viable for up to one year. *A. albopictus*, although more common in rural areas, has increasingly established itself in urban settings and tolerates a broader range of breeding sites [15,17]. Currently, *A. albopictus* is established throughout much of Europe, while *A. aegypti* is mainly present in Cyprus, around the Black Sea, and in the outermost region of Madeira [14].

Climate change significantly affects the expansion of these vector habitats. Warmer temperatures and altered precipitation patterns create new environments conducive to mosquito breeding, enabling the spread of dengue into previously unaffected regions. Predictive models indicate that climate change will drive the expansion of *Aedes* mosquitoes into temperate areas, including parts of Europe and North America, increasing the risk of outbreaks [18,19].

Among the regions at risk for new outbreaks are those adjacent to current mosquito habitats in tropical areas, especially where health systems are underdeveloped, as increased temperatures and precipitation create favorable conditions for vector proliferation [18,19].

Severe dengue outbreaks recently observed in Brazil and across Latin America have been driven by a combination of climatic, ecological, and socioeconomic factors,

necessitating immediate interventions to mitigate their impacts. In Brazil, the resurgence of dengue following the Zika epidemic is alarming. After a decline in dengue and Zika incidence in 2017–2018, the country experienced a large outbreak in 2019 with approximately 2.1 million reported cases [20]. In 2024, Brazil recorded over 9 million dengue cases, reaching a cumulative incidence of 3,233 cases per 100,000 inhabitants. This exceeds the alert threshold of 18 to 20 cases per 100,000 inhabitants per week by several orders of magnitude, as defined by PAHO/WHO [21]. Such magnitude constitutes a critical scenario, and projections suggest that the next decade may witness further deterioration if structural measures are not implemented.

The current dengue scenario in Brazil reflects a dichotomy between officially reported data and deep uncertainty regarding the near future. Despite facing the largest dengue epidemic in history in 2024, with over 9 million reported cases and an incidence exceeding 3,200 cases per 100,000 inhabitants, laboratory and genomic surveillance remained extremely limited. It is estimated that only 5 to 10% of cases were confirmed by laboratory testing [21], meaning that over 8 million cases were either treated or recorded without serotypic or genotypic confirmation.

In terms of genomic surveillance, the situation is even more concerning. Initiatives such as the Fiocruz Genomic Network, which sequenced approximately 200 samples across 115 municipalities between 2023 and 2024 [22], are highly relevant but negligible on a population scale, representing less than 0.002% of the cases registered in the country. States such as Ceará, for example, sequenced only 20 samples during the peak epidemic periods of 2024 [23].

These figures reveal a serious asymmetry between the absolute number of cases and the country's actual viral monitoring capacity, which undermines the early detection of emerging variants, assessment of vaccine impact, and formulation of territorialized public health policies. This mismatch exposes Brazil's structural vulnerability to dengue and challenges the institutional narrative of active surveillance.

This resurgence has been attributed to the persistence of local DENV lineages that circulated at low levels before and after the Zika epidemic. Climatic conditions, including increased rainfall and temperature anomalies, also facilitated mosquito proliferation and viral transmission [20, 24, 25].

By Epidemiological Week 34 of 2024, Brazil had reported 6,497,167 probable dengue cases and 253,748 chikungunya cases. The prevalence of 3,199 cases per 100,000 inhabitants

reflects the gravity of the situation. Dengue deaths in 2024, up to that same week, exceeded the total number of deaths recorded over the previous seven years combined [26].

Since the earliest reports in the Americas, dengue incidence has shown a steady upward trend (Figure 1), peaking in 2024 with the largest outbreak in the disease's history. Notably, Brazil has consistently maintained the highest absolute number of cases in the Americas throughout this historical series.

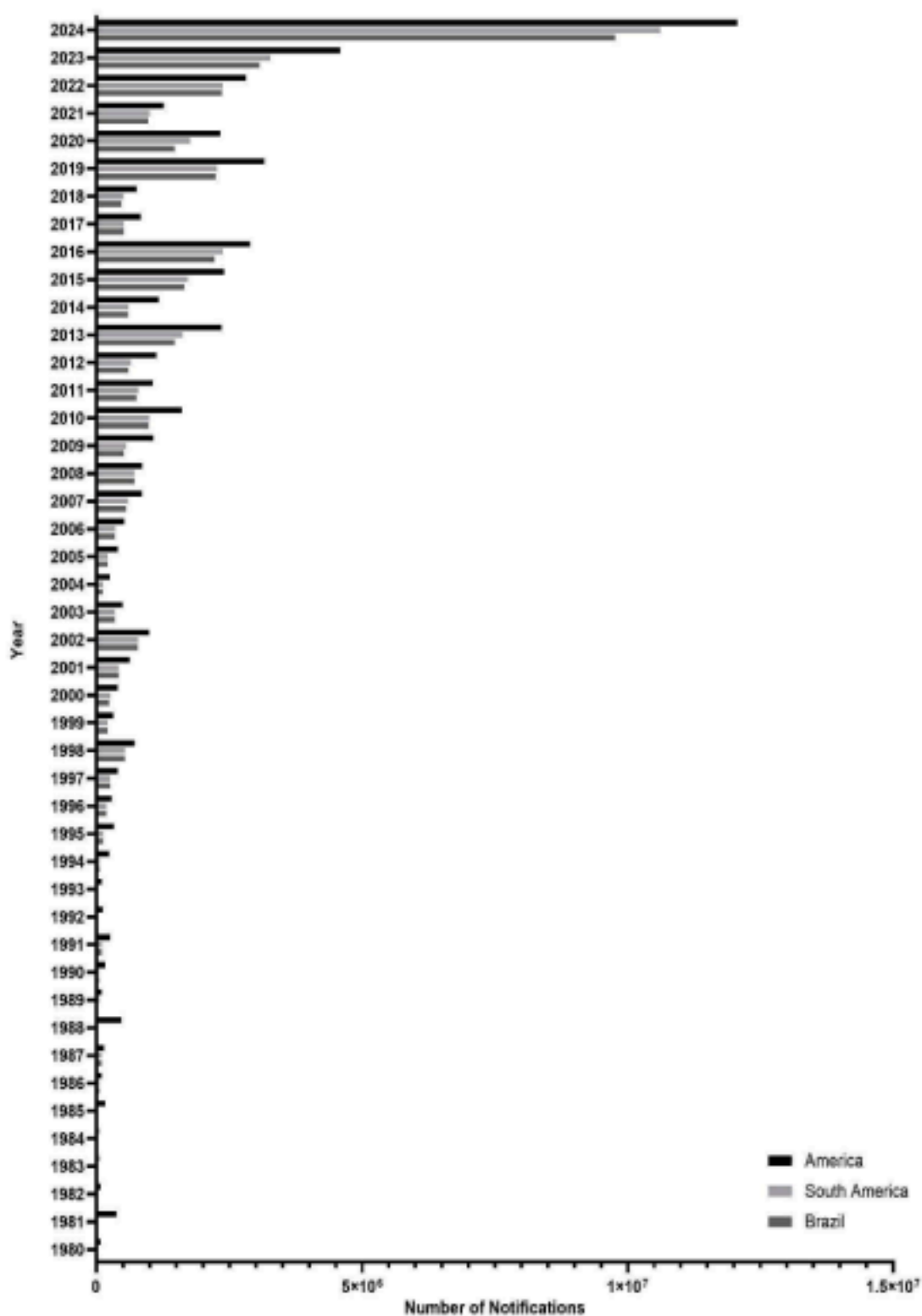


Figure 1 - Dengue incidence in the Americas from 1980 to October 2024. The chart displays the absolute incidence for Brazil (light gray bars), South America (dark gray bars), and the Americas region (black bars), as defined by the Pan American Health Organization (PAHO). **Source:** Health Information Platform for the Americas (PLISA), PAHO.

Between the 1950s and 1970s, an estimated 9.5 million people from Northeastern Brazil migrated to the South and Southeast regions, with approximately 40% settling in the metropolitan area of São Paulo. The lack of adequate housing in these urban centers led to the formation of informal settlements, resulting in a “belt” of marginalized communities. These environments became conducive to the proliferation of *A. aegypti* breeding sites, contributing to the spread of mosquito-borne diseases. The 1980s marked the onset of modern globalization, characterized by intense flows of people, goods, and tourism. According to the World Tourism Organization, around 940 million people engaged in international travel in 2010, with a significant increase observed in South America [27].

In addition, climate change, marked by a global warming rate estimated at 0.18°C per decade, totaling about 1°C by 2024, has intensified the conditions favorable to *A. aegypti*. Higher temperatures accelerate the mosquito's life cycle and activity, increasing its potential to transmit diseases such as dengue, Zika, and chikungunya. Simultaneously, the accumulation of plastic waste in the environment provides additional breeding sites. Stagnant water retained in discarded plastics creates ideal conditions for mosquito reproduction, especially in vulnerable regions [28].

These interconnected factors, climate change, urban waste accumulation, and increased human mobility, significantly amplify public health risks, particularly in tropical and subtropical regions where warm and humid climates naturally favor the reproduction of vectors like *A. aegypti* [1, 2].

The emergence and exponential growth of arboviruses, especially dengue, are deeply linked to socioeconomic, structural, and educational inequalities in South American countries such as Brazil. In many urban areas, the combination of exposed water reservoirs, substandard housing, and a lack of basic sanitation creates ideal conditions for vector multiplication. At the same time, globalization and international flows enable the rapid spread of both vectors and viral serotypes to previously unaffected regions, including subtropical and temperate zones in Europe and North America.

From a public policy perspective, a troubling gap persists: health technologies are implemented superficially and in a fragmented manner, disproportionate to the severity of the ongoing epidemiological emergency. The limited reach of genomic surveillance, institutional resistance to citizen science, and the fragmentation of intersectoral responses reveal a reactive, delayed, and uneven disease control model.

2.2 Chikungunya

Like dengue, chikungunya virus infections have increased significantly across the Americas. Chikungunya virus (CHIKV), an alphavirus transmitted by female *A. aegypti* and *A. albopictus*, causes acute febrile polyarthralgia, inflammatory arthritis, acute skin rashes, and other systemic manifestations. The inflammatory arthritis, caused by viral invasion of the synovium, is characterized by joint swelling and prolonged morning stiffness, which can persist for months or years in up to 60% of individuals, representing a substantial public health burden [29].

Although it usually follows a benign course, severe and potentially fatal complications can occur during the acute phase, including multiple organ failure, septic shock, and death [30].

CHIKV infection was first described during an outbreak in southern Tanzania in 1952. In 2013, the virus reached the Americas, triggering a large-scale epidemic across several Central American countries and Caribbean islands, with over 1 million reported cases in the first year following its introduction [31].

In the second half of 2014, Brazil confirmed autochthonous CHIKV transmission in the states of Amapá and Bahia through laboratory testing. Since then, all Brazilian states have reported local transmission [32].

According to data from the Brazilian Ministry of Health, probable chikungunya cases totaled 158,060 in 2023, 265,545 in 2024, and by Epidemiological Week 24 of 2025, had already reached 105,048. The number of deaths has also risen sharply, with 122 in 2023, 243 in 2024, and 82 in 2025 through the same week [32].

These scenarios reflect a decade of continuous epidemiological escalation, marked by territorial expansion and the persistence of severe cases, without the implementation of efficient and sustained intersectoral public policies and integrated prevention and response strategies. The absence of a sustained approach grounded in the One Health paradigm highlights serious deficiencies in epidemiological surveillance, vector control, and health system preparedness for recurrent and deadly outbreaks.

Across the Americas, the rise in incidence has been equally alarming. Chikungunya cases increased by 97.8% from 2021 to 2022, followed by a further 34.7% increase through Epidemiological Week 40 of 2023 compared to the previous year. Mortality rose disproportionately as well, with a 308.1% increase during the same period, underscoring the worsening epidemiological scenario [21].

Currently, a live attenuated vaccine, VLA1553, is in Phase III clinical trials and has shown promising results. However, additional studies are required in endemic regions with broader populations to confirm its efficacy in preventing chikungunya [33].

2.3 Zika

Although on a smaller scale, Zika virus (ZIKV) infections have also increased over the years. This flavivirus is transmitted by female *Aedes*, primarily *A. aegypti*. Infection may cause rash, fever, conjunctivitis, muscle and joint pain, malaise, and headache. While symptoms are generally mild, the disease gained international attention during the 2015 epidemic in northeastern Brazil, when it was linked to cases of microcephaly, a brain development disorder, and other neurological conditions in adults, such as meningoencephalitis and Guillain-Barré syndrome [31,34].

The first ZIKV outbreak was recorded in 2007 in Micronesia, where approximately 75% of the local population presented symptoms [35]. In subsequent years, a few cases were reported in the Americas, but widespread transmission occurred after the 2015 epidemic in Brazil. In 2016, the World Health Organization declared the outbreak a Public Health Emergency of International Concern due to neurological abnormalities and congenital malformations, particularly microcephaly, observed in newborns [36].

During that period, 651,470 cases were reported across the Americas, with 273,904 in Brazil, representing 42% of the regional total [37]. In addition, countries such as Canada, France, and Spain reported imported cases from endemic regions [38].

Since 2017, a global decline in Zika cases has been observed. Currently, local transmission of the virus occurs in 89 countries, while 61 UN-recognized countries and territories with the presence of *A. aegypti* have yet to report ZIKV transmission [39].

In 2022, a total of 40,528 Zika cases were reported in the Americas, of which 34,176 occurred in Brazil, accounting for 84% of the regional total. In 2023, an 8% decrease in regional cases was recorded, but Brazil experienced a 5% increase. In 2024, Zika cases rose by approximately 4% compared to the 2022–2023 average. By Epidemiological Week 53 of 2024, 39,785 cases had been reported in the Americas, of which 39,133 occurred in Brazil, 98% of the total [37].

These data indicate that although there has been a reduction in cases since 2017, Zika continues to affect a significant portion of the population in the Americas and is returning to higher levels of transmission, particularly in Brazil.

Currently, there are no licensed vaccines or specific antivirals for the treatment or prevention of Zika, despite ongoing research efforts [40]. Prevention still relies primarily on

vector control, with increased protective measures for pregnant women and children [36]. Health education is also essential to mobilize the population in the fight against the disease.

3. THE *Aedes* GENUS

In the Americas, *A. aegypti* is the primary vector of dengue, Zika, and chikungunya viruses. Native to Africa, this mosquito spread globally during the era of European maritime exploration, reaching Brazil during the colonial period [41]. Now highly urbanized and cosmopolitan, it prefers tropical and subtropical regions. Its global distribution has expanded significantly due to environmental changes and their impacts [42].

A. albopictus, originally from Asia, has invaded other continents such as the Americas and Africa [43,44,1]. In Brazil, it was first detected in 1986 and is now present in all states [45,46].

Both species exhibit a holometabolous life cycle, which includes the egg, larval (four instars), pupal, and adult (male or female) stages. *A. aegypti* is more common in urban areas, while *A. albopictus* is found in green spaces within cities, such as parks, as well as in peri-urban and rural areas [47]. Recent studies indicate that *A. albopictus* is becoming increasingly adapted to urban environments [48,49].

Climate change has been associated with the broader dispersion of these insects, especially into previously unaffected areas [50,2].

During the larval and pupal stages, the mosquito inhabits aquatic environments; in the adult phase, it is terrestrial. Under laboratory conditions, optimal development occurs at a temperature of 28 °C (± 1 °C) and relative humidity of 80% ($\pm 10\%$), with the complete life cycle taking about 10 days. The eggs are dark-colored and cylindrical, measuring approximately 0.6 mm in length, and are deposited by females (oviposition) on surfaces near relatively clean standing water [51].

Although *A. aegypti* females prefer water with low organic content, larvae have been found in saline water or in environments rich in organic matter [52, 53].

The cycle begins with oviposition in containers with standing water, followed by aquatic larval and pupal stages. After approximately 10 days, the adult emerges, and the female restarts the cycle by laying new eggs (Figure 2).

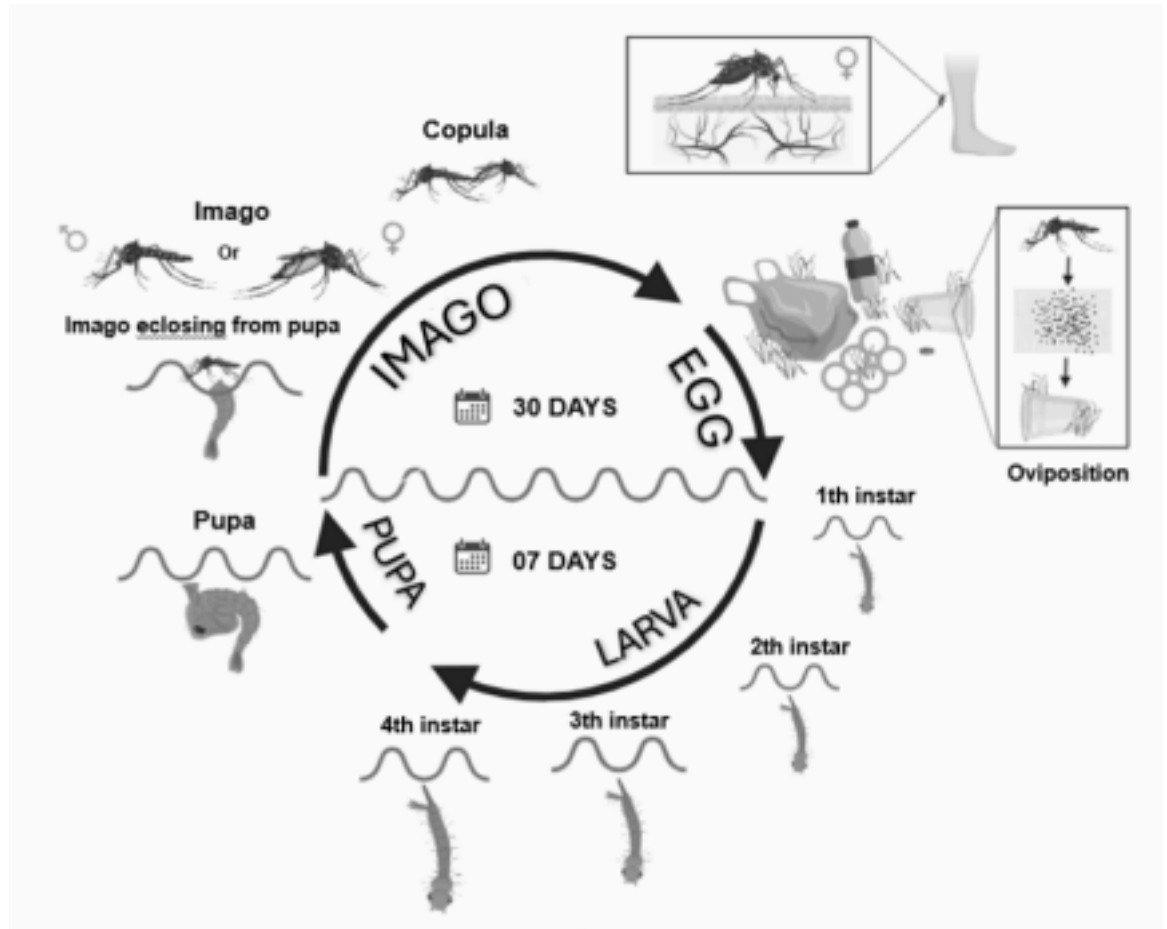


Figure 2. Life cycle of *Aedes* mosquitoes.

3.1 After Oviposition

Following oviposition, embryos complete their development within 48 to 72 hours, leading to the hatching of first-instar larvae, which emerge upon contact with water in the breeding site. Under favorable conditions, these larvae progress through four instar stages over approximately seven days and then transform into pupae.

The pupae, characterized by a comma-shaped brown appearance, are highly active but non-feeding. They complete metamorphosis into adult mosquitoes within approximately two days [51].

Adults emerge with a dark brown or black coloration, bearing white scales on specific areas of the legs and thorax. In *Aedes aegypti*, these scales form a distinctive lyre-shaped pattern on the dorsal thorax. In contrast, *A. albopictus* presents a single white longitudinal stripe on the thorax.

Both males and females feed on sugary substances such as plant sap; however, only females engage in hematophagy (blood-feeding), preferentially targeting human hosts, which makes them key vectors in arbovirus transmission [51].

3.2 Vector Control

In Brazil, chemical control of *Aedes aegypti* relies on the biological larvicide *Bacillus thuringiensis israelensis* (Bti), the residual adulticide Clotianidin + Deltamethrin, and the adulticide Imidacloprid + Prallethrin in outbreak scenarios, applied through ultra-low volume spraying (ULV) [54].

In addition, source reduction and health education efforts are prioritized. Personal protection measures are also encouraged to reduce human-mosquito contact, such as the use of repellents and window screens [57].

Despite a range of control strategies, including mechanical removal of breeding sites, educational campaigns, and insecticide use, *A. aegypti* populations remain high in many regions [55]. This persistence, compounded by seasonal fluctuations, sustains elevated incidence of diseases such as dengue and raises concerns about the vector's potential to transmit emerging pathogens.

The rapid spread of chikungunya (2014) and Zika (2015) viruses in Brazil underscored the country's vulnerability to new arbovirus introductions [56,57].

3.3 Insecticide Resistance

Insect populations are considered resistant to an insecticide when they begin to tolerate concentrations that were previously lethal to individuals of the same species. In other words, resistance is an evolutionary phenomenon whereby populations acquire genetic and/or biochemical alterations that reduce susceptibility to toxic compounds [58].

Resistance in *A. aegypti* can arise via multiple mechanisms. One is metabolic resistance, marked by elevated enzymatic activity, such as carboxylesterases, that degrade the insecticide before it reaches its target site [59, 60]. Another involves target-site mutations that alter the protein structure, reducing or nullifying the insecticide's efficacy [61, 62]. Cuticular thickening may also hinder insecticide penetration, adding another layer of resistance [63].

Resistance in *A. aegypti* is a growing public health concern. Initial reports date back to 1956, when Gilkes et al. [64] observed reduced mortality in DDT-exposed populations in Trinidad. Since then, cases have multiplied globally. Latin America and Southeast Asia now harbor the largest populations of insecticide-resistant *A. aegypti*, particularly against temephos and deltamethrin [65,66].

In Brazil, chemical control remains dominant despite growing resistance. Studies indicate that genetic variability in *A. aegypti* populations facilitates rapid selection for resistance to organophosphates (e.g., temephos) and pyrethroids (e.g., deltamethrin), with

resistance ratios (RR₉₅) ranging from 1.2 to 254.9 for temephos and 6.0 to 110.0 for deltamethrin [67, 68].

Cross-resistance with DDT has also been documented, exacerbated by knockdown resistance (kdr) mutations in the sodium channel gene (V1016I, F1534C, V410L), which confer protection not only against pyrethroids but also other organochlorines related to DDT [69, 70].

This scenario suggests that resistance does not stem solely from intense insecticide exposure but also from the intrinsic genetic diversity of mosquito populations, which supports the persistence and spread of resistance alleles even in the absence of chemical pressure [69,70].

Therefore, urgent implementation of integrated vector management strategies, including insecticide rotation, biological control, and continuous genetic surveillance, is essential to prevent the collapse of programs reliant exclusively on chemical interventions.

3.4 Biological Control

As an alternative to chemical insecticides, biological control strategies have gained traction, notably the use of *Wolbachia* bacteria. This approach is being developed in Brazil through a collaboration between the Oswaldo Cruz Foundation, the Ministry of Health, and the World Mosquito Program (WMP).

Wolbachia is an intracellular bacterium that infects various invertebrates, including arthropods and nematodes, and has shown efficacy in blocking infection by dengue, Zika, and chikungunya viruses in *A. aegypti*. It is believed that *Wolbachia* reduces viral transmission by competing with arboviruses for essential fatty acids, such as cholesterol, required for viral replication, and by activating immune pathways in the mosquito. Some strains may also interfere with viral entry into mosquito cells [71, 72].

The bacterium is vertically transmitted from females to offspring through ovarian tissues. To establish itself in wild populations, *Wolbachia* induces cytoplasmic incompatibility (CI), whereby offspring from infected males and uninfected females do not survive, promoting the spread of infected individuals.

However, further field studies are needed to assess CI efficacy across diverse environmental contexts, considering variables such as temperature, humidity, and *Wolbachia* strain, which are critical to sustained transmission blocking [73].

With appropriate ecological and population-level adjustments, this sustainable approach aims to maintain *Wolbachia*-infected mosquito populations over time without the need for ongoing releases, ensuring long-term suppression of arbovirus transmission [74].

More recently, large-scale field trials have confirmed the success of this technique. Cities such as Niterói (Brazil), Yogyakarta (Indonesia), and regions of Vietnam and Australia reported dengue reductions of up to 96 percent following population replacement with *Wolbachia*-positive mosquitoes, positioning this method among the most effective in modern vector control [75, 76].

It is important to emphasize that this technology does not eliminate *A. aegypti* mosquitoes but renders them incapable of transmitting arboviruses. In other words, mosquitoes remain in the environment, but virus-free [77, 78, 79].

4. OTHER VECTORS

Although *A. aegypti* and *A. albopictus* are widely known vectors for arboviruses such as dengue, Zika, and chikungunya, other arboviruses are increasingly gaining attention in Brazil and require urgent focus. Among them, the Oropouche virus, transmitted by different insect vectors, like *Culicoides paraensis* (biting midges) and *Culex quinquefasciatus*, has emerged as a growing concern. This increase is particularly significant in 2024, with the number of Oropouche fever cases rising sharply across several regions in the country.

This surge in cases presents additional challenges, given that Oropouche also has a considerable potential for spread in urban environments, threatening densely populated areas.

Oropouche fever is characterized by symptoms very similar to dengue, including sudden fever, headache, muscle and joint pain, dizziness, nausea, and vomiting. In some severe cases, neurological damage can occur [80]. Oropouche fever cases have risen since the end of 2022. Brazil has been the most affected, with 7,930 confirmed cases by August 2024, more than eight times the number recorded in 2023 [81,2].

Recent data suggest that the current strain is different enough from previous ones that people infected a decade ago have almost no immunity against today's version. The current hypothesis suggests that the virus is not entirely new or unknown but has highly efficient and fast replication and is more virulent [82], with cases of fetal malformations, miscarriages, and deaths in healthy children and adults [80, 2].

Since the discovery of the Oropouche virus in Trinidad and Tobago in 1955, around 30 known outbreaks have occurred, mostly in villages within the Amazon Basin.

However, over the past year, the virus has spread throughout much of Brazil, with countries like Bolivia, Colombia, and Peru also reporting increases in Oropouche cases, though they have not reported birth defects or fetal deaths associated with it. Scientists attribute the virus's spread to changing conditions, including deforestation and increased human mobility, which may favor the spread of the vector insect [82]. Besides deforestation,

climate change likely also plays a role in Oropouche's spread. Higher temperatures accelerate the maturation of vector insects, and increased rainfall and flooding create more standing water areas where these insects can breed [81].

Currently, there are no vaccines or antiviral drugs for the treatment and prevention of Oropouche [80]. Moreover, due to its small size, *C. paraensis* can easily pass through mosquito protection nets and is immune to the most widely used repellents [81]. Current prevention measures include controlling the presence of the vector mosquito by reducing food waste and the accumulation of dead leaves near homes, as these are factors that attract the mosquito, and preventing the formation of water reservoirs where the female vector insects lay their eggs, similar to the management of other arboviruses [82].

Furthermore, the lack of specific diagnostic tests for Oropouche, along with the limited genomic surveillance for acute febrile diseases, underscores the need for renewed efforts in surveillance and awareness [2]. The situation is even more alarming considering that the 500,000 cases of Oropouche virus infection reported in the Americas since 1955 may be underestimated [2]. This underreporting can be attributed to the similarity of Oropouche symptoms with those of dengue and Zika, which often results in clinical-epidemiological diagnoses that do not capture the true magnitude of the disease [81].

5. CONCLUDING REMARKS

Vector-borne infectious diseases, particularly those associated with the *Aedes* genus, remain a persistent global public health threat. Once confined to sylvatic environments, many arboviruses have adapted remarkably to anthropogenic settings, now circulating widely in densely populated urban areas.

Rapid population growth over recent decades, driven largely by increased life expectancy, has fueled the expansion of urban settlements into previously undisturbed ecosystems. This transformation has heightened human exposure to vectors, fostering the emergence of zoonotic outbreaks. Within these evolving urban and peri-urban landscapes, children have emerged as the most vulnerable group, frequently exhibiting more severe and lethal clinical manifestations, thus requiring targeted and urgent protective actions.

As of 2024, it is estimated that approximately 2.5 billion people live in areas of high susceptibility to arboviral infections. Global warming, accelerating since the 1980s, has extended the reproductive cycles of mosquito vectors, while formerly stable ecosystems undergo constant transformation. The interaction between unplanned urban growth, ecological disruption, and climate change has created a novel disease ecology, most notably exemplified by arboviruses.

Despite technological advances, such as the release of *A. aegypti* infected with *Wolbachia*, which has demonstrated efficacy in several cities across Brazil and other countries, these strategies still lack robust public policy frameworks to ensure broad implementation. Economic models suggest that every real invested in this technology could yield up to fourteen reais in public health savings. Nonetheless, many governments continue to ignore cost-effective and sustainable interventions, deviating from scientific evidence and reason.

Simultaneously, collective negligence has become a critical issue. Segments of the population neglect basic preventive measures, improper waste disposal, unclean gutters and yards, or leaving bottle caps and containers on the streets, all of which create ideal breeding sites for mosquitoes. Public authorities often fail to provide adequate infrastructure, while society at large fails to engage in responsible behavior. For the mosquito, every omission becomes a gesture of hospitality, transforming the environment into a sanctuary for its proliferation.

This scenario illustrates what may be termed “epidemiological synergism,” wherein environmental, social, and behavioral factors converge to intensify disease transmission. This concept is especially pertinent to arboviruses, which thrive in densely populated and ecologically degraded urban environments. In such settings, *A. aegypti* encounters multiple hosts within confined areas, facilitating rapid and sustained spread of infectious agents.

In the face of accelerating environmental, social, and economic changes, only an integrated, multidisciplinary approach rooted in the One Health paradigm can halt the expansion of arboviruses and ensure equitable protection of both vulnerable and non-vulnerable populations. The convergence of science, effective public policy, and collective responsibility represents the only viable path to disrupt this cycle of neglect and foster an environment inhospitable to vectors and favorable to life.

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THIRD PART

3. FINAL CONSIDERATIONS

The expansion of arboviruses in the Americas, particularly Dengue, Zika, Chikungunya, and Oropouche fever, constitutes one of the greatest contemporary challenges in public health. The epidemic nature of these diseases, combined with their capacity for ecological adaptation and their disproportionate impact on vulnerable populations, demonstrates that traditional control models, based on insecticides and sporadic campaigns, have become insufficient.

The results discussed in this thesis reaffirm the need to move beyond fragmented approaches and adopt an integrated One Health paradigm, in which human, animal, and environmental health are understood as interdependent dimensions. This shift in perspective is an essential condition for reducing morbidity and mortality, especially in low- and middle-income countries, where social vulnerability and fragile surveillance systems are more pronounced.

The analysis carried out demonstrates that innovation is not limited to the biomedical dimension, but also involves social and institutional technologies, including:

- sustainable elimination of breeding sites, linked to sanitation policies;
- intelligent entomological surveillance, incorporating monitoring of vector resistance;
- release of mosquitoes infected with *Wolbachia* as an effective biological tool;
- genomic surveillance to map serotypes and emerging lineages;
- rational vaccination, guided by epidemiological and genomic data;
- real-time data integration, through artificial intelligence and big data, for the identification of hotspots and rapid responses.

When articulated, these axes constitute a technological model in health capable of transforming the approach to arboviruses: from reactive and fragmented to proactive, integrated, and sustainable.

From the perspective of public policies, three priority points emerge:

1. Interinstitutional governance: effective integration among human, veterinary, and environmental health is indispensable, overcoming bureaucratic and sectoral barriers.
2. Permanent and less reactive funding: arbovirus epidemics should not be treated as episodic emergencies but as permanent threats that require constant surveillance, given the ongoing scenario of increase over the last four decades.
3. Community engagement: active citizenship, with population participation in eliminating breeding sites and adherence to vaccination, is an essential component of successful interventions.

It is concluded that the fight against arboviruses in the Americas is not limited to a health issue but is part of a broader context of social justice, environmental sustainability, technological innovation, culture, and integration. The thesis presented here reinforces that health technology must be understood as the integration of science, policy, and citizenship, aimed at achieving better public health outcomes and effective spending in addressing the arboviruses that have affected Brazil and the Americas for decades.

The future trajectory will depend on the ability of governments, academic institutions, and communities to consolidate this integrated approach. Success in reducing the morbidity and lethality of arboviruses will be not only a scientific advance but, above all, a civilizational achievement.

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