

# Infant Mortality and Regional Inequality in Northeast Brazil: A Long-Term Spatial Analysis with Panel Data

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## Keywords:

infant mortality; spatial analysis; socioeconomic determinants.

## JEL Codes:

C21, C31, I15

## Abstract

This study investigates the socioeconomic determinants of infant mortality due to intestinal infectious diseases in municipalities of Northeast Brazil between 2007 and 2021, with an emphasis on the spatial dimension of the phenomenon. It hypothesizes that the infant mortality rate (IMR) exhibits significant spatial effects, meaning that the risk of mortality in a municipality is influenced not only by its internal characteristics but also by the socioeconomic conditions of neighboring municipalities. Based on panel data and spatial autocorrelation tests, the Spatial Durbin Model (SDM) was adopted. The SDM captures the direct and indirect effects of explanatory variables. The results reveal that vaccination coverage and the number of families benefiting from the Bolsa Família program significantly reduce IMRs associated with intestinal infectious diseases, with coefficients of -1.43 and


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-1.20, respectively, and positive effects in bordering municipalities. On the other hand, variables such as GDP per capita and sanitation expenditure did not show a statistically significant impact. Spatial analysis identified the persistence of high mortality clusters in inland and historically vulnerable areas. We conclude that territorial public policies, integrated into and sensitive to the spatial distribution of inequalities, are fundamental to addressing the problem, and this conclusion points to future investigations that incorporate environmental, institutional, and intersectional dimensions.

## Mortalidad infantil y desigualdad regional en el noreste de Brasil: un análisis espacial a largo plazo con datos de panel

### Resumen

Este estudio investiga los determinantes socioeconómicos de la mortalidad infantil por enfermedades infecciosas intestinales en municipios del noreste de Brasil entre 2007 y 2021, haciendo hincapié en la dimensión espacial del fenómeno. Se plantea la hipótesis de que la tasa de mortalidad infantil (TMI) presenta efectos espaciales significativos, lo que significa que el riesgo de mortalidad en un municipio no solo está influenciado por sus características internas, sino también por las condiciones socioeconómicas de los municipios vecinos. Basándose en datos de panel y pruebas de autocorrelación espacial, se adoptó el modelo espacial. El modelo de Durbin (SDM) permite captar los efectos directos e indirectos de las variables explicativas. Los resultados revelan que la cobertura de vacunación y el número de familias beneficiarias del programa Bolsa Familia reducen significativamente las tasas de mortalidad infantil (TMI) asociadas a las enfermedades infecciosas intestinales, con coeficientes de -1,43 y -1,20, respectivamente, y efectos positivos en los municipios limítrofes. Por otro lado, variables como el PIB per cápita y el gasto en saneamiento no mostraron un impacto estadísticamente significativo. El análisis espacial identificó la persistencia de grupos de alta mortalidad en zonas del interior y históricamente vulnerables. Se concluye que las políticas públicas territoriales, articuladas y sensibles a la distribución espacial de las desigualdades, son fundamentales para abordar el problema, y esta conclusión apunta a futuras investigaciones que incorporen dimensiones ambientales, institucionales e interseccionales.

#### Palabras clave:

Mortalidad infantil; análisis espacial; determinantes socioeconómicos.

#### Códigos JEL:

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## Introduction

The infant mortality rate (IMR) is one of the most relevant indicators for assessing a population's living conditions (Paes & Silva, 2020). It is widely used to assess the health situation in countries and regions (Caldeira *et al.*, 2005). Its importance lies mainly in the fact that many of the causes of death in young children are considered preventable, that is, amenable to prevention through timely and effective interventions that prevent their progression to fatal outcomes (Boing & Boing, 2008). Among these causes, intestinal infectious diseases, such as diarrhea, stand out, still representing a persistent challenge to child health in Brazil.

This problem is part of a global effort to combat infant mortality, particularly the commitments made within the framework of the Sustainable Development Goals (SDGs), established by the United Nations (UN), which aimed to reduce child mortality under five years of age. Despite progress, millions of children still die annually from preventable causes, highlighting the urgency of maintaining effective public policies, especially in developing countries (Tavares *et al.*, 2016).

In Brazil, several studies have highlighted the close relationship between infant mortality and socioeconomic conditions, emphasizing the importance of understanding its determinants to support more effective public policies (Boing & Boing, 2008, 2025; Bugelli *et al.*, 2021; Nascimento *et al.*, 2014; Souza *et al.*, 2021).

Problems such as diarrhea have historically been among the leading causes of infant mortality in developing countries, especially in the 1980s and 1990s. They are strongly associated with environmental, nutritional, and socioeconomic factors (Irfi *et al.*, 2008). The persistence of these factors in contexts of poverty highlights the complexity of the phenomenon.

In this sense, spatial analysis methods have become increasingly relevant for understanding infant mortality, as they allow for the investigation of the distribution of incidence across the territory and the identification of risk patterns among neighboring areas (Faria, 2022; Pasklan *et al.*, 2021; Shimakura *et al.*, 2001; Silva & Silva, 2020). The territorial dimension of the problem is particularly critical in the Brazilian semi-arid region, an area marked by profound social inequalities, poor sanitation infrastructure, and water scarcity. Studies such as that of Rocha and Soares (2015) demonstrate that the effects of drought are directly associated with increased IMRs, lower birth weight, and reduced gestational age, with intestinal infections and malnutrition as the leading causes. Thus, the scarcity of potable water, aggravated by drought, compromises access to adequate hygiene and sanitation

conditions, favoring the spread of waterborne diseases, such as diarrhea, especially among young children.

4 Considering these factors, the use of spatial tools becomes strategic for understanding the persistence and location of clusters of preventable mortality. According to Silva and Silva (2020), spatial analysis helps identify the most vulnerable areas and guide more targeted public policies. In this context, studying the geographical distribution of infant deaths from preventable causes, such as diarrhea, becomes essential to support interventions capable of mitigating health risks and promoting greater equity in access to health.

Given this, the present study is justified by seeking to understand the socioeconomic determinants of IMRs due to diarrhea, using a spatial approach applied to municipalities in the Brazilian Northeast between 2007 and 2021. Considering the low levels of human development in a large part of these territories and the deleterious effects of water scarcity on child health (Rocha & Soares, 2015), the hypothesis guiding this research is that IMR presents significant spatial effects, that is, that mortality in a municipality is influenced not only by its internal characteristics, but also by the socioeconomic conditions of neighboring areas. As argued by Shimakura *et al.* (2001), understanding the territorial determinants of infant mortality is fundamental to advancing development, improving living conditions, and enhancing children's well-being in Brazil.

To meet the objective of this study, the work adopts the Spatial Durbin Model data methodology. Furthermore, it uses panel data to simultaneously capture the spatial and temporal effects of infant mortality due to diarrhea in municipalities of Northeast Brazil. The originality of the research lies precisely in this integrated approach, still little explored in the national context, especially when applied to specific causes of infant mortality.

This article is organized into five sections, in addition to this introduction. The second section presents a literature review on the socioeconomic determinants of infant mortality, with an emphasis on studies that incorporate spatial approaches. The third section details the methodological procedures adopted, including the characterization of the study area, the analysis period, the databases used, the specification of the econometric models, and the tests for choosing between fixed effects (FE), random effects (RE), and spatial models. The fourth section presents and discusses the empirical results of the analysis, highlighting the direct and indirect effects of the explanatory variables on IMRs. The fifth and final section presents concluding remarks, summarizes the main findings, discusses the im-

plications for public policy formulation, and outlines avenues for future research exploring the environmental, institutional, and intersectional dimensions of infant mortality.

## Literature Review

Infant mortality outcomes exhibit an uneven distribution both between and within countries. To understand these variations in outcomes, Kim and Saada (2013) broaden the traditional focus on health services and consider broader social determinants to explain these outcomes. Thus, the authors propose a conceptual framework of the social determinants of infant mortality and conduct a systematic review of the empirical literature on hypothetical social determinants (such as social policies, neighborhood socioeconomic deprivation, and individual socioeconomic status), as well as intermediate determinants, including health behaviors. This perspective is consistent with the broader theoretical tradition that views health outcomes as embedded within regional structures of inequality: income concentration, territorial deprivation, and unequal access to public goods tend to reproduce vulnerabilities spatially. From the analysis of the selected studies, it was found that income inequality, social policies, and neighborhood socioeconomic conditions are consistently associated with variations in infant mortality and birth outcomes, both between and within countries.

Multinational studies presented by the authors suggest that countries with lower income inequality and more robust social policies have better child health indicators. At the intra-country level, especially in the United States, evidence shows that socioeconomically disadvantaged neighborhoods and greater inequality are associated with worse outcomes. At the individual level, the findings are heterogeneous: associations between socioeconomic status, race/ethnicity, and intermediate factors, such as psychosocial stress, vary across studies and are not consistent. This variability reflects methodological limitations that make it difficult to draw conclusions (Kim & Saada, 2013). Despite this heterogeneity, the core insight aligns with both regional inequality theory and the social determinants literature: structural disparities at the territorial scale shape opportunities for health and survival, underscoring the need to analyze infant mortality through a multilevel, spatially sensitive framework.

In Brazil, the IMR has declined in recent decades, reflecting advances in public policies and health interventions. During the 1980s, the widespread dissemination of oral rehydration therapy led to a significant reduction in infant deaths from acute diarrhea. Despite these advances, in 1991 diarrhea still caused approximately 4.5 million deaths among children under five years of age, with about 60 % attributed to dehydration (Neto *et al.*, 1991). Given this scenario, multiple studies have investigated the determinants of the IMR, with particular attention to socioeconomic inequalities and the quality of health services. These efforts mirror the broader understanding that infant mortality is not solely a biomedical phenomenon but a territorial expression of unequal development.

Boing and Boing (2008) analyze data from 296 Brazilian municipalities with populations exceeding 80,000 inhabitants between 2000 and 2002, aiming to test the association between infant mortality from preventable causes and socioeconomic indicators and health investments. The authors find that municipalities with higher mortality rates from preventable causes also had lower municipal human development index (MHDI) scores and greater income inequality, as measured by the Gini coefficient. These results reinforce the role of socioeconomic conditions in determining infant deaths and highlight how regional disparities shape structural capacities for prevention—an essential element in the theoretical connection between inequality and health outcomes.

In the Northeastern context, although the downward trend in IMRs has continued, the levels are still alarming. Souza *et al.* (2021) analyze the states of the Northeast between 2001 and 2015 and identify stationary behavior in the rate across specific federative units, indicating the persistence of regional inequalities. Studies in Salvador (BA) corroborate this panorama: Guimarães *et al.* (2001) observe a significant 78.8 % drop in the proportion of infant mortality due to diarrhea between 1977 and 1995. Complementarily, they verify a 91.9 % reduction in diarrhea-induced IMRs between 1977 and 1998. However, the risk of death from this cause remained 90 % higher in lower social strata, indicating the reproduction of social inequities in child health. These findings underpin the theoretical claim that improvements in aggregate indicators may coexist with persistent territorial inequalities, a central concern of regional inequality theory.

A similar analysis was conducted in Recife (PE) by Nascimento *et al.* (2014) for the period 2000–2009. The authors identify a decrease in the IMR from 20.4 to 12.1 per thousand live births, corresponding to 76.4 % of deaths being preventable. Adequate attention to the health of pregnant women stands out as a central element

in the reduction of deaths. These findings reaffirm the importance of preventive care and the strengthening of primary health care as essential strategies for reducing infant mortality. These strategies operate at the interface between individual determinants and structural public policies.

Several studies have incorporated spatial analysis methods to identify territorial patterns of infant mortality. Shimakura *et al.* (2001) argue that the risk of infant death is not limited to individual family characteristics but is also influenced by the socioeconomic conditions of the areas where families live. This insight aligns with regional inequality theory: territories concentrate and reproduce disadvantages. In this sense, exposure to collective risks in critical regions becomes a determining factor. Pasklan *et al.* (2021), in investigating the correlation between the quality of primary care services and the IMR in 5,011 Brazilian municipalities, find an overall reduction of 45.07% in the IMR between 2000 and 2015, with particular emphasis on the Northeast. However, they observe the formation and expansion of high-mortality clusters, especially in the North and Northeast, revealing the persistence of territorial pockets of vulnerability. This evidence underscores the relevance of spatial econometric tools, which are specifically designed to detect such clusters and capture interdependence between neighboring municipalities.

To analyze the geographical distribution of infant mortality in Brazilian municipalities between 2013 and 2017, Faria (2022) uses the Global and Local Moran's I indices to identify spatial clusters of high and low rates. His results show a highly fragmented and unequal Brazil, with high IMRs in several areas, especially in municipalities on the northern border, in the interior of the Legal Amazon, in the semi-arid region, in the mid-north, and in the northeastern coastal zone. Furthermore, the author identifies a marked regional disparity between "Northern Brazil" and "Southern Brazil," the latter characterized by lower IMRs and better indicators of social and health deprivation. The explicit detection of these patterns underscores the importance of spatial analysis in operationalizing theories of regional inequality in empirical health research.

Within the context of spatial analysis, in Ceará, Bezerra Filho *et al.* (2007) find that qualified assistance during pregnancy, childbirth, and the newborn period, when associated with better income distribution, is decisive in reducing mortality in the first month of life. On the other hand, factors such as inadequate nutrition, low vaccination coverage, poor sanitation, low education levels, and poverty are identified as determinants of post-neonatal mortality. Although they recognize the contribution of selective health actions, the authors highlight the need for

structural and intersectoral changes to sustain improvements and achieve levels comparable to those of developed countries. This supports the multidimensional nature of infant mortality, which intersects with health systems, social inequality, and territorial disparities.

With an analysis focused on a more recent period (2010 to 2022), Boing and Boing (2025) identify only a slight reduction in infant mortality in Brazil. The IMR fell from 13.0 to 12.7 per thousand live births, and mortality among children aged one to four years remained at 2.5 per thousand. Regional inequalities changed little. For example, in 2022, municipalities with lower Municipal Human Development Index (HDI-M) still had substantially higher rates: about 49% higher in infant mortality and 93% higher in mortality among children aged 0 to 4 years. Territorial contrasts also persisted, with 42.2% of the microregions in the North being among the 100 with the highest IMRs, compared to only 3.2% in the South. These findings clearly align with both the theory of regional inequality and spatial epidemiology: territorial disparities remain a core predictor of infant health.

The slowdown in the rate of decline in IMRs in Brazil is also observed by Bugelli *et al.* (2021), beginning in 2009. According to the authors, this slowdown occurs despite social policies (such as the Bolsa Família Program) and health policies (expansion of SUS coverage, PSF, and decentralization of resources and autonomy of municipal governments), which positively impact the health of the Brazilian population. To understand the determinants of IMRs, the authors conduct a scoping review of the national literature, in which the results show that conditions such as income, poverty, and nutritional status, in addition to individual characteristics such as genetic and biological factors, are identified as the main determinants of infant mortality in the country. Here again, the intersection between social determinants and territorial inequality emerges despite strong social programs; uneven regional development limits their effectiveness.

In this context, the literature presented by the authors suggests that public policies, such as the implementation of the SUS (Unified Health System), the PSF (Family Health Program), and the PBF (Family Grant Program), have proven important in reducing infant mortality and mitigating socioeconomic determinants. The problem lies in inequalities in access to quality health services, which have important implications for reducing IMRs (Bugelli *et al.*, 2021). According to Santos *et al.* (2010), the current challenge in infant mortality is to build equity in access to quality health services and to institute public policies that reduce socioeconomic inequalities. In short, although the IMR has decreased over time

in Brazil, significant inequalities persist, especially in preventable causes such as diarrhea. As highlighted by Oliveira and Latorre (2010) and Silva (2001), such diseases are easily managed and do not require high-cost technologies. Thus, the continued high rates in certain territories underline shortcomings in the coverage and equity of health services. Infant mortality, therefore, expresses not only biological vulnerabilities but also social and territorial inequalities. Boing and Boing (2008) reiterate that disparities in IMRs between population groups and regions indicate that prevention policies are not being applied equitably, emphasizing the need for territorially sensitive public policies guided by spatial evidence.

## Methodological Procedures

This section presents the methodological procedures used to analyze the socio-economic determinants of infant mortality in municipalities in Northeast Brazil between 2007 and 2021. The spatial and temporal scope of the research is initially described, followed by an explanation of the data sources used and the variables selected. Next, the panel econometric modeling is detailed, along with the tests used to choose between fixed and random effects. Subsequently, the spatial dependence tests and the selection criteria among the spatial models are presented.

## Scope and Time Frame

This study uses municipalities in the Northeast region of Brazil as its unit of analysis, comprising nine states and 1,794 municipalities, resulting in significant territorial, socioeconomic, and institutional diversity. The choice of this region is justified by both the historical persistence of adverse social indicators and the high IMR, with substantial variability across the region's states and municipalities (Souza *et al.*, 2021). The time frame spans 2007 to 2021, encompassing 15 consecutive years of panel data, enabling the capture of both temporal dynamics and spatial patterns in the IMR and its determinants. This interval covers important phases of Brazilian social policy, including the consolidation of the PBF and the expansion of health and sanitation policies into the country's interior.

## Database and Variables Used

10 The information used was extracted from different public and reliable databases. The IMR (deaths of children under 1 year of age per thousand live births) due to causes associated with intestinal infectious diseases was obtained from DATASUS/IBGE and used as the dependent variable in the model. Thus, the IMR can be described as (Equation 1):

$$\text{IMR} = \left( \frac{\text{number of infant deaths (under 1 year of age)}}{\text{total number of live births}} \right) * 1000 \quad (1)$$

For data extraction from the DATASUS database, codes A00 to A09 of the ICD-10 were considered, encompassing intestinal infectious diseases, including cholera, amebiasis, viral and bacterial infections, as well as cases of gastroenteritis of presumably infectious origin. According to Camargo-Cruz (2017), these diseases have diarrhea as their primary clinical symptom. To him, the importance of studying the group of intestinal infectious diseases, classified in the International Classification of Diseases (ICD-10) under codes A00 to A09, stems from the fact that they remain among the leading causes of infant morbidity and mortality in Brazil.

The following variables were used as explanatory variables: vaccination coverage rate (PNI/SIPNI), the number of families benefiting from Bolsa Família (Ministry of Social Development), per capita public expenditure on sanitation (SI-OPS/SNIS), average schooling of the formally employed population (RAIS-MTE), and municipal GDP per capita (IBGE – Regional Accounts). These variables were selected for their theoretical relevance as determinants of the IMR and for their use in previous studies on health inequalities. All independent variables were transformed into natural logarithms, except for the IMR. Thus, Table 1 presents the variables and their relationships with social and economic issues in the literature over the years.

Table 1. Variables, Description, Source, Studies That Used Them, and the Expected Sign (Coefficient)

Variable	Description	Source	Use in socioeconomic analysis models	Expected sign
tx_mortinfant	IMR (deaths of children under 1 year old per thousand live births)	DATASUS / IBGE	A classic indicator of health conditions and socioeconomic development. Used in studies, such as those by Barros <i>et al.</i> (2010), to evaluate the impact of social policies	Dependent
vacc_coverage_rate	Vaccination coverage rate (proportion of the target population vaccinated)	PNI / SIPNI (Ministry of Health)	Assesses access to and the effectiveness of public health policies. Used in studies, such as that of Victora <i>et al.</i> (2011)	Negative
Bf_beneficiary_families	Number of families receiving Bolsa Família benefits in the municipality	Ministry of Social Development (MDS)	Income transfer measure. Used to measure redistributive effects (Soares <i>et al.</i> , 2010)	Negative
mun_health_sanitation_exp_pc	Per capita public expenditure on basic sanitation in the municipality	SIOPS / SNIS	Related to urban infrastructure and quality of life. Used by Medeiros <i>et al.</i> (2020) in public health models	Negative
Schooling	Average schooling in years of the formally employed population in the municipality	Demographic censuses / PNAD (IBGE)	Key variable for human capital. Frequently used in growth and well-being models (Barro & Lee, 2013)	Negative
gdp_mun_per	Municipal GDP per capita	IBGE – Regional Accounts	General indicator of local economic development. Widely used in convergence and inequality models (Ferreira, 2017)	Negative

Source: Own elaboration

## Econometric Modeling: Traditional Panel

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Initially, a panel data model with a two-dimensional structure (municipalities and years) was adopted, considering three basic models: the FE, RE, and pooled OLS models. The estimated general equation is as follows (Equation 2):

$$\begin{aligned} \text{tx\_mortinfant}_{it} &= \alpha + \beta_1 \log(\text{tx}_{\text{cob}_{\text{vacinal}}}) + \beta_2 \log(\text{bf\_beneficiary\_families}) \\ &+ \beta_3 \log(\text{despsasan}_{\text{mun}_{\text{per}}}) + \beta_4 \log(\text{schooling}) \\ &+ \beta_5 \log(\text{gdp}_{\text{mun}_{\text{per}}}) + \mu_i + \lambda_t + \varepsilon_{it} \end{aligned} \quad (2)$$

Where  $i$  represents the municipality and  $t$  the year. The term  $\mu_i$  incorporates the individual effects, the temporal effects ( $\lambda_t$ ), and the idiosyncratic error ( $\varepsilon_{it}$ ). The statistical tests applied included the  $F$ -test for fixed effects, the Breusch-Pagan tests for random effects, and the Hausman test (standard, robust, and auxiliary) to choose between FE and RE. The results indicated the superiority of the two-dimensional FE model (individual and temporal), as evidenced by the rejection of the null hypotheses of the absence of specific effects and of correlation between effects and regressors.

## Tests for Choosing the Spatial Model

Lagrange multiplier (LM) tests and their robust counterparts were applied to test for spatial autocorrelation in the residuals. These tests were performed based on both the FE model and the SLX (spatial autocorrelation) model, which includes the spatial lag of  $X$ . The results indicated significant spatial dependence in the residuals, both in the error and in the spatial lag types. Therefore, four alternative spatial panel models with two-dimensional fixed effects were estimated: the Spatial Autoregressive Model (SAR), the Spatial Error Model (SEM), the Spatial Durbin Model (SDM), and the Spatial Durbin Error Model (SDEM). After testing, the SDM model was chosen, according to Equation 3:

$$y_{it} = \rho \sum_j w_{ij} y_{jt} + X_{it} \beta + \sum_j w_{ij} X_{j0} \theta + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

Where  $(Y_{it})$  represents the dependent variable (in this case, *tx\_morteinfant*), in the spatial unit under analysis (northeastern municipality)  $i_t$ , at time  $t$ ;  $\rho$  corresponds to the spatial lag coefficient of the dependent variable;  $w_{ij}$  is the spatial weight matrix  $W$ , which indicates the neighborhood between units  $i$  and  $j$ , and the queen matrix was considered here;  $X_{it}$  refers to a vector of explanatory variables;  $WX_{it}$  assumes a vector of spatial means of the explanatory variables, i.e., lags;  $\beta$  represents a vector of direct effect coefficients;  $\theta$  is a vector of spillover effect coefficients;  $\mu_i$  refers to the individual fixed effect (structural differences between Brazilian municipalities);  $\lambda_t$  is the temporal fixed effect; and  $\varepsilon_{it}$  represents the idiosyncratic error term.

### Final Choice of the Spatial Model

The choice between spatial models was based on likelihood-ratio (LR) and information criteria (AIC) tests, as well as Baltagi’s methodological recommendations. The results indicated that the SAR and SDM models were statistically equivalent. However, the choice fell on the SDM due to its theoretical superiority, which allows simultaneous control for spatial effects on the dependent variable and covariates, capturing territorial externalities and more complex spatial contagion dynamics. Thus, the SDM model with fixed spatial and temporal effects was considered the most suitable for explaining the territorial patterns of infant mortality in Northeast Brazil.

## Results and Discussion

This section presents and discusses the main empirical results obtained from the econometric and spatial modeling of IMRs in municipalities of Northeast Brazil, from 2007 to 2021. Descriptive statistics of the variables used are presented here, followed by an analysis of the panel model selection tests and verification of the presence of spatial autocorrelation. Finally, the SDM-estimated coefficients are

presented in detail. The SDM highlights the direct and indirect effects of the explanatory variables. The section also explores the statistical significance and substantive interpretations of the results, engaging with the relevant literature to identify territorial patterns and social implications.

## Descriptive Data Analysis

Table 2 presents descriptive statistics for socioeconomic and demographic variables related to the IMR due to intestinal infectious diseases in northeastern municipalities over three five-year periods (2007–2011, 2012–2016, and 2017–2021). Analyzing these indicators in light of the literature enables identification of relevant trends and their association with structural and contextual factors that influence child health.

Table 2. Descriptive Statistics of the Socioeconomic and Demographic Variables Used

Variables	2007–2011		2012–2016		2017–2021	
	Average	CV	Average	CV	Average	CV
tx_mortinfant	7.9	97.9	9.0	95.1	9.2	93.6
vacc_coverage_rate	1.8	14.0	1.6	23.9	1.5	10.8
bf_beneficiary_families	3,403.9	229.2	3,897.0	223.7	3,924.5	213.0
mun_health_sanitation_exp_pc	672.6	54.0	850.6	47.2	1,045.1	40.9
Schooling	10.1	14.2	10.9	11.0	11.4	9.4
gdp_mun_per*	1,462.77	102.3	17,406.3	89.6	1,918.7	104.8

Note: \*The values for GDP\_mun\_per refer to the municipal GDP per capita, expressed in Reais (R\$).

Source: Own elaboration using data from the research

IMRs due to intestinal infectious diseases are observed, rising from 7.9 to 9.2 deaths per thousand live births between the analyzed periods, with a progressive reduction in the coefficient of variation (CV), indicating possible stabilization at high levels. This behavior contradicts the national trend of a significant decrease in IMR in recent decades (Boing & Boing, 2008; Sousa *et al.*, 2021), and suggests a worrying stagnation in the municipalities of the Northeast, in line with

the findings of Souza *et al.* (2021). These authors point to stationary behavior in infant mortality in some states of the region, reflecting structural limitations and persistent inequality in access to essential public goods.

The vaccination coverage rate (*vacc\_coverage\_rate*) shows a downward trend over time (from 1.8 to 1.5), with an increase in relative variability in the second period (CV from 14% to 23.9%) and, subsequently, a reduction (to 10.8%). This behavior is concerning, as vaccination is widely recognized as one of the most effective instruments for reducing infant mortality from preventable causes (Guimarães *et al.*, 2001; Victora *et al.*, 2011). The literature indicates that fluctuations in vaccination coverage reflect both operational problems in the National Immunization Program (PNI) and territorial inequalities in access to primary care (Pasklan *et al.*, 2021).

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Regarding the number of families benefiting from Bolsa Família (*bf\_beneficiary\_families*), there has been a continuous increase in the average value, though with a slight reduction in the CV, suggesting an expansion of the income transfer policy and greater regional homogeneity. The literature shows that Bolsa Família has a positive effect on reducing IMR, mainly by addressing social determinants such as poverty, food insecurity, and access to health services (Paes & Silva, 2020; Soares *et al.*, 2010). This increase coincides with the policy's consolidation in the 2010s and its expansion into the most vulnerable territories.

Expenditure on health and basic sanitation (*mun\_health\_sanitation\_exp\_pc*) increased by more than 50% between the first and last periods, with a reduction in CV. This suggests greater investment in sanitation infrastructure, a crucial factor in addressing preventable causes of infant mortality, such as diarrhea (Oliveira & Latorre, 2010; Rocha & Soares, 2015). Even so, the effect of these expenditures on the IMR may be limited in the short term, as structural improvements take time to translate into health outcomes.

The average schooling of the formally employed population also shows gradual growth (from 10.1 to 11.4 years), with a consistent decrease in CV. This progress aligns with investments in universalizing basic education in recent decades and with evidence that higher maternal and community education are associated with lower infant mortality (Barro & Lee, 2013). This relationship is due to increased knowledge about health practices and better use of public services.

Finally, GDP per capita showed progressive growth throughout the three periods: it increased from R\$1,462.77 (2007–2011) to R\$1,741.30 (2012–2016) and reached R\$1,918.70 in the period 2017–2021. Although the values are modest, this

continuous advance indicates a trend of local economic growth, albeit at a slow pace. However, the high CV across all periods (greater than 89%) indicates significant inequality in income distribution among municipalities, reinforcing the idea that aggregate gains do not necessarily translate into a generalized improvement in socioeconomic conditions. This high dispersion suggests that economic growth may be concentrated in a few regional centers, with little impact on infant mortality determinants. This diagnosis aligns with the findings of Bezerra Filho *et al.* (2007), which highlight the need for structural and intersectoral changes to ensure that economic development effectively translates into better child health indicators, especially in the most vulnerable territories.

Overall, the analysis suggests that, despite advances in sanitation, education, and income transfer programs, the persistence or increase in IMRs indicates that these policies have not been sufficient to break the structural mechanisms that perpetuate inequalities in child health in Northeast Brazil. Furthermore, reduced vaccination coverage and high economic inequality remain significant obstacles to the equitable improvement of health indicators.

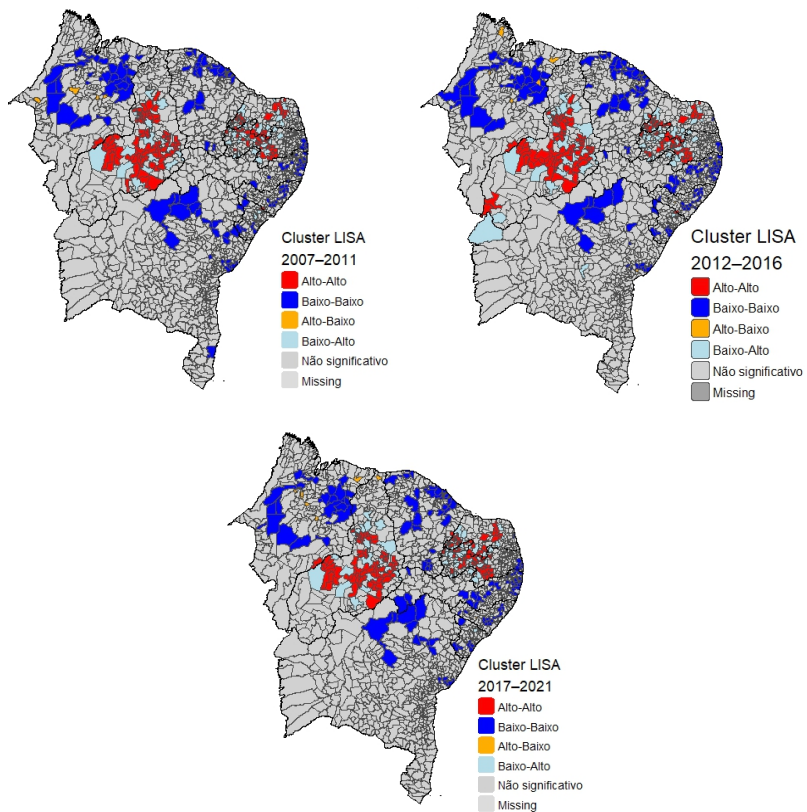
## Spatial Analysis

The temporal sequence of LISA maps of IMRs for the periods 2007–2011, 2012–2016, and 2017–2021 reveals persistent spatial patterns and gradual changes in the distribution of significant clusters across the analyzed territory. In the first period (2007–2011), important clusters of high infant mortality (*Alto-Alto*) are observed, concentrated mainly in the territory's central region, notably in southern Piauí, western Pernambuco, Paraíba, and Rio Grande do Norte (Figure 1). These clusters indicate municipalities with high IMRs, surrounded by municipalities with similar patterns, reflecting structural vulnerabilities and persistent deficits in basic sanitation, access to health care, and social infrastructure. These factors are widely recognized in the literature, as argued by Szwarcwald *et al.* (2014), who associate infant mortality with the precariousness of essential public services.

In the interim period (2012–2016), the spatial pattern of infant mortality remained very similar to that observed in the previous five-year period, with persistent High-High clusters concentrated in southwestern Maranhão, central Piauí, Paraíba, Rio Grande do Norte, and Pernambuco, revealing a continuation of socio-spatial vulnerabilities in these regions. At the same time, stable Low-Low areas were observed in the interior of Pernambuco, the central and metropolitan

region of Ceará, and the rural region of Paraíba, suggesting the maintenance of favorable contexts in these territories. Although public policies such as the expansion of the Family Health Strategy, the decentralization of neonatal care, and investments in sanitation and housing have contributed to the improvement of indicators in some localities (Silva & Pereira, 2019; Souza *et al.*, 2021), the effects of these actions were not distributed homogeneously.

Figure 1. LISA Index of the Average IMR in the Selected Periods in the Municipalities of the Northeast Region



Source: Own elaboration

In the most recent analysis (2017–2021), the spatial distribution of LISA clusters remains remarkably similar to that of previous periods, although there are occasional signs of reduced cluster intensity. Areas with High-High formations remain practically the same, and these areas continue to stand out negatively, alongside regions such as western Bahia and the surroundings of the Araripe Valley. Low-Low clusters, in turn, remain evident on the eastern coast of the Northeast, particularly in municipalities of Paraíba, Rio Grande do Norte, and Pernambuco, signaling the consolidation of progress in these regions. These results reflect both the cumulative effect of structural policies and the limitations in the coverage and effectiveness of actions in areas of greater vulnerability (Lima *et al.*, 2020; Victora *et al.*, 2011).

Thus, the three maps present a widely recurring spatial pattern: hotspots of high infant mortality persist in inland and economically fragile regions, while municipalities with greater institutional integration and public response capacity tend to cluster in low-mortality areas. The consistency of these patterns over 15 years reveals that advances in reducing infant mortality have been unequal, selective, and territorially concentrated, which requires more integrated public health strategies, sensitive to the territory and oriented towards overcoming the persistent socio-spatial inequalities in the Brazilian Northeast.

## Econometric Analysis of the Results

This section presents the econometric analysis of panel data with a spatial structure. The following subsection selects the most suitable model among fixed, random, and pooled effects based on statistical tests such as the Hausman test. In the following subsection, the spatial models (SAR, SEM, SLX, and SDM) are evaluated through the execution and analysis of tests. Finally, the selected model is interpreted, highlighting the direct and indirect effects of the explanatory variables on the IMR.

### *Choosing between Fixed, Random, and Pooled Effects*

Table 3 presents the statistical tests used to select the most suitable model for analyzing the IMR due to causes associated with intestinal infectious diseases in municipalities of Northeast Brazil, considering the alternatives, pooled OLS, FE, and RE. The results robustly indicate that the model with two-dimensional fixed effects (space and time) is superior in the panel analysis.

Table 3. Tests for Choosing between Pooled, Fixed Effects, and Random Effects Models for Infant Mortality in Municipalities of Northeast Brazil

Test	Statistic	<i>gl</i>	<i>p</i> -value	Decision
Standard Hausman	$Chi^2 = 687.93$	5	<0.0001	Reject H0
Robust Hausman (HC3)	$Chi^2 = 93.531$	5	<0.0001	Reject H0
Auxiliary Hausman	$Chi^2 = 687.93$	5	<0.0001	Reject H0
F (FE vs. Pooled)	$F = 17.801$	$gl1 = 1,806; gl2 = 25,083$	<0.0001	Reject H0
Breusch-Pagan—Individual	$Chi^2 = 47,504$	1	<0.0001	Reject H0
Breusch-Pagan—Temporal	$Chi^2 = 801.77$	1	<0.0001	Reject H0
Breusch-Pagan—Two-way	$Chi^2 = 48306$	2	<0.0001	Reject H0
Wald (CRE)	$Chi^2 = 220.89$	5	<0.0001	Reject H0

Source: Own elaboration using data from the research

The F-test (FE vs. Pooled) yields a high statistical value ( $F = 17.801; p < 0.0001$ ), rejecting the null hypothesis that the pooled model is sufficient and indicating that the fixed effects are statistically significant. Complementarily, the Breusch-Pagan tests detect significant heterogeneity both between units ( $Chi^2 = 47.504$ ) and between periods ( $Chi^2 = 801.77$ ), as well as the combined effect ( $Chi^2 = 48.306$ ), all with a *p*-value less than 0.0001. These results reinforce the presence of municipality- and year-specific effects, which should be controlled to avoid bias in the estimates.

The decision between FE and RE models is informed by Hausman tests (standard, robust [HC3], and auxiliary), which in all cases reject the null hypothesis of no correlation between individual effects and regressors ( $p < 0.0001$ ). This indicates that municipality-specific effects are correlated with the explanatory variables, which violates a fundamental assumption of the RE model. Consequently, the FE model is preferable, since it provides consistent estimates even in the presence of such correlation (Wooldridge, 2010).

Furthermore, the Wald test for correlation of random effects (CRE) also rejects the null hypothesis ( $Chi^2 = 220.89; p < 0.0001$ ), corroborating the evidence that RE is not adequate for the analyzed context. This conclusion is consistent with the results in the Appendix, which show that the FE model provides significant coefficients with signs consistent with the literature. In contrast, pooled and RE

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models tend to overestimate the effects of the explanatory variables (such as  $\log(-\text{vacc\_coverage\_rate})$  and  $\log(\text{bf\_beneficiary\_families})$ ), probably because they do not adequately control for unobserved heterogeneity across municipalities.

Therefore, based on the convergence of the tests presented in Table 3 and the comparison of the coefficients estimated in the Appendix, it is concluded that the two-dimensional FE model is the most suitable for analyzing IMRs caused by intestinal infectious diseases in the Northeast. It controls for unobservable, time-invariant characteristics across municipalities and for common temporal effects, thereby improving the robustness and validity of inferences about the socioeconomic determinants of infant mortality.

### *Choosing from the Spatial Models*

Table 4 presents the tests used to select the most suitable model for analyzing infant mortality in municipalities in the Northeast region of Brazil, using a spatial panel data structure. Initially, the two-way FE model yields a very low coefficient of determination ( $R^2 = 0.00296$ ), indicating low explanatory power. Even so, the  $F$ -test reveals that the regressors are statistically significant ( $F = 14.8972$ ;  $p < 0.0001$ ), which justifies their consideration as a reference model for applying the LM tests.

Table 4. Tests on the FE and SLX Models to Assess Spatial Effects and Select the Model for Estimating Infant Mortality in Municipalities of the Northeast Region

Test/Model	Statistic	$gl$	$p$ -value	Decision
FE- $R^2$ model	0.00296			
FE-F model	14.8972	5; 25,083	<0.0001	
LM (FE)—Lag	23,099	1	0.00000154	Reject H0
LM (FE)—Error	21,795	1	0.00000303	Reject H0
Robust LM (FE)—Lag	9.7701	1	0.001774	Reject H0
Robust LM (FE)—Error	8.4665	1	0.003617	Reject H0
LM (SLX)—Lag	21,194	1	0.00000415	Reject H0
LM (SLX)—Error	20,844	1	0.00000498	Reject H0
Robust LM (SLX)—Lag	5,102	1	0.0239	Reject H0
Robust LM (SLX)—Error	4.7516	1	0.02927	Reject H0

(Continued)

Test/Model	Statistic	<i>gl</i>	<i>p</i> -value	Decision
LogLik—SAR	-73,687.7			
LogLik—SDM	-73,678.3			
LogLik—SEM	-172,686			
LogLik—SDEM	-172,677			
AIC—SAR	147,389.4			
AIC—SDM	147,380.6			
AIC—SEM	345,386.8			
AIC—SDEM	345,377.1			
Baltagi Rule	SDM			

Source: Own elaboration using data from the research

The sequence of spatial dependence tests (LM and robust LM) on the FE model clearly indicates the presence of spatial autocorrelation in the residuals, both in the form of spatial lag of the dependent variable and spatial error. The LM tests (lag = 23,099; error = 21,795) and their robust equivalents (lag = 9.7701; error = 8.4665) both reject the null hypothesis in all cases ( $p < 0.01$ ), reinforcing the inadequacy of traditional models that do not account for the spatial structure of the data. As highlighted by Elhorst (2014), the presence of residual spatial autocorrelation compromises the validity of the inferences and requires the adoption of appropriate spatial models.

Tests applied to the SLX model, which includes spatial lags of the explanatory variables, also reveal the persistence of spatial effects not captured by this structure. The LM tests (lag = 21,194; error = 20,844) and the robust tests (lag = 5.102; error = 4.7516) continue to reject the null hypothesis at the 5% significance level ( $p < 0.05$ ). This shows, according to LeSage and Pace (2009), that lags of the covariates alone are not sufficient to eliminate residual spatial effects, which require more comprehensive models, such as SAR or SDM.

SEM, SDM, and SDEM spatial models were guided by the log-likelihood and information criteria (AIC). The SDM model had the lowest AIC value (147,380.6), followed by SAR (147,389.4), while the SEM and SDEM models had much higher values (345,386.8 and 345,377.1, respectively), indicating substantially worse fits. Similarly, the log-likelihood values confirm SDM's better performance (logLik = -73,678.3), surpassing the other models. These results are consistent with Elhorst's (2014) arguments, which hold that the SDM model is the most flexible among

the standard spatial models, as it simultaneously incorporates the spatial lag of the dependent variable and the covariates.

Based on Baltagi's rule and likelihood ratio tests between nested models (SAR vs. SDM and SEM vs. SDEM), the final decision indicated that the SDM model was the most suitable for estimating infant mortality in Northeast Brazil. This decision is supported by both formal tests and spatial econometric theory, which recommends SDM in contexts with robust evidence of multiple spatial dependence. The adoption of the SDM model allows for the simultaneous capture of direct, indirect, and spatial feedback effects, offering greater robustness to policy and academic inferences about the determinants of infant mortality.

These results are consistent with studies such as those by Silva and Pereira (2019) and Souza *et al.* (2021), which highlight the importance of local and structural factors in the territorial configuration of infant mortality in Brazil. Incorporating the spatial dimension into the model allows us to highlight the influence of regional externalities and the spatial diffusion of public policies and socioeconomic conditions, both of which are essential for designing more equitable and efficient public health strategies. Thus, the analysis not only ensures statistical rigor but also contributes to a more precise and territorially sensitive understanding of inequalities in child health.

Furthermore, the use of time lags in the covariates is based on the recognition that the socioeconomic and institutional determinants of infant mortality do not produce immediate effects on health outcomes but rather operate through cumulative, delayed mechanisms. Changes in vaccination coverage, expansion of the Bolsa Família program, investments in sanitation, and educational variations, for example, require time to alter living conditions, behavioral patterns, and effective access to public services. Thus, the inclusion of lags helps adequately represent the temporal dynamics of the infant mortality production process, avoiding the assumption of unrealistic contemporary cause-and-effect relationships.

From an econometric perspective, lags help mitigate potential endogeneity problems, especially simultaneity and reverse causality, since public policy indicators and socioeconomic variables may respond within the same period to worsening child health in municipalities, generating spurious correlation with the error term. By temporally shifting the covariates, the possibility that current IMRs directly influence the regressors is reduced, thus increasing the consistency of the estimates. Furthermore, in spatial models, lags allow for the adequate capture of sociospatial diffusion effects, recognizing that policies, investments,

and social changes gradually spread across the territory and between neighboring municipalities. Therefore, the choice to use lags is consistent with the literature on infant mortality and with methodological recommendations for spatial panel models, reinforcing the robustness of the inferences.

### Analysis of the results

Table 5 presents the coefficients estimated by the spatial model. The SDM for IMR due to intestinal infectious diseases in municipalities of Northeast Brazil between 2007 and 2021. The model captures not only the direct effects of the explanatory variables but also the indirect spatial effects by incorporating the spatial lags of the covariates. The analysis of the results reveals the relevance of socioeconomic, public health, and structural factors in the behavior of the IMR, in line with the literature.

Table 5. Estimated Coefficients by the SDM for Infant Mortality in Municipalities of the Northeast (2007–2021)

Variable	Estimated I	Standard error	t-value	p-value	Significance
log(vacc_coverage_rate)	-1.4384	0.3033	-4.7425	0.0000	***
log(bf_beneficiary_families)	-1.2038	0.2095	-5.7457	0.0000	***
log(mun_health_sanitation_exp_pc)	0.0242	0.0182	1.3272	0.1844	
log(schooling)	0.5359	0.2795	1.9176	0.0552	
log(gdp_mun_per)	-0.0266	0.1593	-0.1670	0.8674	
lag_vacc_coverage_rate	-0.0263	0.5415	-0.0486	0.9612	
lag_bf_beneficiary_families.x	-1.5232	0.3982	-3.8254	0.0001	***
lag_mun_health_sanitation_exp_pc	0.0259	0.0403	0.6425	0.5206	
lag_schooling	-1.0180	0.6240	-1.6316	0.1028	
lag_gdp_mun_per	-0.3389	0.2744	-1.2352	0.2168	
Lambda	0.0502	0.0094	5.3498	0.0000	***

Source: Own elaboration using data from the research

Vaccination coverage shows a negative and highly significant coefficient (log(-vacc\_coverage\_rate) = -1.4384;  $p < 0.0001$ ), indicating that the increase in the

proportion of the vaccinated population is associated with a reduction in infant mortality, as pointed out by Guimarães *et al.* (2001) and Victora *et al.* (2011). This result confirms the central role of immunization as one of the most effective measures to prevent avoidable deaths, especially in contexts of high vulnerability.

The number of families benefiting from Bolsa Família is also negatively associated with IMRs due to its association with intestinal infectious diseases ( $\log(\text{bf\_beneficiary\_families}) = -1.2038$ ;  $p < 0.0001$ ), corroborating studies such as those by Boing and Boing (2008) and Soares *et al.* (2010), which highlight the redistributive effects of the program on the social determinants of health. This impact is reinforced by the spatial component ( $\text{lag\_bf\_beneficiary\_families.x} = -1.5232$ ;  $p = 0.0001$ ), indicating that the program's coverage in a municipality also contributes to reducing infant mortality in its neighbors. This finding highlights positive externalities of income transfer policies in regional contexts, reinforcing the argument of Bezerra Filho *et al.* (2007) on the importance of intermunicipal and integrated policies.

The variable per capita expenditure on basic sanitation did not show statistical significance ( $p = 0.1844$ ) at either the local or the neighboring level, suggesting a structural nature to its effects, which manifest only in the long term. Studies such as those by Oliveira and Latorre (2010) and Rocha and Soares (2015) emphasize that sanitation is essential to prevent diseases, such as diarrhea, which causes preventable infant deaths. Thus, the lack of significance may stem more from the time lag between investment and impact than from the absence of an effect.

The average schooling of the employed population ( $\log(\text{schooling}) = 0.5359$ ;  $p \approx 0.0552$ ) shows a positive and marginally significant coefficient, which may seem counterintuitive. However, as observed in other analyses (Silva, 2001), this result may be due to collinearity or to the fact that the schooling of the economically active population does not directly reflect the educational level of mothers or guardians of young children, which is the factor most directly related to child health. In the spatial component ( $\text{lag\_schooling}$ ), the effect is also adverse, but not significant.

This point deserves further discussion regarding the positive coefficient associated with the average schooling of the formally employed population. This result, at first glance, contradicts the classic literature, which holds that higher levels of education tend to reduce infant mortality by increasing access to information, adopting preventive practices, and using health services more effectively. However, some hypotheses may help to explain this seemingly paradoxical behavior.

First, the variable used, average schooling of the formally employed population, may not adequately reflect the educational level of mothers, which is the factor most directly related to infant outcomes. Thus, municipalities with more sophisticated economic sectors tend to have higher levels of formal education among workers, but this does not necessarily imply better socioeconomic or educational conditions for families with young children.

Second, this indicator may capture the effects of urban composition: more economically developed municipalities tend to concentrate on regional hospitals and referral maternity wards, which increases the number of deaths registered locally (a case-attraction effect), artificially increasing the local IMR.

Third, schooling may be correlated with omitted variables, such as intra-municipal inequality, informality, or precarious housing, which may bias the coefficient. These factors, combined, suggest that the result does not invalidate the expected relationship between education and child health, but reveals limitations of the indicator used and territorial complexities that deserve to be explored in future studies, either through more specific measures of maternal schooling or through additional controls for inequality and the local socioeconomic structure.

The municipal GDP per capita ( $\log(\text{gdp\_mun\_per})$ ) and its spatial lag were not statistically significant ( $p = 0.8674$ ). This lack of association reinforces the idea, already pointed out by Bezerra Filho *et al.* (2007) and Pasklan *et al.* (2021), that economic growth, by itself, does not guarantee better living conditions, especially when development is unequal and concentrated in specific urban centers.

Finally, the lambda parameter (spatial autocorrelation coefficient) was positive and highly significant ( $\lambda = 0.0502$ ;  $p < 0.0001$ ), confirming the presence of spatial dependence in the IMR. This validates the adoption of the SDM model, which is more appropriate for incorporating the effects of spatial contagion, both direct and indirect, of socioeconomic and institutional factors.

Thus, the results show that IMRs due to intestinal infectious diseases in the Northeast are strongly associated with vaccination coverage and the presence of the Bolsa Família program, including its neighborhood effects. The absence of an impact from GDP per capita and sanitation expenditures demonstrates that economic growth alone, or a one-off infrastructure investment, is insufficient to reverse infant mortality patterns in contexts of high inequality. Universal social policies and intermunicipal protection mechanisms remain the most effective instruments in combating inequalities in child health.

## Final Considerations

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The analyses conducted in this study sought to understand the socioeconomic determinants of infant mortality in municipalities of Northeast Brazil between 2007 and 2021, with special attention to the spatial effects associated with the phenomenon. Based on the hypothesis that territories with lower socioeconomic development tend to have higher IMRs, a spatial panel econometric model, SDM, was adopted. This methodological choice allowed for capturing not only the direct effects of the explanatory variables in the analyzed municipalities, but also the indirect effects resulting from the influence of neighboring municipalities. The spatial approach is justified by the diffuse nature of health determinants, which often transcend local administrative boundaries. Furthermore, the analysis was supported by a solid empirical basis and a theoretical framework that highlights the importance of public policies in health, education, sanitation, and income transfer for reducing infant mortality.

The results revealed that the IMR due to causes associated with intestinal infectious diseases, despite showing a trend towards stability in recent years, remains high in many municipalities in the Northeast of Brazil, mainly in inland regions and those historically more vulnerable. Descriptive analysis highlighted important advances, including increased public spending on sanitation, higher average educational attainment, and expanded coverage of the Bolsa Família program. However, these advances were insufficient to sustain and broaden a decline in infant mortality, indicating the persistence of structural inequalities. High coefficients of variation in variables such as GDP per capita and vaccination coverage indicate an unequal distribution of resources and basic services, compromising the effectiveness of public policies in reaching the populations most at risk.

In the econometric model, vaccination coverage and the proportion of families receiving Bolsa Família benefits, both within the municipality and in its neighbors, were statistically significant determinants of the reduction in IMRs. These findings reinforce the importance of universal public policies and income transfer programs in mitigating health inequalities. On the other hand, the absence of significant effects on GDP per capita and on spending on health and basic sanitation suggests that aggregate economic improvements and targeted infrastructure investments do not automatically translate into better health indicators, especially when not accompanied by structural, integrated, and territorially targeted actions. The marginal significance of schooling also raises reflections on the type of indi-

cator used, suggesting that variables more directly related to maternal education and childcare could have greater explanatory power.

The significant spatial autocorrelation coefficient ( $\lambda$ ) and lagged spatial effects for some variables highlight regional contagion patterns in infant mortality, in which the socioeconomic and institutional contexts of neighboring municipalities directly influence local outcomes. This finding supports the relevance of spatial models for understanding public health problems and confirms that the social geography of municipalities matters for the effectiveness of public interventions. The SDM proved to be the most appropriate, as it incorporates second-order effects associated with the distribution of services, people's mobility, and the diffusion of public policies across adjacent territories, revealing that addressing infant mortality requires a logic of regional and cooperative planning.

The results of this research have important implications for public and economic policies in the Northeast region of Brazil. Empirical evidence demonstrates that combating infant mortality depends not only on economic growth but also on the coordinated action of redistributive social programs and high-impact public health policies. The Bolsa Família program and vaccination coverage were the most relevant factors in reducing the IMR studied, underscoring the need to maintain and expand these policies, especially during periods of fiscal contraction. Furthermore, the finding of positive externalities between neighboring municipalities reinforces the strategic role of federative cooperation and networking among subnational entities. From an economic policy perspective, the findings highlight that the social return on investments in basic child protection is significant and contributes directly to the formation of human capital and the reduction of intergenerational inequalities.

Based on these findings, new opportunities arise to deepen understanding of the spatial dynamics of infant mortality and other public health indicators. Future studies could incorporate environmental variables (such as access to drinking water, drought, or temperature indices), institutional dimensions (such as the quality of municipal public management or the effectiveness of primary care), and disaggregations by sex and race/color of the affected children. Additionally, the use of more sophisticated spatial analysis techniques, such as spatial dynamic panel models or Bayesian approaches, can yield a more refined understanding of interactions between territories. Thus, this study not only confirms the relevance of the spatial dimension in the analysis of infant mortality but also suggests that

overcoming health inequalities requires an integrated, multi-scalar approach sensitive to local realities.

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## Appendix. Estimated Models for Choosing the Adjustment for the Infant Mortality Rate (Up to 1 Year)

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Variables	Dependent variable: tx_mortinfant		
	Pooled OLS	Fixed effects	Random effects
log(vacc_coverage_rate)	-6.1569 *** (0.2464)	-1.4065 *** (0.2964)	-3.2278 *** (0.2621)
log(bf_beneficiary_families)	-6.7617 *** (0.0397)	-1.4572 *** (0.2059)	-5.5647 *** (0.0979)
log(mun_health_sanitation_exp_pc)	0.2457 *** (0.0243)	0.0251 (0.0188)	0.0736 *** (0.0188)
log(schooling)	3.8217 *** (0.2524)	0.5320 * (0.2868)	2.0757 *** (0.2697)
log(gdp_mun_per)	0.9425 *** (0.0779)	-0.0702 (0.1505)	0.3767 *** (0.1243)
Constant	50.6420 *** (0.7234)		46.8065 *** (1.0042)
Observations	26,895	26,895	26,895
R <sup>2</sup>	0.5406	0.0030	0.1126
Adjusted R <sup>2</sup>	0.5405	-0.0690	0.1124

Note. \*  $p < 0.10$ ; \*\*  $p < 0.05$ ; \*\*\*  $p < 0.01$

Source: Own elaboration