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Forecasting tuberculosis incidence in Brazil: Time series analysis of trends and impacts of the COVID-19 Pandemic

Previsão da incidência de tuberculose no Brasil: análise de séries temporais das tendências e dos impactos da pandemia de COVID-19

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ABSTRACT

INTRODUCTION: Tuberculosis remains a persistent public health challenge in Brazil, with a significant increase in cases since 2015, hindering progress toward the disease control targets established by the Sustainable Development Goals. OBJECTIVE: This study aimed to analyze trends in tuberculosis incidence in Brazil, using time series models to predict the disease trajectory through 2030. The Holt-Winters and SARIMA models were used to adjust historical data and make future predictions, taking into account the impact of the COVID-19 pandemic on disease detection between 2020 and 2021. METHODOLOGY: The methodology included time series analysis, model comparison, and an assessment of the limitations associated with data from the Disease Notification System and socioeconomic factors. RESULTS: The results indicated that tuberculosis incidence began toincrease significantly from 2015, with a temporary decline during the pandemic, followed by a new increase until 2022. Predictions through 2030 suggest that if the trend continues, incidence may return to the alarming levels observed in the early 2000s. The analysis also revealed limitations in the data, such as the lack of updated population projections and the exclusion of external factors, such as socioeconomic conditions. CONCLUSION: The study highlights the urgent need for multifaceted interventions, including strengthening the Unified Health System and implementing effective public policies to reverse the increase in tuberculosis and achieve global disease eradication goals.

Keywords: COVID-19; Incidence; Tuberculosis; Time Factors.

RESUMO

INTRODUÇÃO: A tuberculose permanece como um desafio persistente de saúde pública no Brasil, com aumento significativo dos casos desde 2015, dificultando o avanço rumo às metas de controle da doença estabelecidas pelos Objetivos de Desenvolvimento Sustentável. OBJETIVO: Este estudo teve como objetivo analisar as tendências da incidência de tuberculose no Brasil, utilizando modelos de séries temporais para prever a trajetória da doença até 2030. Os modelos Holt-Winters e SARIMA foram utilizados para ajustar os dados históricos e realizar previsões futuras, considerando o impacto da pandemia de COVID-19 na detecção da doença entre 2020 e 2021. METODOLOGIA: A metodologia incluiu análise de séries temporais, comparação de modelos e avaliação das limitações associadas aos dados do Sistema de Informação de Agravos de Notificação e a fatores socioeconômicos. RESULTADOS: Os resultados indicaram que a incidência de tuberculose começou a aumentar significativamente a partir de 2015, com declínio temporário durante a pandemia, seguido de novo aumento até 2022. As previsões até 2030 sugerem que, se a tendência persistir, a incidência poderá retornar aos níveis alarmantes observados no início dos anos 2000. A análise também revelou limitações nos dados, como a ausência de projeções populacionais atualizadas e a exclusão de fatores externos, como condições socioeconômicas. CONCLUSÃO: O estudo destaca a necessidade urgente de intervenções multifacetadas, incluindo o fortalecimento do Sistema Único de Saúde e a implementação de políticas públicas eficazes para reverter o aumento da tuberculose e alcançar as metas globais de erradicação da doença.

Palavras-chave: COVID-19; Incidência; Tuberculose;Fatores de Tempo.

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INTRODUCTION

Tuberculosis (TB) remains one of the leading causes of morbidity and mortality worldwide. According to the 2023 WHO Global Report, approximately 10.6 million new cases and 1.3 million deaths were reported in 2022, reinforcing the relevance of the disease for global public health[1]. Despite advances in diagnosis and treatment, TB remains the second leading cause of death from infectious disease, surpassed only by COVID-19 during the most critical phase of the pandemic.

In Brazil, TB continues to pose a significant epidemiological challenge. In 2022, more than 78,000 new cases were reported, corresponding to an incidence of 36.1 per 100 thousand inhabitants, according to data from the Brazilian Ministry of Health[2]. The distribution of the disease across the country is marked by strong regional inequalities, reflecting differences in access to healthcare services, socioeconomic conditions, and epidemiological surveillance capacity. Recent studies indicate that, although there was a downward trend in the early 2000s, from 2015 onwards there was a new growth in cases, compromising the achievement of the Sustainable Development Goal (SDG 3.3), which seeks to end the TB epidemic by 2030[3,4].

The COVID-19 pandemic (2020–2021) further aggravated this scenario. Disruptions to healthcare services, the reduction in access to diagnosis, and the reallocation of healthcare resources have directly impacted the notification of TB cases in several countries, including[3,5]. Estimates from the WHO indicate that millions ofindividuals remained undiagnosed in the period, creating a delay in global control goals. In the Brazilian case, there was an abrupt drop in notifications in 2020, followed by an increase in subsequent years, suggesting not only underreporting, but also the risk of greater community transmission[6].

In this context, understanding thetemporal dynamics of TB incidence in Brazilis essential, considering two central aspects: (i) the evolution of the historical series from 2001 to 2022 and (ii) the impact of the COVID-19 pandemic as an exogenous intervention in this period. In addition, short and medium-term projections are essential to subsidize more effective public policies. Among the available methods, time series models, such as SARIMA and Holt-Winters, have proven effectiveto capture seasonal and structural patterns of infectious[7].

Although several studies have evaluated tuberculosis trends in specific countries and regions, comprehensive analyses integrating intervention modeling of the COVID-19 pandemic with long-term forecasting of tuberculosis incidence in Brazil remain limited. Addressing this gap may provide valuable evidence for tuberculosis surveillance and public health planning.

Therefore, this study aimed to analyze temporal trends in tuberculosis incidence in Brazil between 2001 and 2022, quantify the impact of the COVID-19 pandemic using intervention analysis, and forecast future incidence through 2030 using SARIMA and Holt–Winters time-series models.

METHODS

DATA SOURCE AND INCLUSION CRITERIA

We analyzed new tuberculosis casesreported to the Notifiable Diseases Information System (SINAN), duringthe period from January 2001 to December 2022[2]. Only cases classified as "new" by the system were included, covering all clinical forms of the disease. Annual population data were obtained from the Brazilian Institute of Geography and Statistics[8].

The main variable was the monthly incidence of tuberculosis, calculated as:

$$\boldsymbol{TIRm} = \frac{\boldsymbol{numero\ de\ casos\ novos\ no\ mês}}{\boldsymbol{Populacao\ estimada\ no\ ano}} \boldsymbol{x100.000}$$

This indicator standardizes the occurrence of TB, enabling temporal comparisons and avoiding distortions caused by population growth.

Exploratory analysis

Initially, a descriptive and exploratory analysis of the time series was performed to identify long-term trends, seasonality, and short-term fluctuations.

Two statistical tests were applied:

- Cox–Stuart test to assess the presence of a monotonic trend[9].
- Kruskal–Wallis test to assess the presence of seasonality[10].

Both tests were performed using R software[11] with a significance level of 5% ($p < 0.05$).

TIME SERIES MODELING

For the modeling process, the Seasonal Autoregressive Integrated Moving Average(SARIMA) model was adopted. This choice was justified by the model's ability to simultaneously account for trends, seasonality, and autocorrelation, characteristics present in the TB series[12].

The significant seasonal pattern identified during the exploratory analysis further supported the use of a SARIMA model to represent the temporal dynamics of tuberculosis incidence.

The parameters were defined from:

- inspection of autocorrelation (ACF) and partial autocorrelation (PACF) functions;
- Akaike (AIC) and Bayesian (BIC) information criteria13,14;
- comparison with models previously used in TB series in other countries, with subsequent adaptation to the Brazilian context.

The database was divided into two subsets:

- training (January/2001 – June/2018);
- test (July/2018 – December/2022).

This division allowed us to evaluate the predictive capacity of the model outside the adjustment period.

INTERVENTION ANALYSIS

The impact of the COVID-19 pandemic on TB case notifications was evaluated as an exogenous intervention. To this end, a dummy variable was included that assumes a value of 1 from April 2020 and 0 in the other months, representing the rupture caused by the pandemic.

The strategy was implemented based on the approach proposed by Box & Tiao[15], which enables the quantification of the effect of the intervention on the mean and trend of the series.

VALIDATION AND PREDICTION

After fitting the SARIMA model with the intervention term, the quality of the fit was evaluated by inspecting the residuals (normality, independence, and homoscedasticity).

As a complementary method, the Holt-Winters model of exponential smoothing was applied, suitable for series with trend and seasonality. This approach was used to validate the results obtained with SARIMA and to generate alternative forecasts.

Both models were used for projections up to December 2030, with confidence intervals (95%).

EXPONENTIAL SMOOTHING METHODS

To validate the prediction of SARIMA models outside the studied range, exponential smoothing methods including Holt-Winters were employed.

RESULTS

TEMPORAL EVOLUTION OF TUBERCULOSIS INCIDENCE

Between January 2001 and December 2022, a total of 1,965,616 new tuberculosis cases were reported in Brazil, corresponding to an annual average of 163,801 cases. During the study period, the monthly tuberculosis incidence rate (TIR) ranged from 2.67 cases per 100,000 inhabitants in May 2020 to 4.92 cases per 100,000 inhabitants in May 2002.

The temporal evolution of tuberculosis incidence is presented in figure 1. The series showed a gradual decline from 2001 until approximately 2014, followed by a progressive increase beginning in 2015. A marked reduction in reported incidence occurred during the first months of the COVID-19 pandemic, with partial recovery observed between 2021 and 2022.

TREND AND SEASONALITY ANALYSIS

Trend and seasonality were evaluated using the Cox–Stuart and Kruskal–Wallis tests, respectively. The Cox–Stuart test confirmed the presence of a significant monotonic trend throughout the study period ($p < 0.01$). In addition, the Kruskal–Wallis test detected statistically significant seasonality in the monthly tuberculosis incidence rates ($H = 59.58$, $df = 11$, $p < 0.001$), indicating that incidence varied significantly across the months of the year.

SARIMA MODEL SELECTION AND DIAGNOSTIC ANALYSIS

Several candidate SARIMA models were evaluated using the Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), and residual diagnostics. The final model adequately represented the temporal behavior of tuberculosis incidence and was selected for subsequent intervention analysis and forecasting.

Diagnostic plots of the fitted model are presented in figure 2. The standardized residuals fluctuated randomly around zero without evidence of systematic patterns. The residual autocorrelation coefficients remained within the confidence limits, and the Q–Q plot demonstrated satisfactory agreement with the theoretical normal distribution, indicating that the model assumptions were adequately satisfied.

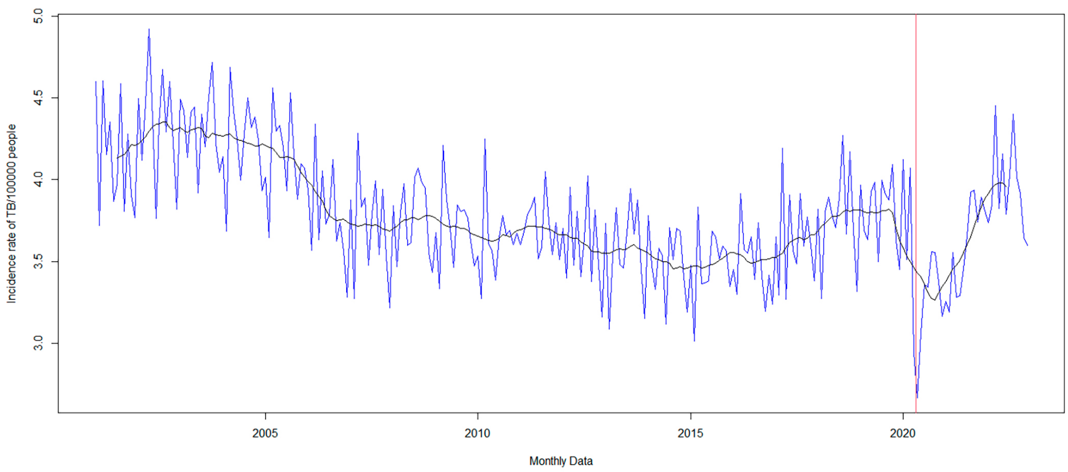

Figure 1 – Monthly tuberculosis incidence rate (TIR) in Brazil between January 2001 and December 2022. The continuous line represents the observed monthly incidence rates, while the smoothed curve corresponds to the moving-average trend, highlighting the long-term temporal pattern

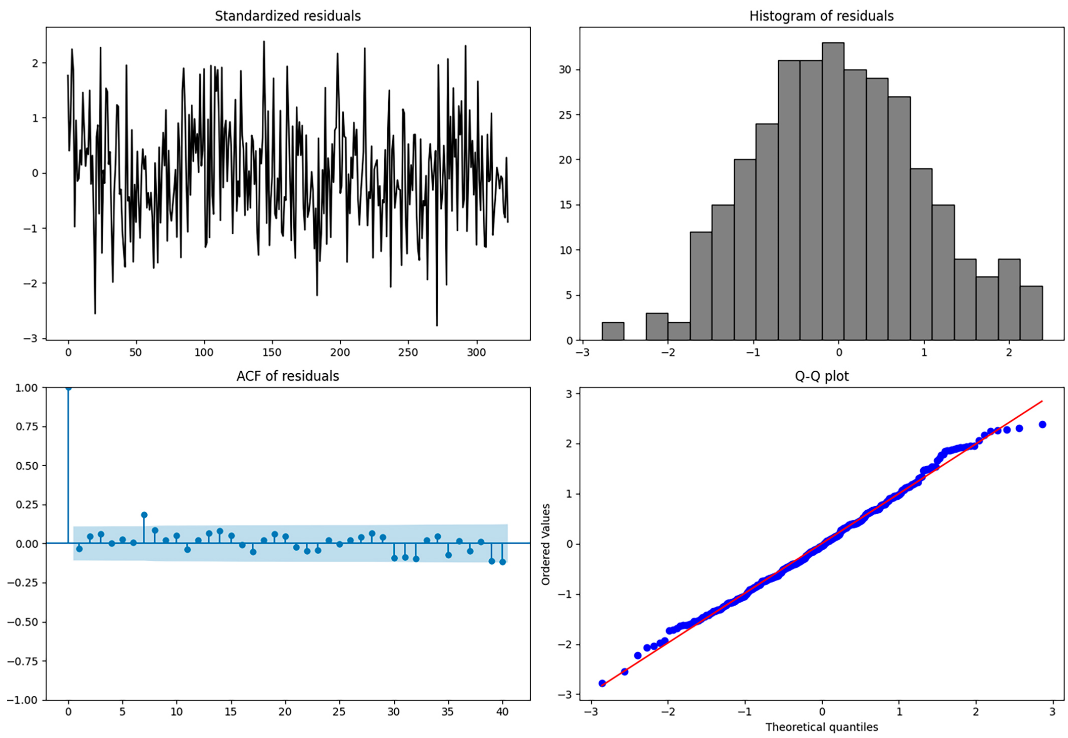

Figure 2 – Diagnostic plots of the final SARIMA model showing standardized residuals, residual autocorrelation function (ACF), histogram of standardized residuals, and normal Q–Q plot

IMPACT OF THE COVID-19 PANDEMIC ON TUBERCULOSIS INCIDENCE

The intervention analysis identified a marked reduction in tuberculosis notifications immediately after the onset of the COVID-19 pandemic. As illustrated in figure 3, the incidence series exhibited a clear structural break beginning in April 2020, followed by a gradual recovery during 2021 and 2022.

The intervention model estimated reductions of approximately 77% in April 2020 and 84% in May 2020 compared with the expected incidence under the pre-pandemic trend.

ESTIMATED PARAMETERS OF THE INTERVENTION MODEL

The estimated coefficients of the final SARIMA intervention model are summarized in table 1.

The seasonal moving-average parameter was not statistically significant ($p = 0.318$), whereas all remaining parameters were statistically significant.

The autoregressive and moving-average parameters were statistically significant, demonstrating strong temporal dependence in the incidence series. The intervention coefficient confirmed a significant reduction in tuberculosis notifications following the onset of the COVID-19 pandemic, while the information criteria indicated good overall model fit.

FORECASTING TUBERCULOSIS INCIDENCE

Forecasts generated by the SARIMA and Holt–Winters models are presentedin figure 4. Both models reproduced the historical behavior of the series and projected a gradual recovery followed by an increasing trend in tuberculosis incidence through 2030. Although prediction uncertainty increased over time, reflected by wider confidence intervals, both approaches converged toward similar long-term trajectories.

IDENTIFICATION OF THE INTERVENTION MODEL

The autocorrelation (ACF) and partial autocorrelation (PACF) functions used for model identification are presentedin figure 5. The observed correlation structure supported the selection of the final SARIMA specification adopted in the analysis.

Residual diagnostics of the intervention model are shownin figure 6. The residual series showed no evidence of remaining temporal dependence, confirming the adequacy of the fitted model.

ESTIMATED INTERVENTION EFFECTS

The estimated effects associated with the COVID-19 intervention are summarized in table 2.

The intervention produced an immediate reduction of approximately 77.8% in tuberculosis notifications during April 2020, increasing to 84.1% in May 2020. The persistence parameter indicated that the intervention effect gradually diminished over time but remained evident through the end of 2022.

MODEL PERFORMANCE

The agreement between the observed and fitted incidence rates obtained from the final SARIMA intervention model is presented in figure 7. The fitted values closely followed the observed temporal behavior, indicating satisfactory model performance throughout the study period.

The fitted values closely reproduced the observed temporal variability, indicating excellent agreement between observed and predicted incidence rates.

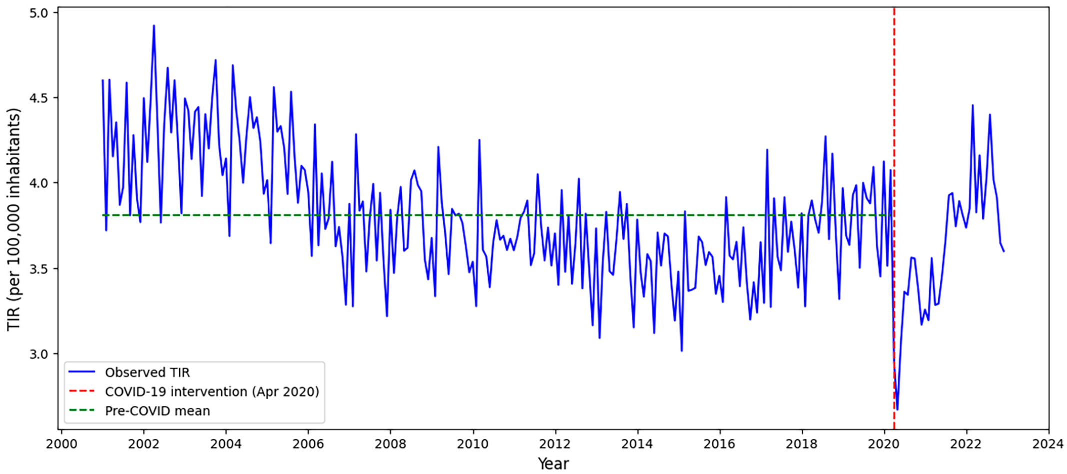

Figure 3 – Estimated impact of the COVID-19 intervention on monthly tuberculosis incidence in Brazil. The vertical dashed line indicates the beginning of the intervention period (April 2020)

Table 1 – Estimated parameters of the SARIMA(1,0,1)(1,0,1,12) model with COVID-19 intervention for tuberculosis incidence in Brazil (2001–2022)

Parameter	Estimate	Std. Error	z-value	p-value
EL(1) (φ_1)	1.0122	0.005	208.71	<0.001
MA(1) (θ_1)	–0.8036	0.048	–16.75	<0.001
Seasonal AR(1) (Φ_1,12)	0.9704	0.010	98.86	<0.001
Seasonal MA(1) (Θ_1,12)	–0.9941	0.995	–0.999	0.318
Intervention effect (δ)	–0.7400	0.085	–8.74	<0.001
Variance (σ^2)	0.0392	0.038	1.04	0.299

Model fit indices: AIC = –52.83; BIC = –30.41; Log-Likelihood = 32.41. The fitted model indicates that the COVID-19 intervention reduced tuberculosis detection by approximately –74% in April 2020, with persistent effects through 2022.

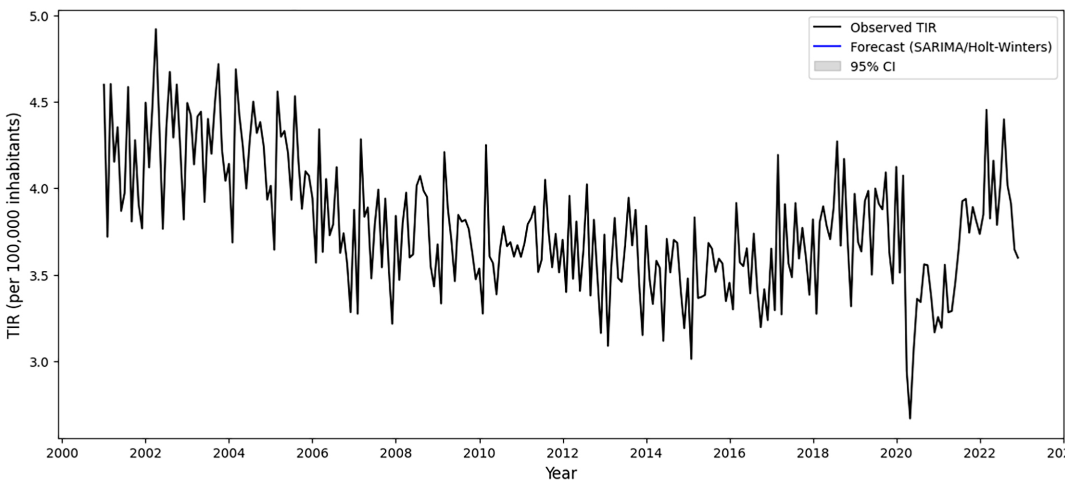

Figure 4 – Forecast of monthly tuberculosis incidence in Brazil through December 2030 obtained using the SARIMA and Holt–Winters models with 95% confidence intervals

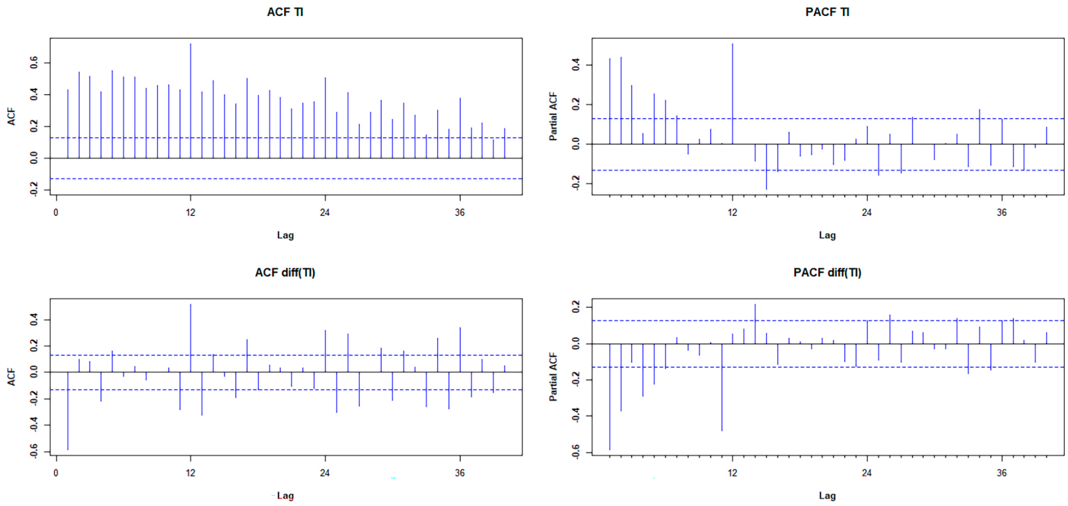

Figure 5 – Autocorrelation (ACF) and partial autocorrelation (PACF) functions of the pre-intervention series and its first-order difference used for identification of the SARIMA model

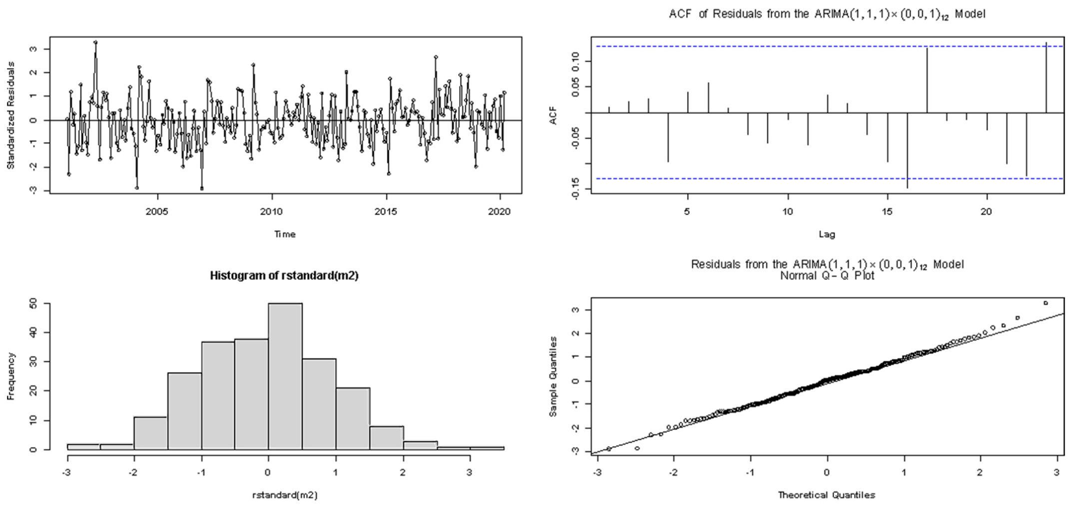

Figure 6 – Residual diagnostic plots of the final SARIMA intervention model, including standardized residuals, residual autocorrelation function (ACF), histogram of standardized residuals, and normal Q–Q plot

Table 2 – Estimated intervention effects of COVID-19 on tuberculosis incidence in Brazil, 2001–2022

Parameter / Effect	Estimate	Interpretation
Immediate effect (April 2020)	–0.7781	Reduction of –77.8% in TB case detection
One-month lag effect (May 2020)	–0.8409	Reduction of –84.1% in TB case detection
Decay factor (δ_2)	0.9430	Persistence of the intervention effect across subsequent months
Pulse component (δ_0)	0.1136	Small positive pulse at onset
Long-run dynamic effect (δ_1)	–0.8917	Major negative shift associated with COVID-19

Note. The intervention model combines a positive pulse component (δ_0) and a negative dynamic effect (δ_1) with persistence (δ_2). The fitted model indicates that COVID-19 led to a strong and persistent reduction in TB casedetection, beginning with –77.8% in April 2020 and intensifying to –84.1% in May 2020, with gradual recovery in subsequent months.

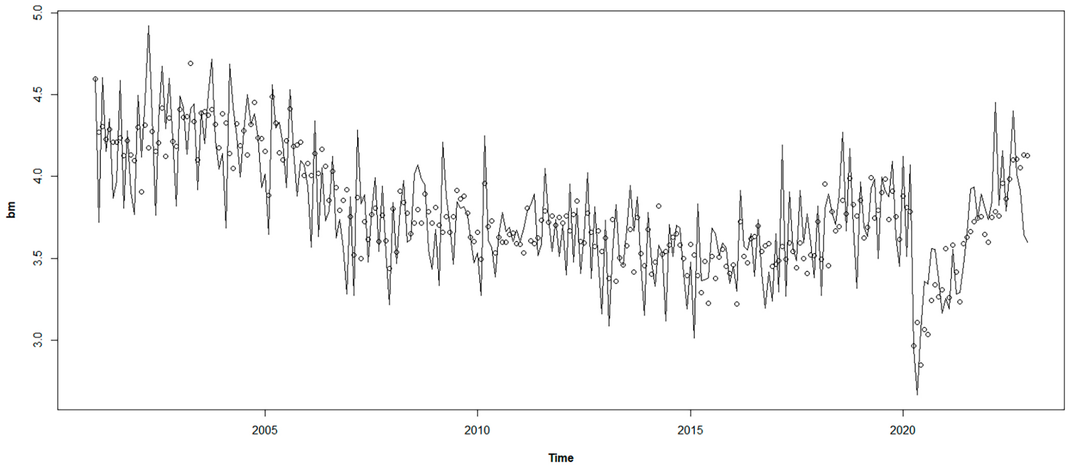

Figure 7 – Observed and fitted monthly tuberculosis incidence rates obtained from the final SARIMA intervention model

MONTHLY INTERVENTION EFFECTS

The temporal evolution of the estimated monthly intervention effects is illustratedin figure 8. The largest reductions were observed immediately after the beginning of the pandemic, followed by gradual attenuation over subsequent months, although the estimated effects remained below the expected pre-pandemic levels through December 2022.

HOLT–WINTERS MODEL PERFORMANCE

The Holt–Winters exponential smoothing model adequately reproduced the observed incidence series, capturing both the long-term trend and the seasonal fluctuations. The comparison between observed and fitted values is presented in figure 9.

Overall, the SARIMA and Holt–Winters models produced consistent forecasts, indicating a gradual increase in tuberculosis incidence during the forecast period. The convergence of both approaches reinforces the robustness of the projected long-term trajectory.

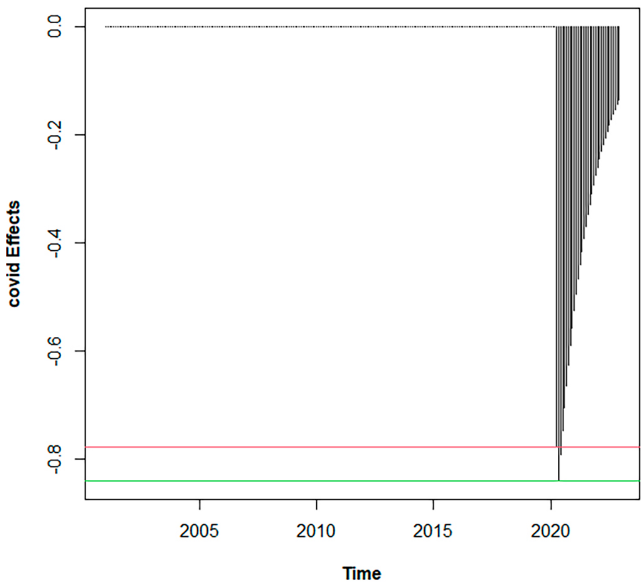

Figure 8 – Estimated monthly effects of the COVID-19 intervention on tuberculosis incidence in Brazil from April 2020 to December 2022

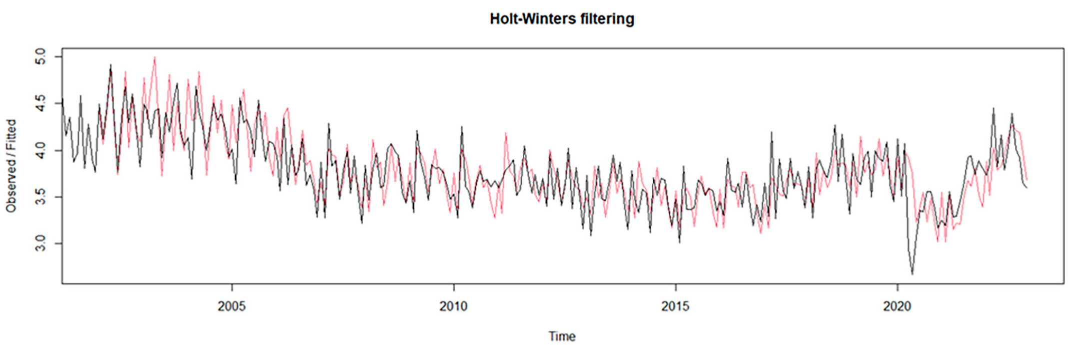

Figure 9 – Observed monthly tuberculosis incidence rates and fitted values obtained using the Holt–Winters exponential smoothing model

The forecast generated by the Holt–Winters model is presented in figure 10. Similar to the SARIMA projections, the model indicated a gradual increase in tuberculosis incidence over the forecast period, assuming the maintenance of the historical temporal pattern.

Overall, both forecasting approaches produced consistent projections, indicating that tuberculosis incidence may continue increasing in the coming years if current epidemiological conditions remain unchanged.

DISCUSSION

COMPARISON WITH RECENT STUDIES

The findings of this study are consistent with both national and international evidence egarding tuberculosis (TB) incidence trends and the impacts of the COVID-19 pandemic. In Brazil, SARIMA models have demonstrated similar patterns to those observed here, with a declining trend until 2014, a reversal beginning in 2015, and a sharp decline in 2020 due to the pandemic[16]. This trajectory highlights the robustness of time-series models in capturing structural breaks and projecting future scenarios.

At the international level, several studies conducted in China have applied SARIMA and Holt–Winters models to forecast tuberculosis (TB) incidence, confirming the applicability of these approaches. Table 3 summarizes the principal findings of these works and their relation to the present study.

IMPACT OF THE PANDEMIC AND PERSISTENT UNDERREPORTING

Consistent with global reports[5,21], our findings indicate that the COVID-19 pandemic led to abrupt and persistent reductions in TB case notifications, reaching up to 84% in May 2020. Although a partial recovery occurred in subsequent years, incidence rates remained below historical levels, suggesting ongoing underreporting and diagnostic delays. Similar patterns were described internationally, reinforcing the magnitude of the pandemic's impact on essential health services worldwide.

MODEL ROBUSTNESS AND IMPLICATIONS

The convergence of SARIMA and Holt–Winters models reinforces the robustness of our results and their usefulness for epidemiological surveillance and forecasting. As in the Chinese studies, both models showed good fit and predictive ability when applied to TB time-series data. However, it is important to recognize that forecasts assume the persistence of historical patterns, and do not account for structural changes in healthcare systems or in the social determinants of TB.

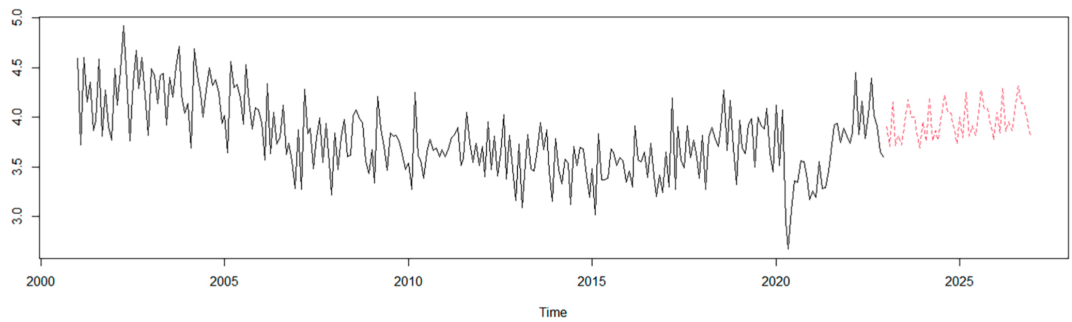

Figure 10 – Forecast of monthly tuberculosis incidence in Brazil through the forecast horizon using the Holt–Winters exponential smoothing model

Table 3 – International studies on forecasting tuberculosis incidence using SARIMA and Holt–Winters models

Study	Location/Period	Main models	Key findings compared to the present study
Mao et al. (2018)[17]	China, national (2004–2015)	SARIMA (1,0,0)(0,1,1)[12]	Clear seasonal pattern detected; validated as white noise model
Zhao et al. (2024)[18]	12 provinces, Western China	SARIMA, Holt–Winters	Strong seasonality identified; models consistent regionally
Huang (2024)[19]	China (2004–2018)	ARIMA (4,1,0)(0,1,1)[12]	High predictive accuracy (R^2 = 0.89; MAPE = 4.07%)
Zhang et al. (2022)[20]	Henan Province, China	Holt–Winters	Effective for regional forecasting of TB incidence

TUBERCULOSIS HEALTHCARE SERVICE DISRUPTIONS DURING THE COVID-19 PANDEMIC

Our findings are consistent with recent international evidence documenting the substantialdisruptions in tuberculosis healthcare services during the COVID-19 pandemic. De Villiers et al[22], using n national-level data from Brazil, India, and South Africa, applied ARIMA models to assess changes in diagnostic testing, treatment initiation, and treatment outcomes. Their findings revealed marked reductions in 2020, followed by partial recovery in 2021–2022.

Specifically, the authors reported reductions in TB diagnostic testing of –24.3% in Brazil, –27.8% in India, and –32.0% in South Africa, relative to expected values. Treatment initiation declined by –17.4% in Brazil, –43.3% in India, and –27.0% in South Africa. In addition, treatment-related mortality increased by +13.7% in Brazil, +1.7% in India, and +21.8% in South Africa. By 2022, indicators showed signs of recovery, with some approaching or surpassing pre-pandemic levels[22].

These findings converge with our analysis, which estimated a reductions of 77% to 84% in TB case notifications in Brazil during April and May 2020, followed by a gradual but incomplete recovery by the end of 2022. Together, the two studies suggest that the pandemic not only caused an acute disruption in TB detection but also led to persistent underreporting and diagnostic delays.

From a methodological perspective, the two approaches are complementary: while De Villiers et al. focused on programmatic indicators of TB control, the present study examined national tuberculosis incidence trends and produced forecasts up to 2030. Collectively, these findings underscore the urgent need to strengthen TB surveillance systems and ensure the continuity of essential tuberculosis services even during global health crises.

FUTURE PROSPECTS

The integration of classical methods, such as SARIMA and Holt–Winters, with more advanced approaches—including machine learning models and neural networks—may further enhance predictive capacity and provide more robust evidence for policy-making. Such advancements may be particularly important for high-burden countriessuch ascBrazil to achieve the SDG 3.3 target of ending the TB epidemic by 2030.

CONCLUSION

This study analyzed the tuberculosis incidencein Brazil between 2001 and 2022, highlighting the declining trend until 2014, a reversal beginning in 2015, and the abrupt rupture caused by the COVID-19 pandemic. Modeling using the SARIMA and Holt–Winters methods showed significant reductions in TB notifications in April (-77%) and May (-84%) of 2020, followed by partial recovery in thesubsequent years, but still without a return to historical levels by the end of 2022. Projections until 2030 indicate a trend of growth in incidence, with the possibility of returning to levels similar to those observed in the early 2000s, if there are no structural interventions.

The findings of the present study are consistentwith the study by de Villiers et al[22], who documented substantial reductions in TB diagnostic testing and treatment initiation, as well as increases in mortality among patients receivingTB treatment in Brazil, India, and South Africa. Collectively, the evidence from both studies indicates that the COVID-19 pandemic profoundly disrupted essential tuberculosis services, contributing to delays in diagnosis, persistent underreporting, and interruptions in continuity of care.

Thus, both the incidence data analyzed in the present study and the programmatic indicators evaluated in international investigations reinforce the urgent need to strengthenthe Unified Health System (SUS), ensure the continuity of TB screening, diagnosis, and treatment services even during global health emergencies. The integration of robust predictive models with targeted public health actions is critical to prevent a resurgence of the disease and ensure compliance with the Sustainable Development Goal (SDG 3.3) of eliminating tuberculosis as a public health problem by 2030.

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INFORMED CONSENT STATEMENT:

Not applicable because the data are anonymous, without any variables that would allow the identification of the subject, so consent to participate in the research was not necessary.

DATA AVAILABILITY STATEMENT:

Information regarding TB cases was obtained through the Information Technology Department of the Unified Health System (DATASUS—accessed at: https://datasus.saude.gov.br/, accessed on July 2024). Information on COVID-19 cases was obtained from the Panel Coronavirus (accessed at: https://covid.saude.gov.br/, accessed on July 2024).

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

ETHICAL CONSIDERATIONS

The present study is based on secondary, publicly available data, which do not constrain groups of populations and/or individuals in the presentation of the results found, ensuring the confidentiality of the information collected. Thus, the ethical aspects of research with human beings were respected, according to Resolution 466/2012.

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