



Original Research

Association between socioeconomic and health variables and community-acquired pneumonia mortality rates in Chile from 1990 to 2021

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ABSTRACT

Objectives: To describe long-term trends in mortality attributed to community-acquired pneumonia (CAP) in Chile from 1990 to 2021, stratified by age group, and to evaluate associations with selected socioeconomic and demographic indicators.

Study design: Ecological, observational, longitudinal study using national secondary data.

Methods: CAP mortality rates were analyzed for the total population and by age group. Associations with the Human Development Index (HDI), poverty rate, aging index, and life expectancy at birth were examined using a hierarchical analytical approach. This included Spearman's rank correlation for initial exploration, multivariable linear regression to assess adjusted associations, and Prais–Winsten generalized least squares regression to account for first-order autocorrelation and shared temporal trends. Stationarity was evaluated using augmented Dickey–Fuller tests, with supplementary analyses using first-differenced variables. Missing data were imputed using time-based regression or interpolation, with sensitivity analyses performed.

Results: CAP mortality declined substantially across all age groups over the study period. Strong bivariate correlations were observed between mortality and all socioeconomic indicators; however, these associations were attenuated after adjustment for confounding and temporal autocorrelation. In multivariable and time-series models, HDI and the aging index remained significantly associated with CAP mortality in children (0–9 years) and older adults (≥ 65 years), whereas associations in intermediate age groups were not robust after accounting for shared secular trends. Poverty and life expectancy did not demonstrate independent associations in adjusted models.

Conclusions: CAP mortality in Chile has decreased markedly over the past three decades. Associations with socioeconomic indicators are strongest at the extremes of age and persist after accounting for temporal structure, although the ecological design precludes causal inference. These findings highlight the importance of considering demographic and socioeconomic context in population-level analyses of infectious disease outcomes.

1. Introduction

The intricate interaction between health and disease poses an ongoing challenge at both individual and societal levels, where sick individuals can disrupt community development and require the

allocation of resources for improvement and relief efforts. Consequently, societies with better health outcomes tend to be more productive,^{1,2} enjoy a higher quality of life,³ and have higher happiness indices.^{4,5} Health and disease are influenced not only by individual factors but also by external elements such as the environment, social norms, economic

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status, education level, and social support networks. Considering the interconnectedness of today's globalized world, these external factors play a crucial role in shaping health outcomes.^{6,7}

Mortality and morbidity associated with infectious agents have declined globally, particularly among children and older adults which has contributed to a global decrease in the burden of diseases from 1990 to 2019 due to advances in medicine and the promotion of health and prevention measures.⁸ The reduction in the global burden of diseases has also been associated with improvements in risk factors such as the availability of quality drinking water, basic sanitation, and household air pollution.^{9,10} Therefore, government health policies must be consistent and continuous over time, especially in countries with low social development indices.¹¹

Respiratory diseases are among the leading causes of health consultations worldwide, with significant morbidity and mortality rates. In 2019, the European Union estimated the annual cost of chronic respiratory diseases to be 380 billion euros.¹² While morbidity and mortality rates decreased significantly between 1990 and 2017, the prevalence of chronic respiratory diseases continues to rise, representing a multifaceted health challenge due to the significant economic burden on healthcare systems.^{12–15} Community-acquired pneumonia (CAP) is one such respiratory disease that presents a significant challenge to healthcare systems worldwide, characterized by high incidence and prevalence rates. It occurs more frequently at the extremes of life and is caused by various pathogens, including *Streptococcus pneumoniae*¹⁶ and other bacterial pathogens such as *Haemophilus influenzae* type b.^{17,18} These pathogens often complicate health conditions, leading to hospitalization and increased financial costs, which may also result in mortality.^{19–21}

Globally, pneumonia caused 2.5 million deaths in 2019, generating high hospitalization costs. In the United States alone, a cost of 6.4 billion dollars was incurred in 2017 in hospitalized patients, with mortality rates among these CAP patients ranging from 20% to 50%.^{21,22} Altogether, CAP imposes an estimated economic burden of approximately 17 billion dollars annually in the United States and over 10 billion euros in Europe.²² Key risk factors for CAP include age, especially at the extremes of life, tobacco exposure, immunosuppression, poor oral health, corticosteroid use, the presence of chronic respiratory diseases, and inadequate nutrition.^{23–25} Additionally, severe episodes of CAP, especially in older adults, are associated with an increased risk of long-term mortality, emphasizing the importance of appropriate treatment strategies.^{22,26–28}

CAP is influenced not only by infectious agents but also by environmental, social, and economic conditions. Thus, comprehensive health policies to prevent these diseases must consider a broad perspective, encompassing biopsychosocial, environmental, and ecological aspects.^{29–31} Given the multifactorial nature of complex diseases such as CAP, it is crucial to analyze environmental and social factors. The Human Development Index (HDI) is a sociodemographic variable encompassing education, economic income, and longevity. It is known to differentiate and classify maternal mortality risk and is inversely associated with the mortality-to-incidence ratio in gynecological cancer studies.³² Similarly, the percentage of poverty reflects individuals' dissatisfaction with basic needs, which impacts cancer mortality rates and overall health, particularly among older adults.^{33–35}

Life expectancy at birth measures population health and societal development, and is influenced by various environmental and social factors.^{36,37} Moreover, the aging index, which reflects the proportion of older adults, highlights demographic changes and the need to promote healthy aging.^{38–40} Systematic reviews on the prevalence, treatments, and nursing care of pneumonia in older adults report that CAP, as a respiratory infectious disease, reaches an average global incidence of 3 to 8 cases per 1000 inhabitants per year, with higher rates among older adults, especially those with comorbidities.^{41,42}

The reality of CAP in the Americas has been analyzed by epidemiological studies from 2019, reporting that children and older adults are the most vulnerable populations. The mortality rate from pneumonia

was highest among those aged 70 years or older, with 291.87 per 100,000 people. Meanwhile, the mortality rate for that year from CAP in children under 5 years old was 28.11.⁴³ In the United States, pneumonia along with influenza ranked as the eighth leading cause of death in the general population in 2016, reaching a rate of 13.5 deaths per 100,000 inhabitants. They were also the leading cause of death from infectious diseases. That same year, CAP in Chile reached a figure of 14.4 deaths per 100,000 inhabitants.⁴⁴

Previous studies showed different CAP mortality rates (per 100,000 inhabitants) as 200 in Mexico^{13,45} in Colombia.⁴⁶ In Chile, the Chilean Ministry of Health reports that respiratory diseases cause the death of 1 in 10 people. CAP is the leading cause of infectious diseases and the leading specific cause of death in the population over 80 years old,⁴⁷ also, using AI can be useful for creating a predictive model for the mortality of CAP.⁴⁸

It is relevant to understand that CAP is a public health threat⁴⁹ and needs specific interventions to improve outcomes in CAP patients;⁵⁰ it has also been reported the use of AI to improve the management of CAP.^{51,52} Although mortality rates have decreased in recent years, CAP continues to burden healthcare resources financially and physiologically, causing complications and associated mortality. This health impact has not yet been well studied or quantified.

This study hypothesizes that CAP mortality rates are significantly associated with socioeconomic and health variables such as HDI, poverty percentage, life expectancy at birth, and the aging index in Chile. Therefore, the objectives include examining the association between these variables and CAP mortality rates in Chile between 1990 and 2021, describing mortality rates in different age groups, examining the characteristics of socioeconomic and health variables, and evaluating their correlation with CAP mortality rates.

2. Methods

2.1. Database

This study employed an analytical, observational, longitudinal, and retrospective approach to examine trends in mortality rates from community-acquired pneumonia (CAP) in Chile from 1990 to 2021. The population was stratified into age groups ranging from 0–9 years to 80 years and older. Freely accessible Chilean secondary data sources were used, including statistical yearbooks from the National Institute of Statistics of Chile,⁵³ as well as publicly available data from the Central Bank of Chile,⁵⁴ the Ministry of Health,⁵⁵ the Ministry of Education,⁵⁶ the Ministry of Social Development,⁵⁷ and specialized websites providing epidemiological, demographic, and economic data.^{58,59}

2.2. Variables

CAP mortality rates, both general and across all age groups, served as the dependent variable.

The independent variables were defined as follows. The Human Development Index (HDI) is a composite indicator developed by the United Nations Development Programme, ranging from 0 to 1, that aggregates measures of life expectancy, education (mean and expected years of schooling), and gross national income per capita; values were obtained from the United Nations Development Programme reports for Chile. The poverty rate was defined as the percentage of the population living below the national poverty line, as reported by the Ministry of Social Development through the National Socioeconomic Characterization Survey (CASEN). Life expectancy at birth, expressed in years, represents the average number of years a newborn is expected to live under current mortality conditions and was obtained from the National Institute of Statistics of Chile and the World Bank. The aging index was calculated as the ratio of the population aged 65 years and older to the population aged 0–14 years, multiplied by 100, based on demographic data from the National Institute of Statistics of Chile. These four

indicators were selected based on their established relevance in the public health literature as determinants or correlates of population health outcomes and infectious disease mortality.

2.3. Statistical analysis

Statistical analysis was performed using SPSS 29.0 and R 4.3.0 software. Descriptive statistics including the mean, 95% confidence intervals, standard deviation, and variance were calculated for all variables. A multi-stage analytical strategy was employed to assess the relationships between CAP mortality rates and socioeconomic and health indicators, progressing from bivariate correlation to multivariable regression and time-series analysis. First, normality of all variables was assessed using the Shapiro–Wilk test. As none of the variables followed a normal distribution (all $p < 0.05$), Spearman's rank correlation coefficients were used to assess bivariate monotonic associations between CAP mortality rates (general and age-group-specific) and the independent variables (HDI, poverty rate, life expectancy at birth, and aging index). Second, to assess the independent contribution of each socioeconomic variable while adjusting for potential confounders, multivariable linear regression models were fitted for each age-group-specific CAP mortality rate as the dependent variable. All four independent variables were entered simultaneously. Model assumptions were evaluated through residual diagnostics, variance inflation factors (VIF) to assess multicollinearity, and the Durbin–Watson statistic for autocorrelation. Third, given that both dependent and independent variables exhibited strong secular trends over the 31-year study period, Prais–Winsten generalized least squares (GLS) regression with first-order autoregressive error correction (AR1) was employed to account for temporal autocorrelation and reduce the risk of spurious associations arising from shared time trends. The Cochrane–Orcutt iterative procedure was used to estimate the autocorrelation parameter. Additionally, augmented Dickey–Fuller (ADF) tests were conducted to assess stationarity of the time series; where non-stationarity was detected, first-differenced variables were used in supplementary analyses to evaluate whether associations persisted after removing secular trends. A significance level of 0.05 was used for all analyses.

Missing data were addressed using two imputation approaches depending on the variable and the pattern of missingness. For most variables, simple linear regression against time was used to estimate missing values, under the assumption of a linear temporal trend. For the aging index, linear interpolation was employed between available data points, supplemented by reference to projected estimates from the National Institute of Statistics of Chile for 2024 to complete data from 2018 to 2021. The proportion of imputed data points was small (less than 15% of total observations across all variables). Sensitivity analyses were conducted by comparing results with and without imputed values to assess the robustness of the findings.

While bivariate correlation analysis provides an initial assessment of association strength, it does not adjust for confounding or establish causal relationships. To address these limitations, the multivariable regression and time-series approaches described above were employed. It is important to note that even with these additional analytical methods, the ecological and observational design of this study precludes causal inference, and residual confounding from unmeasured variables cannot be excluded. A conceptual framework (Fig. 1) was developed to illustrate the hypothesized relationships between socioeconomic indicators, demographic factors, and CAP mortality, and to explicitly account for the potential confounding influence of shared temporal trends.

Ethical approval

This study was conducted following the Declaration of Helsinki of 1964 and its subsequent amendments.⁶⁰ Since secondary data sources from publicly available government databases of Chile were used, no ethics committee approval was required.

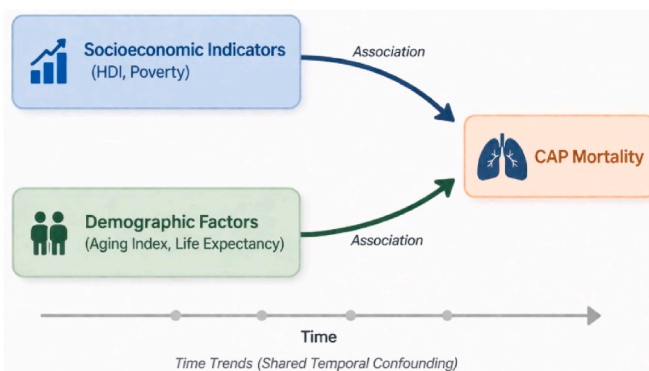


Fig. 1. Conceptual framework of associations between socioeconomic indicators and CAP mortality. Directed acyclic graph illustrating the relationships between socioeconomic indicators (HDI, poverty), demographic factors (aging index, life expectancy), and CAP mortality. Arrows represent associative relationships. Shared temporal trends are shown as a potential confounder influencing all variables.

3. Results

3.1. Mortality rates

The average mortality rates for community-acquired pneumonia (CAP) ranged from 5.13 in the 0–9 age group to 1021.72 in the 80-year-old and older age group. As Table 1 shows, high average mortality rates for CAP were evident in the elderly population.

The trend in CAP mortality rates between 1990 and 2021 is shown in Fig. 2, revealing a 60.5% decrease from 1990 to 2021.

The analysis of CAP mortality rates by age group can be seen in Fig. 3. There was an 88.37% decrease in mortality rates in the 0–9 years group between 1990 and 2021. Additionally, the mortality rate for the 10–19 years group decreased by 63.64% between 1990 and 2021.

For the 20–39 years age group, the mortality rate decreased by 72.95% between 1990 and 2021. In the 40–64 years age group, the mortality rate decreased by 66.33% over the same period (Fig. 4).

In the 65–79 years age group, the mortality rate decreased by 87.47% between 1990 and 2021. The 80-year-old and older age group showed an 82.08% decrease over the same period (Fig. 5).

Overall, the age groups with the largest percentage decreases during the study period were the 0–9 years group, with an 88.37% decrease, followed by the 65–79 years group with an 87.47% decrease in CAP mortality rates.

Table 1

Descriptive statistics of CAP mortality rates in Chile's general and various age groups between 1990 and 2021.

| Mortality Rates | Mean | 95.0% CL Lower for mean | 95.0% CL Upper for Mean | Standard Deviation | Variance |
|--------------------------|---------|-------------------------|-------------------------|--------------------|-----------|
| MR CAP General | 26.71 | 23.23 | 30.20 | 9.67 | 93.55 |
| MR CAP 0-9 years | 5.13 | 3.75 | 6.50 | 3.81 | 14.55 |
| MR CAP 10-19 years | 0.40 | 0.30 | 0.49 | 0.27 | 0.07 |
| MR CAP 20-39 years | 1.40 | 1.10 | 1.70 | 0.84 | 0.70 |
| MR CAP 40-64 years | 9.64 | 7.72 | 11.55 | 5.31 | 28.24 |
| MR CAP 65-79 years | 113.93 | 84.96 | 142.90 | 80.35 | 6456.49 |
| MR CAP 80 and more years | 1021.72 | 819.07 | 1224.37 | 562.08 | 315936.50 |

MR: Mortality Rate, CAP: Community-Acquired Pneumonia.

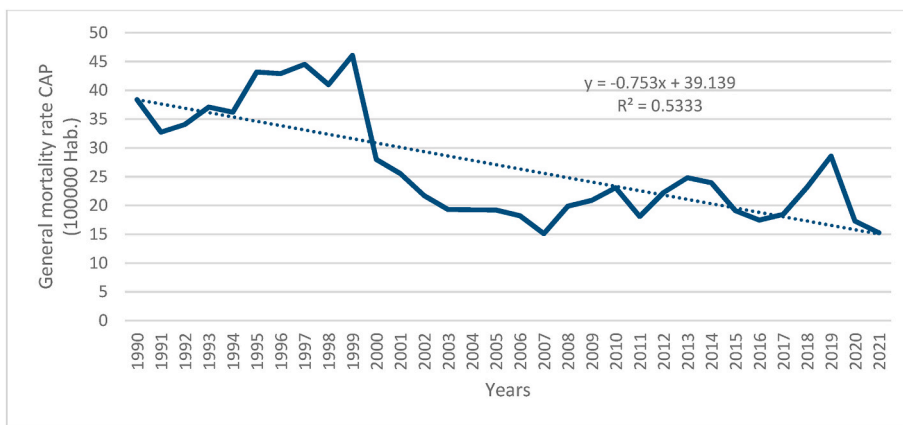


Fig. 2. General CAP mortality rate, Chile 1990-2021.

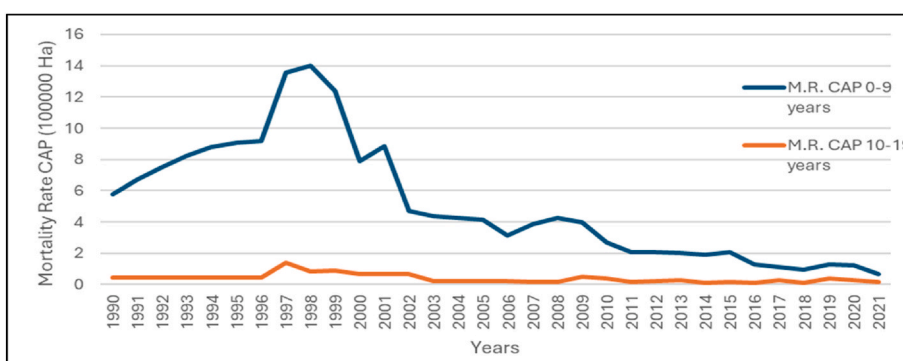


Fig. 3. CAP mortality rate for 0–9 and 10–19 years, Chile 1990-2021.

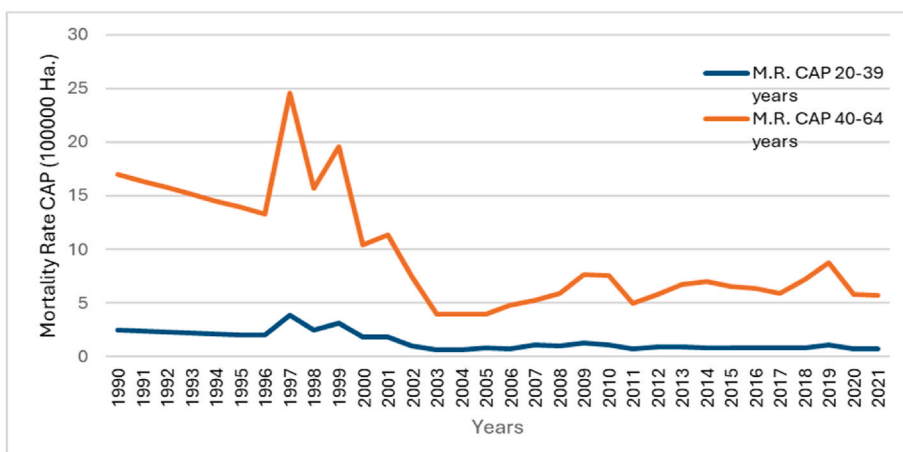


Fig. 4. CAP mortality rate for 20–39 and 40–64 years, Chile 1990-2021.

3.1.1. Socioeconomic and health variables

Table 2 summarizes the socioeconomic and health variables, including the Human Development Index, population poverty rate, life expectancy at birth, and aging index.

The average values of the different variables in the study show that the Human Development Index reached 0.8, the Population Poverty Index averaged 23.9%, life expectancy at birth in Chile was 77 years on average, and the Aging Index averaged 59.89. To better understand the behavior of the socioeconomic and health variables, they were disaggregated for analysis.

3.1.2. Human Development Index (HDI)

The Human Development Index (HDI) in Chile showed an upward trend over the study period, increasing by 21.14% from 1990 to 2021, as shown in Fig. 6.

3.1.3. Population Poverty Rate

The behavior of Population Poverty Rate in Chile showed a downward trend, decreasing by 74.87% from 1990 to 2021 (Fig. 7).

3.1.4. Life expectancy at birth

Life expectancy at birth in Chile showed a general upward trend

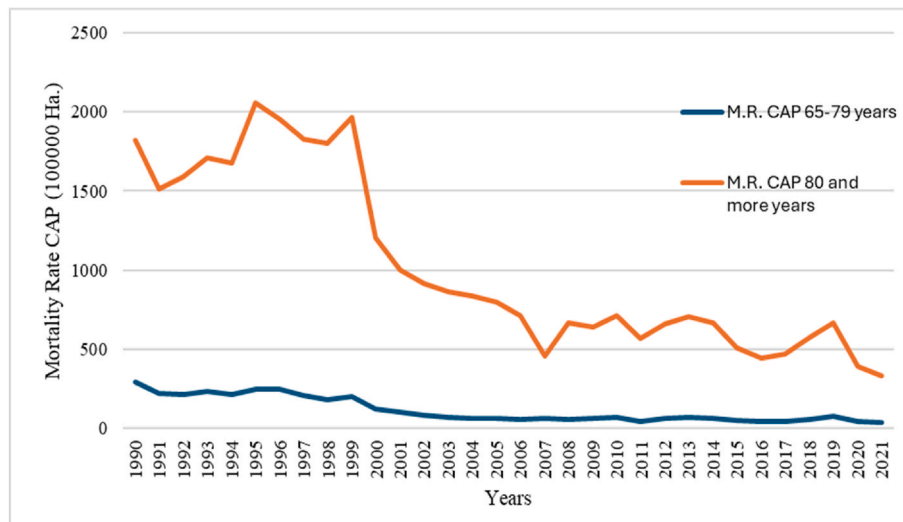


Fig. 5. CAP mortality rate for 65–79 and 80+ years, Chile 1990–2021.

Table 2
Descriptive statistics of socioeconomic and health variables, Chile 1990–2021.

| Independent Variables | Mean | 95.0% CL Lower for mean | 95.0% CL Upper for mean | Standard Deviation | Variance |
|-------------------------------|------|-------------------------|-------------------------|--------------------|----------|
| Human Development Index | 0.8 | 0.8 | 0.8 | 0.0 | 0.0 |
| Poverty in the population (%) | 23.9 | 20.4 | 27.4 | 9.6 | 92.4 |
| Life Expectancy at Birth | 77 | 77 | 78 | 2 | 5 |
| Aging Index | 59.9 | 51.7 | 68.0 | 22.6 | 511.4 |

during the study period, with a slight decline in 2021. However, it increased by 6.37 years between 1990 and 2021 (Fig. 8).

3.1.5. Aging Index

The Aging Index increased consistently by 142.23% between 1990 and 2021. However, a decline has been observed in recent years, and this trend should be monitored (Fig. 9).

3.1.6. Correlation analysis between CAP mortality rates and socioeconomic and health variables

The CAP mortality rates in the 0–9 years, 10–19 years, 65–79 years, and 80 years and older groups showed correlation and statistical significance with all variables studied, including the Human Development

Index, Population Poverty Rate, Life Expectancy at Birth, and Aging Index. The only exception was the poverty rate, where no correlation or statistical significance was found (Table 3) for the general population and adult population (20–39 years and 40–64 years) CAP mortality rates.

On the other hand, the variables Human Development Index, Life Expectancy at Birth, and Aging Index showed correlation and statistical significance with all mortality rates, both overall and by age groups. The highest correlation was found between the Mortality Rate from Community-Acquired Pneumonia (CAP) in the 0–9 age group and the Human Development Index and Aging Index, with values of -0.905 and -0.907 (<0.001), respectively. These findings suggest a statistically significant association between CAP mortality rates and the examined socioeconomic and health variables, though the ecological design of the study precludes causal interpretation of these relationships.

3.1.6.1. Multivariable and time-series regression analysis. To assess the independent contribution of each socioeconomic variable while controlling for the others, multivariable linear regression models were fitted for each age-group-specific CAP mortality rate. For the 0–9 years age group, the overall model was statistically significant ($F = 48.7$, $p < 0.001$, adjusted $R^2 = 0.86$), with the aging index ($\beta = -0.12$, $p = 0.003$) and HDI ($\beta = -49.2$, $p = 0.011$) emerging as significant independent predictors after mutual adjustment. For the 65–79 and 80+ age groups, similarly strong models were observed (adjusted $R^2 = 0.78$ and 0.82 , respectively), with HDI and the aging index again showing independent

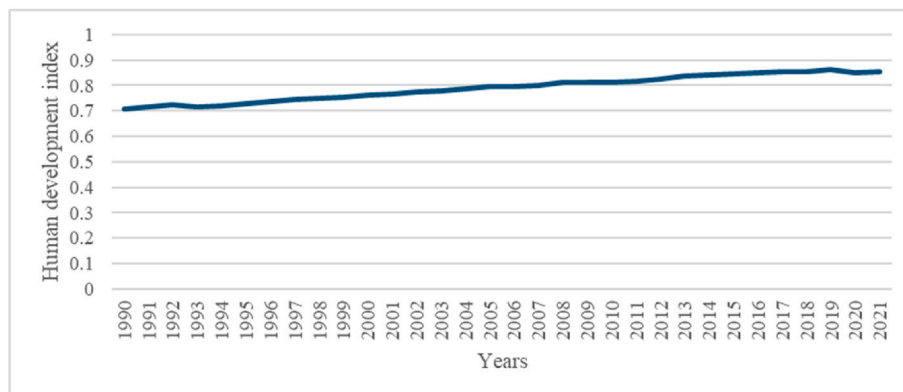


Fig. 6. Human Development Index behavior, Chile 1990–2021.

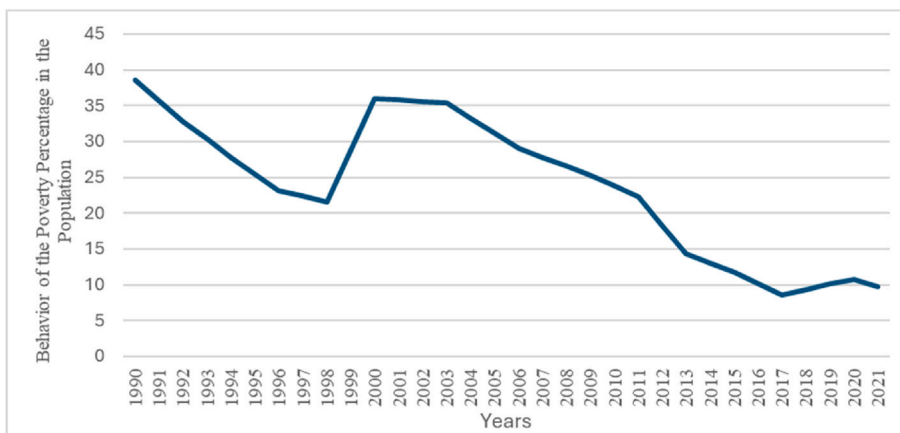


Fig. 7. Population poverty rate behavior, Chile 1990-2021.

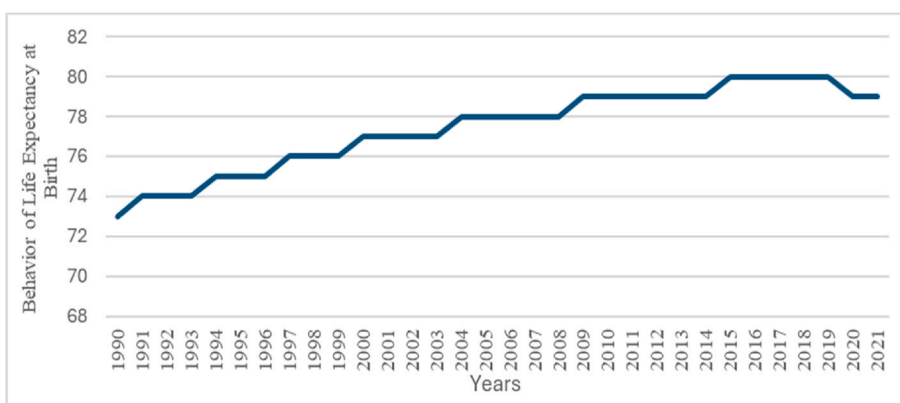


Fig. 8. Life expectancy at birth behavior, Chile 1990-2021.

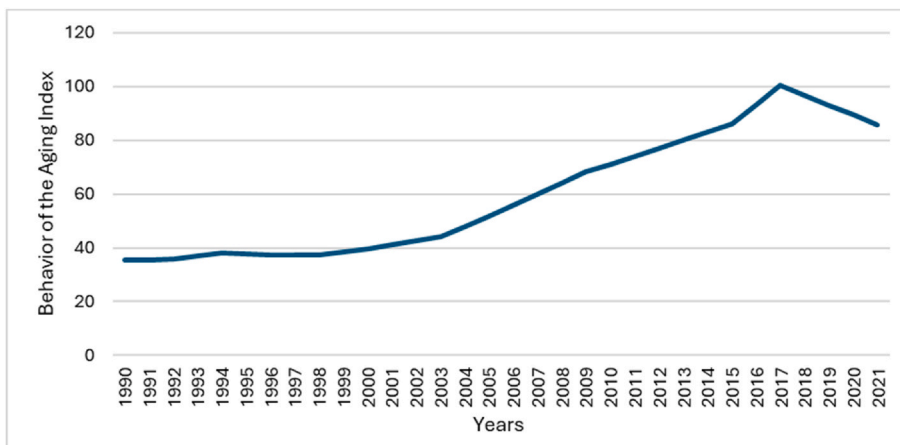


Fig. 9. Aging Index behavior, Chile 1990-2021.

significance. The poverty rate did not reach statistical significance in any multivariable model after adjustment for the other covariates (all $p > 0.10$), consistent with the bivariate findings for the general and adult populations. Variance inflation factors were below 5.0 for all predictors in all models, indicating acceptable levels of multicollinearity. The Durbin–Watson statistic ranged from 1.1 to 1.4 across models, suggesting positive autocorrelation in the residuals, which motivated the subsequent time-series analysis. Prais–Winsten generalized least squares regression with AR(1) correction was then employed to account for

temporal autocorrelation. After this correction, the association between HDI and CAP mortality remained statistically significant for the 0–9 years ($\beta = -38.6, p = 0.024$), 65–79 years ($\beta = -812.4, p = 0.008$), and 80+ years ($\beta = -5340.2, p = 0.003$) age groups. The aging index also remained significant for the 0–9 and 80+ age groups ($p < 0.05$). However, associations that were significant in the unadjusted correlation analysis were attenuated for the 10–19 and 20–39 year age groups after autocorrelation correction ($p > 0.05$), suggesting that some of the observed bivariate correlations in these groups may have been partly

Table 3
Correlation between all mortality rates and socioeconomic and health variables.

| Mortality Rates per 100,000 persons | Statistics | Human Development Index | Percentage of Poverty in the Population | Life Expectancy at Birth | Aging Index |
|-------------------------------------|-------------------------|-------------------------|---|--------------------------|-------------|
| M.R. CAP General | Correlation coefficient | −0.675** | 0.285 | −0.651** | −0.691** |
| | Significance (two-way) | <0.001 | 0.110 | <0.001 | <0.001 |
| M.R. CAP 0-9 years | Correlation coefficient | −0.905** | 0.655** | −0.882** | −0.907** |
| | Significance (two-way) | <0.001 | <0.001 | <0.001 | <0.001 |
| M.R. CAP 10-19 years | Correlation coefficient | −0.680** | 0.493** | −0.657** | −0.696** |
| | Significance (two-way) | <0.001 | 0.005 | <0.001 | <0.001 |
| M.R. CAP 20-39 years | Correlation coefficient | −0.703** | 0.335 | −0.688** | −0.709** |
| | Significance (two-way) | <0.001 | 0.062 | <0.001 | <0.001 |
| M.R. CAP 40-64 years | Correlation coefficient | −0.624** | 0.226 | −0.608** | −0.631** |
| | Significance (two-way) | <0.001 | 0.212 | <0.001 | <0.001 |
| M.R. CAP 65-79 years | Correlation coefficient | −0.864** | 0.587** | −0.851** | −0.871** |
| | Significance (two-way) | <0.001 | <0.001 | <0.001 | <0.001 |
| M.R. CAP 80 and more | Correlation coefficient | −0.877** | 0.597** | −0.850** | −0.883** |
| | Significance (two-way) | <0.001 | <0.001 | <0.001 | <0.001 |

**The correlation is significant at the 0.01 level (two-tailed).

driven by shared secular trends rather than direct associations. Supplementary analyses using first-differenced variables (to further control for non-stationarity and common temporal trends) yielded results broadly consistent with the Prais–Winsten models: year-over-year changes in HDI and the aging index were significantly associated with year-over-year changes in CAP mortality rates in the youngest and oldest age groups, providing additional evidence that these associations are not solely attributable to parallel time trends.

4. Discussion

This study provides a long-term descriptive analysis of CAP mortality trends in Chile and examines their association with selected socioeconomic and demographic indicators using progressively more rigorous analytical approaches. Although initial correlation analyses suggested strong relationships between CAP mortality and all socioeconomic variables, subsequent multivariable and time-series models demonstrated that many of these associations are sensitive to adjustment for confounding and shared temporal trends, and that associations in the youngest and oldest age groups are the most robust after accounting for these methodological considerations. CAP mortality in Chile has decreased markedly over the past three decades across all age groups. There was a notable increase in all age groups during 1997–1998, followed by a continuous decline, with some fluctuations, but the overall downward trend remains consistent. This pattern mirrors the global trend, where a 22.1% reduction in pneumonia mortality rates was observed between 2006 and 2016, with higher lethality at the extremes of age (children and the elderly).⁴⁴

CAP has a high incidence in the population, a situation reported in the 2019 Global Burden of Disease Report,⁴³ which indicated that 2.5 million people worldwide died of pneumonia, with the most affected populations being those under five years old and the elderly. Studies conducted in Australia show that CAP was responsible for 2% of all hospitalizations;⁶¹ post-discharge studies show that 24% of patients had to be readmitted within 30 days due to late effects and decompensation of their comorbidities.⁶² CAP can be associated with other respiratory diseases, such as influenza, leading to greater severity in its presentation, as well as with external factors that were the focus of this study.

A major methodological consideration in interpreting the associations reported in this study is the potential for spurious correlations arising from parallel time trends, a well-recognized limitation in

ecological time-series analyses. Many variables examined here including HDI, life expectancy at birth, aging index, and CAP mortality rates exhibit monotonic changes over the 31-year study period. Without appropriate adjustment, such co-trending can produce strong, statistically significant correlations that are artefactual rather than substantive. The use of Prais–Winsten generalized least squares regression with AR (1) correction and supplementary first-differenced models was specifically intended to distinguish associations driven primarily by shared secular trends from those that persist after accounting for temporal structure. Associations that remained statistically significant following these corrections particularly for HDI and the aging index in children and older adults are therefore considered more analytically robust, while still being interpreted as associative rather than causal.

The bivariate correlations identified strong monotonic associations between CAP mortality and all socioeconomic indicators, with the greatest correlations observed at the extremes of age particularly between the 0–9 years mortality rate and both HDI ($r = -0.905$) and the aging index ($r = -0.907$). The multivariable regression models demonstrated that HDI and the aging index retained independent statistical significance after mutual adjustment, indicating that these associations are not entirely attributable to collinearity among predictors. Importantly, the Prais–Winsten time-series regression confirmed the persistence of these key associations in the youngest and oldest age groups, while revealing that associations in intermediate age groups (10–19 and 20–39 years) were attenuated after autocorrelation correction consistent with those bivariate correlations being partly driven by shared secular trends. The first-differenced analyses provided further support, showing that year-over-year changes in HDI and the aging index were associated with concurrent changes in CAP mortality in the most vulnerable age groups. These findings should nonetheless be interpreted with caution given the ecological design, as population-level associations may not reflect individual-level causal mechanisms. The following sections discuss each socioeconomic variable in detail.

4.1. Human Development Index

The Human Development Index is associated with population-level outcomes of social health strategies aimed at addressing emerging health problems, such as the COVID-19 pandemic, and has been linked to lethality rates, particularly in severe cases of infection.^{63–65} It has been reported that in 2021, Chile reached a value of 0.856, placing it at a

high level of this index, ranking 42nd globally, with Switzerland taking first place that year with a value of 0.962.⁶⁶ We observed a low negative correlation between the Human Development Index and death from respiratory diseases such as CAP and COVID-19. Furthermore, it was reported that up to 40% of the variance in lethality rates was associated with the Human Development Index. In Brazil, regions with a low Human Development Index showed a higher lethality rate from COVID-19.⁶⁷ There is a significant positive correlation between HDI and non-communicable diseases, including obesity, which is a risk factor for respiratory diseases.⁶⁸ On the other hand, the components of HDI may be associated with the lethality and mortality of acute respiratory infections, especially CAP. A low HDI should be a source for generating strategies for promoting and preventing respiratory health, particularly urgent in the pediatric population.⁶⁹

In countries with insufficient human resources in the health sector, general and cause-specific mortality rates are higher, especially in diseases with greater local prevalence and incidence.⁷⁰ Additionally, the degree of urbanization of cities presents risks, primarily for respiratory diseases. In contrast, risks for cardiovascular diseases are more present in less urbanized areas, with timely access to adequate medical care and better living conditions influencing both.⁷¹ Studies in Italy have shown that the Human Development Index (HDI) correlates with COVID-19 infection and mortality rates. Moreover, HDI is negatively correlated with cigarette consumption.⁷² The results obtained in this study demonstrate that the Human Development Index correlates significantly with both the general mortality rate from CAP and all the age groups analyzed. Importantly, these associations persisted after multivariable adjustment for all covariates and remained statistically significant following Prais–Winsten autocorrelation correction in the 0–9, 65–79, and 80+ age groups, indicating that the inverse relationship between HDI and CAP mortality in the most vulnerable groups is not wholly explained by shared secular trends or collinearity among predictors. This correlation may reflect concurrent improvements in life expectancy at birth, average years of education, and the gross domestic product (GDP) in Chile. These improvements are also influenced by factors such as the availability of efficient and accessible health services, high coverage of basic sanitation conditions, housing infrastructure improvements, health strategies such as vaccination, timely detection and treatment of CAP, and solid educational campaigns.

4.2. Poverty index

In 2021, Chile's poverty index was 9.7%, and according to recent publications from 2022, it reached 6.5%, while in the same year in the United States, it was 11.5%.⁷³ Given this, the present study found a statistically significant correlation between mortality rates from CAP in age groups corresponding to children, adolescents, and the elderly. It is important to note, however, that the poverty rate did not retain statistical significance in any of the multivariable regression models after adjustment for HDI, life expectancy at birth, and the aging index, nor in the Prais–Winsten time-series analyses, suggesting that its bivariate associations with CAP mortality may largely reflect confounding by the other socioeconomic indicators and shared temporal trends rather than an independent relationship. These results should nonetheless be contextualized, as poverty and overcrowding have been associated with a higher incidence of hospitalization due to respiratory syncytial virus (RSV) in children.⁷⁴ To reduce the incidence of respiratory diseases, biological, environmental, and socioeconomic factors must be considered.⁷⁴ In low- and middle-income countries, higher service coverage rates are associated with a lower poverty percentage in the population.⁷⁵

Studies in New York show higher mortality rates from pneumonia and influenza in patients living in urban and suburban areas than in rural areas between 2010 and 2014, a situation that may be associated with poverty.⁷⁶ The reduction of the poverty index in the Chilean population during the study period has been associated with the country's economic growth, the population's education levels, and the

implementation of social programs aimed at alleviating poverty and improving living conditions. This reduction has been achieved through better social, labor, and health support conditions, along with disease prevention programs and healthcare tailored to high-risk groups and sectors. There is a strong association between the poverty index and acute diseases such as pneumonia, potentially related to limited access to medical care, overcrowding, and poor sanitary conditions in households. Parental education, child nutrition, and exposure to environmental pollution have been associated with respiratory morbidity, particularly from CAP.

4.3. Aging Index

The aging of individuals and societies is associated with a set of biological, customs, and lifestyle changes that, if not healthy, accumulate over the years that may increase the risk of morbidity and mortality.⁷⁷ This is why healthy lifestyles, such as physical activity, are factors to consider in the prognosis and evolution of some diseases. Age, along with reduced physical activity, are significant risk factors for mortality associated with respiratory diseases, independent of smoking.⁷⁸ In this study, the Aging Index showed high correlations with mortality rates from CAP, both at the general level and for all age groups analyzed. Multivariable regression confirmed that the aging index was an independent predictor of CAP mortality in the 0–9 and 80+ age groups after simultaneous adjustment for HDI, poverty rate, and life expectancy at birth, and this association remained statistically significant following Prais–Winsten correction for temporal autocorrelation, supporting the robustness of this finding beyond shared secular trends. In Chile, in 2021, this index reached a value of 85.83, which has increased due to rising life expectancy and declining birth rates. However, this increase in the Aging Index implies higher spending on pensions and greater demand for medical services for the elderly, which represents a significant financial burden on the national treasury. The well-established relationship between aging and CAP, especially in adults aged 80 or older, is characterized by comorbidities, decreased immune system efficiency, physiological changes in the respiratory system, and sedentary lifestyles, all of which may contribute to high morbidity and mortality from CAP. Therefore, the Chilean Ministry of Health (MINSAL), along with inter-ministerial participation, works to promote healthy lifestyles from an early age, and adhering to vaccination and health education campaigns on prevention are vital strategies to mitigate or delay the onset of chronic and degenerative diseases, including CAP.

4.4. Life expectancy at birth

In 2021, life expectancy at birth in Chile reached 78.94 years, and by 2022, it increased to 79.52 years; that same year, countries like Switzerland reached 84.20 years, and Spain, 84 years.⁷⁹ This study found statistically significant correlations between life expectancy at birth and mortality rates from CAP, both at the general level and for all age groups analyzed. It should be noted, however, that in the multivariable regression models life expectancy at birth did not emerge as a statistically independent predictor after simultaneous adjustment for the other covariates, suggesting that its bivariate associations with CAP mortality overlap substantially with those of HDI and the aging index. A 2020 mortality report in the U.S. shows that life expectancy at birth reached 77.0 years, a decrease of 1.8 years compared to 2019 due to the influence of COVID-19 deaths.⁸⁰ Globally, life expectancy at birth experienced a significant downward trend between 2019 and 2021, with a decrease of 1.8 years, reflecting the direct and indirect effects of the COVID-19 pandemic.⁸¹ This important indicator allows for the evaluation of the long-term effects of government policies on health and the population's healthy living habits and cultural patterns, which, in turn, influence the social and economic aspects of populations. State investment in human capital, healthcare systems, and health spending policies are positively associated with life expectancy. Greater availability of

doctors and hospital beds, a high percentage of the economically active population, and the population's healthy living habits are positively correlated with life expectancy. However, there is a negative relationship between population size and life expectancy.^{81,82}

In Chile, the overall health impact of the COVID-19 pandemic was reflected in a decrease in Chile's life expectancy, which interrupted decades of continuous increases in this important indicator.⁸³ The increase in life expectancy at birth, which correlates with mortality rates from CAP in this study, may reflect more efficient health systems, lower infant mortality rates, adequate nutrition, higher quality of life indices, and a highly educated population. Investments to improve health systems, increase sanitation coverage, reduce poverty levels, improve education, and enhance infrastructure and living conditions are associated with higher life expectancy at birth. Consequently, efforts to increase life expectancy at birth may also be associated with reductions in the incidence of both acute and chronic diseases, including CAP, potentially contributing to reductions in the associated morbidity and mortality burden.

4.5. Economic burden of CAP

It is important to mention that the healthcare burden of CAP also has an economic aspect, as shown by the fact that, in 2019 in the United Kingdom, the average costs associated with hospitalization for this condition were 3904 sterling pounds, while annual costs reached 731 million sterling pounds.⁶¹ Studies from 2017 in the USA on the hospitalization costs of CAP reached 6.4 billion dollars.²² Studies in the USA on the financial burden of CAP mortality show that it exceeds 17 billion dollars, while in Europe, it amounts to more than 10 billion euros annually.²² It is important to note that, in Europe, the financial burden of indirect costs such as presenteeism, absenteeism, and caregiver impacts has been quantified at 10.1 billion euros per year.⁸⁴ This international financial burden is a relevant factor to consider in the health strategies implemented by the Chilean Ministry of Health (MINSAL) to address this condition, as the high healthcare costs of CAP affect annual fiscal budgets, especially in developing countries like Chile.

4.6. Prevention of CAP

Lastly, it is essential to consider prevention measures for this condition, as they are critical both for avoiding the onset of this disease and for reducing the financial and social costs it generates. Notable strategies include influenza vaccination, anti-smoking campaigns, and pneumococcal vaccination for at-risk groups and the elderly.⁸⁵ These strategies are based on studies that show that in industrialized countries, the incidence of CAP is 1.2 to 2.4 cases per 1000 adults, which is significantly lower than in underdeveloped countries, attributed to higher pneumococcal vaccination coverage rates, especially in extreme age groups (under five years and over 65-70 years), in which, if unprotected, the incidence tends to increase.⁸⁶ For this reason, the Ministry of Health must continue preventive strategies to reduce the incidence of CAP, thereby lowering the high financial costs it generates for both the public and private health systems.

4.7. Strengths and limitations

This study has several methodological limitations that should be considered when interpreting the results. First, the ecological design relies on population-level aggregate data, and associations observed at this level may not reflect individual-level relationships (ecological fallacy); individual-level confounders such as smoking status, comorbidities, and healthcare access could not be controlled. Second, although multivariable regression and time-series models were employed to complement the initial bivariate correlation analysis, residual confounding from unmeasured variables remains possible, and the relatively small number of annual observations ($n = 32$) limits the statistical

power for complex multivariable models. Third, despite employing Prais–Winsten regression with autocorrelation correction and first-differenced analyses to address shared temporal trends, the possibility of spurious associations due to common secular trends cannot be entirely eliminated in ecological time-series data. Fourth, the retrospective design using secondary data sources limits the ability to control for unmeasured confounders and introduces potential biases due to incomplete information, as some indicators (e.g., the poverty rate from CASEN surveys) are compiled biennially or at irregular intervals. Fifth, data imputation through simple linear regression and linear interpolation was used for a small proportion of missing data points; although sensitivity analyses comparing results with and without imputed values showed consistent findings, these methods assume linear temporal patterns. Sixth, the four independent variables studied, while well-established in the public health literature, do not capture the full range of determinants of CAP mortality (e.g., vaccination coverage rates, antibiotic resistance patterns, air quality indices). Finally, data were limited to Chilean government sources for the 1990–2021 period, which may restrict the generalizability of findings to other populations and time periods.

The study's strengths include the use of a multi-stage analytical approach that progressed from bivariate correlation to multivariable regression and time-series analysis with autocorrelation correction, providing a more robust assessment of associations than correlation analysis alone. The 31-year observation period provides sufficient temporal resolution to detect long-term trends. Additionally, the data analyzed comes from governmental information compiled by the National Institute of Statistics (INE) of Chile, together with the Department of Health Statistics and Information (DEIS) of the Chilean Ministry of Health, representing the country's official epidemiological reality. The use of age-stratified analyses allowed for the identification of differential associations across the lifespan, highlighting the particular vulnerability of children and older adults.

Ethical statement

This study was conducted following the Declaration of Helsinki of 1964 and its subsequent amendments. Since secondary data sources from publicly available government databases of Chile were used, no ethics committee approval was required.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Data availability

The survey data can be made available upon request.

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