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Asymmetric Effects of Air Pollution and Public Health Expenditure on Mortality in South Africa: Does Access to Electricity Matter?

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ABSTRACT

Background: There appears to be a decline in public health expenditure per capita amid high levels of air pollution in South Africa, and it is not clear whether this has a toll on the country's crude mortality rate. This study examined the asymmetric effects of particulate matter air pollution (PM2.5) and public health expenditure on crude mortality rates in South Africa. Coal is the major source of electricity in South Africa, and it generates high levels of PM2.5. This has implications for human respiratory systems and airway health, which could affect mortality rates despite increases in public health expenditure.

Aims: The study examined whether increases or decreases in air pollution and public health expenditure per capita significantly affect mortality rate in South Africa, and how access to electricity and income per capita affect mortality amidst these non-linear interactions.

Methods: The study employed annual time-series data covering 35 years (1990 to 2024). The study adopted the Nonlinear Autoregressive Distributed Lag (NARDL) cointegration framework, which separates positive and negative shocks to air pollution and health expenditure and allows estimation of the long- and short-run effects of both types of shocks on mortality. The study also explicitly included the percentage of the population with access to electricity to examine the effect of access to clean energy on the pollution-mortality relationship. The study also used national per capita income to assess its influence on mortality rates in South Africa.

Results: The results show a statistically significant long-run effect of air pollution on mortality. Health expenditure per capita, however, did not produce any significant asymmetric effects on the crude mortality rate, both in the short-run and long run. However, access to electricity has a statistically significant positive effect on mortality, indicating that increased electricity access is a positive and significant factor in productivity, but may also co-evolve with energy-use patterns that require careful environmental management. Mortality is negatively associated with GDP per capita, consistent with the epidemiological transition hypothesis. The error-correction term verifies the quick adjustment towards the long-run equilibrium, indicating that about 90.4% of the disequilibrium is corrected each year.

Conclusion: The study concludes that while positive and negative shocks in public health expenditure did not significantly affect the mortality rate, negative shocks in air pollution did. These findings underscore the need for the government of South Africa to work towards a clean energy transition, target health spending toward pollution-related respiratory illnesses, improve citizens' incomes, and control air pollution to reduce mortality rates.

Keywords: *Air pollution; Crude mortality rate; Public health expenditure; South Africa.*

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1. Introduction

The mortality rates in Sub-Saharan Africa are still some of the highest rates in the world, with a mix of communicable and non-communicable diseases, and more recently, environment-related diseases. South Africa presents a unique case study, in that it is the most industrialised economy in Africa but also has the world's highest ambient air pollution levels, significant public health impacts from inefficient public health spending, and a highly coal dependent energy infrastructure (Thabethe et al. 2021; Simelane, & Langerman, 2024). The joint and asymmetric effects of air pollution and public health spending on mortality outcomes are inextricably linked, and the shift to cleaner energy sources may reduce these effects. It is pertinent to investigate how the two factors interact and to what extent this interaction is moderated by the move to cleaner fuels.

The catastrophic impacts of ambient air pollution on human health are well established worldwide. As asserted by the World Health Organization (World Health Organization, 2021), some 7 million people die each year due to exposure to air pollution, and fine particulate matter (PM2.5) is the most health-damaging pollutant. South Africa's current reliance on coal-fired power stations, including Eskom's fleet, which is among the world's most polluting, is a major area of concern. According to Roomaney et al. (2022) the average PM2.5 concentration in South Africa remains consistently above the World Health Organization guideline of 5 $\mu g/m^3$; particularly in the province of Mpumalanga which is among the highest ambient particulate hubs globally, as it relies on coal as its primary energy source. The combination of these environmental conditions, together with the dual epidemic burden of HIV/AIDS and the increasing prevalence of non-communicable diseases in public health systems, which are already overburdened, calls for critical examination and reflection for public health policy.

At the same time, changes in public health expenditure provide an informative lens into policy. Again, the share of health expenditure as a proportion of national output has also been highly volatile during the study period (1990-2024), driven by successive policy shifts, fiscal consolidation demands, and the pandemic-era spending boom. The implications of changes in expenditure for mortality reduction (or the difference in mortality response when expenditure increases versus decreases) have a direct bearing on health financing policy and the allocation of expenditure under the proposed National Health Insurance (NHI) framework.

The developing literature in environmental and health economics has adopted nonlinear and asymmetric approaches to the study of the pollution-health nexus, acknowledging the nonlinear nature of many aggregate health measures' responses to changes in environmental quality. In time-series settings, Shin et al. (2014) proposed the Nonlinear Autoregressive Distributed Lag (NARDL) model as the methodological choice for capturing asymmetries, using the positive and negative partial sums of explanatory variables to capture differential responses. Despite this methodological development, the application of the pollution-mortality link to the South African economy remains limited.

This study contributes to literature in several major ways. It is unique in its comprehensive use of NARDL to capture the asymmetric effects of air pollution (PM2.5) and public health spending on mortality rate over 35 years in South Africa. This methodology isolates the positive and negative effects of these variables on mortality and produces a nuanced picture of their impact on mortality rate, reflected in both the size of the coefficients and their significance. Also, it explicitly conditions access to clean energy, meaning the pollution-mortality pathway depends on the energy mix available to households. Clean energy reduces air pollution, but if the source of that energy, such as electricity, generates pollutants, it might counterbalance the effect.

Positive shocks in health spending are expected to reduce mortality, while negative shocks are expected to aggravate it. For air pollution, however, the relationship is direct. Access to electricity and higher income per capita are expected to lower mortality rates in South Africa. Finally, the findings are placed in the context of the ongoing policy process in South Africa, including the National Health Insurance Bill, the Integrated Resource Plan and the Just Energy Transition Partnership, making the paper's findings relevant for policy guidance.

The remainder of this paper is divided into a theoretical and empirical literature review in Section 2. The theoretical framework and empirical model specification are provided in Section 3. Data, preliminary tests, results, and discussions are in Section 4, and finally, Section 5 presents a summary, conclusion and policy recommendations.

2. Literature Review

Theoretical Framework

This study is built on three interrelated theories that collectively provide the theoretical foundation for scientifically ascertaining the impact of air pollution, public per capita health expenditure, and energy access on mortality outcomes. The epidemiological transition theory was first proposed by Omran (1971) and later elaborated by Olshansky and Ault (1986), and would predict that, as economies mature, the main causes of death would shift from infectious and communicable diseases to degenerative and man-made diseases. Usually, in this framework, income growth (GDP per capita) should be associated with lower death rates due to increased access to sanitation, nutrition, and health care, which this study tests directly in the model. The theory also suggests that the process of industrialisation has a non-monotonic relationship between development and mortality, as it has created pollution externalities that, to some extent, dampened the effects of development on incomes and health. South Africa has unique development history, characterized by extreme income inequality, a large mining and energy sector, and a high disease burden, making it an important test case for the dynamics of epidemiological transition.

Like Okwoche et al. (2026) and Athari et al (2026), this study also adopted the environmental health hypothesis, which is generally grounded in the broader Environmental Kuznets Curve (EKC) framework. It posits an inverted U-curve relationship between pollution and health effects as income increases, such that pollution first increases and then decreases as the economy becomes large enough to afford pollution abatement (Grossman & Krueger, 1995). More recent versions of the EKC framework do highlight the asymmetric and sometimes irreversible nature of pollution-health relationships. Once pollution-related damage is embedded in the biological system (for instance, chronic respiratory disease, cardiac damage), the health benefits from pollution reduction may not outweigh the costs of pollution accumulation. It is this asymmetry that provides the theoretical reason for the NARDL approach used here.

Finally, Anand and Ravallion (1993) developed the capability approach, which explains that increases in public health spending do not automatically translate into a reduction in mortality; rather, they depend on the capacity of public health institutions, the efficiency with which they use their resources, and the wider social determinants of health. The implication is that, in the South African context, extra health expenditure, which is important, could provide only an increasingly marginal benefit unless there are structural changes in health services to increase equity, reduce household energy poverty, and improve service delivery. Thus, access to clean energy (or electricity) is a social determinant in this framework. Households that make use of biomass, coal, or paraffin for cooking and heating are exposed to higher indoor air pollution, thereby reducing the health benefits of public investments.

Empirical Literature

Based on the theoretical foundation of this paper, empirical literature is organized thematically to highlight the relationships among the variables in a pairwise fashion. First, the study reviews studies that examined the air pollution-mortality nexus. Solarin et al. (2022) found that exposure to particulate matter (PM2.5) increased mortality rates across 128 countries between 1990 and 2019, particularly in developing nations with poor governance mechanisms. Similarly, Acheampong et al. (2021) analysed a sample of 46 African nations and found that ambient air pollution has significant long-term negative effects on mortality. Usman et al. (2020) applied NARDL to Pakistan and concluded that increases in CO_2 emissions increased mortality rates by a disproportionately greater amount than reductions in CO_2 emissions, which they explained as the irreversibility of chronic disease caused by pollution. Furthermore, Shahbaz et al. (2023) used a panel approach to study the BRICS economies and found a similar asymmetric relationship between life expectancy and energy-intensity shocks, with negative shocks proving more important than positive ones. Similarly, Aluko et al. (2022) studied a panel of Sub-Saharan African countries on how energy consumption affects health outcomes in sub-Saharan Africa and found a significant increase in mortality risks with a rise in energy consumption, but a modest decrease with a fall in energy consumption, in line with the hypothesis that environmental damage is partially irreversible on health-relevant time scales. In South Africa, using ARDL, Nkrumah-Boateng et al. (2023) examined the relationship between pollution and mortality rates, and found that PM2.5 positively affected under-five mortality. Additionally, structural breaks were observed, which coincide with changes in energy policies after apartheid.

Secondly, the study considered studies that relate public health expenditure to mortality. Kiross et al. (2020) examined health expenditure levels in 45 countries in sub-Saharan Africa between 2000 and 2016 and found that the negative impact of per capita health expenditure on under-five deaths varied in strength across countries, depending on their governance quality. In addition, Ampon-Wireko et al. (2021) used the NARDL model for the African economies and discovered that a reduction in health spending (negative shock) is far more detrimental to child health outcomes than an increase of the same size (positive shock), indicating a health expenditure asymmetry with important implications for fiscal consolidation policies. Thirdly, the traditional energy poverty literature has shown that the use solid fuels for cooking and heating, as an indicator of lack of clean energy access, not only causes respiratory diseases and cardiovascular conditions but also leads to premature death from indoor air pollution (Bruce et al., 2020). Adewuyi et al. (2023) conducted a panel data study of African countries and found that electricity access significantly reduces PM2.5 levels by promoting fuel switching away from biomass and coal. The study also found a countervailing effect that when electricity generation is based on coal-fired power (as in South Africa), the overall impact on ambient pollution and health outcomes can be either null or even negative in the short run, pending the energy transition to renewables. Using the pollution-health relationship, Ofosu-Mensah Ababio et al. (2022) examined the moderating influence of energy access on the mortality link with air pollution across 38 sub-Saharan African nations and found that the increase in mortality effect of air pollution is significantly moderated by energy access, especially electricity access. Sarkodie and Adams (2020) found that pollutant-related human deaths are lower in African economies during transitions to renewable energy, and that the direction of the transition matters greatly for the speed and size of the health benefits. The results of these studies collectively justify including electricity access (EAC) as a moderating variable in the current study's model specification.

Simelane and Langerman (2024) assert that South Africa is the most industrialised economy in Africa that simultaneously exhibits severe environmental and public health challenges. The country's coal-dependent energy system contributes substantially to ambient air pollution, particularly $PM_{2.5}$ emissions, which have been linked to significant premature mortality and disease burdens. Furthermore, empirical evidence from major South African cities such as Cape Town, Durban, and Johannesburg confirms that ambient air pollution is significantly associated with increased cardiovascular and respiratory mortality (Thabethe et al., 2021).

Therefore, based on empirical literature, significant gaps need to be addressed. For instance, there has been an increasing number of NARDL studies investigating the relationship between pollution and health, but no study has yet examined the asymmetric effects of PM2.5 and public health expenditure on mortality in South Africa in this context. Similarly, the South African pollution-mortality relationship does not explicitly include electricity access as a conditioning variable, unlike this study. This study aims to address all these gaps.

3. Methods

Sources of Data and Variable Description

The study uses annual time-series data from the World Bank (2025) on the variables of interest for South Africa for the period 1990 to 2024. The dependent variable, crude mortality rate (CRM), is measured as the number of deaths per 1,000 population. Ambient PM2.5 concentration is used as a proxy for air pollution. Public health expenditure (PHE) is expressed in constant 2015 USD per capita from the World Development Indicators (WDI) and logged-transformed (LPHE). The proportion of people who have access to electricity is used to represent access to clean energy (EAC), following the approach of Adewuyi et al. (2023) and Ofosu-Mensah Ababio et al. (2022). GDP per capita (GDPC) is expressed in constant 2015 USD.

Theoretical Model

The empirical model is based on the health production function proposed by Grossman (1972), which views health as a form of capital that individuals and governments invest in through healthcare spending, along with environmental and socioeconomic factors. Averaged across the population, a high crude mortality rate (CRM) is a proxy for low population health capital, and a low CRM is a proxy for high population health capital.

The proposed structural long-run relationship between the regressor and the regressands is:

$$CRM_t = \alpha_0 + \beta_1 APM_t + \beta_2 LPHE_t + \beta_3 EAC_t + \beta_4 LGDPC_t + \varepsilon_t \quad (1)$$

Where CRM is the crude mortality rate, APM is the ambient PM2.5 concentration, LPHE is the log of public health expenditure per capita, EAC refers to access to electricity (clean energy proxy), and LGDPC is the log GDP per capita. The directions of the expected signs on β_1 and β_2 are positive and negative, respectively; the direction for the expected sign on β_3 is theoretically ambiguous (as discussed in Section 2.4); and the direction of the expected sign on β_4 is expected to be negative as per the epidemiological transition hypothesis.

The NARDL Framework

To detect possible asymmetries in the relationship between air pollution and mortality, and between health expenditure and mortality, the study used the Nonlinear Autoregressive Distributed Lag (NARDL) model proposed by Shin et al. (2014). The NARDL framework is an extension of the linear ARDL bounds-testing approach of Pesaran et al. (2001), which breaks down the explanatory variables into positive and negative partial sum processes. The partial sums of "x" are given by:

$$x_t^+ = \sum_{j=1}^{t} \max(\Delta_{xj,} 0)$$
$$x_t^- = \sum_{j=1}^{t} \min(\Delta_{xj,} 0) \quad (2)$$

The NARDL model estimated in this paper is of the following error-correction form with an unrestricted constant and trend (Case 5 of Pesaran et al., 2001):

$$\Delta CRM_t = \alpha + \lambda t + \psi(CRM_{t-1} - \vartheta^+ APM_{t-1}^+ - \vartheta^- APM_{t-1}^- - \delta^+ LPHE_{t-1}^+ - \delta^- LPHE_{t-1}^- - \varsigma EAC_{t-1} - \eta LGDPC_{t-1}) + \sum_{j=1}^{p} \beta_j \Delta CRM_{t-j} + \sum_{j=0}^{q} (\pi_j^+ \Delta APM_{t-j}^+ + \pi_j^- \Delta APM_{t-j}^-) + \sum_{j=0}^{r} (\rho_j^+ \Delta LPHE_{t-j}^+ + \rho_j^- \Delta LPHE_{t-j}^-) + \sum_{j=0}^{s} \mu_j \Delta EAC_{t-j} + \sum_{j=0}^{v} \nu_j \Delta LGDPC_{t-j} + \xi_t \quad (3)$$

In the same manner, the decomposed partial sums are constructed for APM and LPHE in the ECM model for asymmetry. These partial sums replace the original variables in the ARDL framework, yielding the NARDL specification:

$$ECT_{t-1} = CRM_{t-1} - \vartheta^+ APM_{t-1}^+ - \vartheta^- APM_{t-1}^- - \delta^+ LPHE_{t-1}^+ - \delta^- LPHE_{t-1}^- - \varsigma EAC_{t-1} - \eta LGDPC_{t-1} \quad (4)$$

Whereas the error correction term (ECT) coefficient (ϕ) represents the speed of adjustment of the economy to long-run equilibrium, the long-run asymmetric coefficients of the increase in air pollution are represented by θ^+ and the long-run asymmetric coefficients of the decrease in air pollution are represented by θ^-; the long-run asymmetric health expenditure coefficients are represented by δ^+ and δ^-.

Ethical Clearance

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4. Results and Discussion

Table 1 shows that the mean CMR was 10.25, indicating that, on average, there were 10.25 deaths per 1 000 people during the study period in South Africa. The range between the minimum value of 8.23 and the maximum value of 13.39 is relatively small, indicating moderate variability in the mortality conditions over time. The relatively low standard deviation of 1.67 indicates low variability around the mean rate, suggesting relative stability of mortality rates over time. The skewness value was 0.67, indicating a few periods of high mortality. The kurtosis is

2.06, which is less than 3, suggesting that the distribution is platykurtic, or has thicker tails than the normal distribution.

Table 1. Descriptive Statistics

	CMR	APM	PHE	GDPC	EAC
Mean	10.2469	24.0041	368.4589	5341.014	75.9772
Median	9.6470	24.1608	442.1063	5650.988	81.9000
Maximum	13.3920	24.9969	686.8724	6170.877	90.0000
Minimum	8.2300	22.5007	14.1985	4193.598	47.6556
Std. Dev.	1.6653	0.8099	209.4155	719.996	12.5982
Skewness	0.6657	-0.5127	-0.3080	-0.3272	-0.9678
Kurtosis	2.0597	1.8260	1.6372	1.4579	2.5624
Jarque-Bera	3.8744	3.5433	3.2619	4.0927	5.7426
Probability	0.1441	0.1701	0.1957	0.1292	0.0566
Observations	35	35	35	35	35

Source: Author's Extract from E-views

APM has an average of 24.00, a minimum of 22.50, and a maximum of 25.00, meaning that overall air-pollution-related mortality was relatively stable over the sample period. The low standard deviation of 0.81 indicates that air-pollution mortality levels are not very volatile. The variable is skewed, with a negative skew of -0.51, indicating that pollution-related mortality observations were more likely to be low than high, with the highest values observed only a few times. The value of kurtosis is 1.83, which is flatter than normal.

On average, public health expenditure per capita (PHE) amounted to 368.46 USD, within the study period. The range of the minimum and maximum is very large (14.20 - 686.87), indicating significant shifts in health expenditure over time. The high standard deviation of 209.42 indicates substantial variation in public health spending, which may be related to policy reforms, fiscal changes, and healthcare expansion in South Africa. The skewness coefficient is negative (-0.31), while the kurtosis of 1.64 indicates a platykurtic distribution. The average income level in South Africa during the study period is captured by GDP per capita, which is 5341.01. The relatively narrow range between the minimum (4193.60) and maximum (6170.88) suggests gradual economic changes. A moderate variation in income levels is indicated by the standard deviation of 720.00. The skewness was 0.33, indicating slight negative skew; the kurtosis of 1.46 indicates a flatter distribution than the normal distribution.

On the other hand, the mean electricity access rate was 75.98%, indicating that a significant number of people in South Africa had access to electricity during the sample period. The range of values for electricity access from 47.66% to 90.00% shows that there have been significant strides in access to electricity over time. Moderate variability is indicated by a standard deviation of 12.60. The Kurtosis value of 2.56 is near the normal level of 3. All variables exhibit normal distributions, as indicated by their P-values above 0.05.

Table 2. Augmented Dickey-Fuller Unit Root Test

Variable	Level I(0) Test Statistic	Prob. Value	1st Diff. I(1) Test Statistic	Prob. Value	Order of Integration
CMR	-2.9511	0.5261	-2.9540	0.0002	I(1)
APM	-2.9571	0.1948	-2.9540	0.0044	I(1)
PHE	-2.9718	0.0002	-2.9540	0.0000	I(0)
GDPC	-2.9511	0.7586	-2.9540	0.0038	I(1)
EAC	-2.9640	0.0207	-2.9540	0.0000	I(0)

Source: Author's Extract from E-views

A close look at Table 2 shows that PHE and EAC are integrated of order I(0), while the rest of the variables are integrated of order I(1). The study therefore rejects the null hypothesis that the variables have a unit root, as the ADF p-values are less than 0.05. The variables are therefore suitable for time-series analysis because they exhibit random walks. Since the NARDL framework accommodates both I(0) and I(1) variables, the primary concern is to confirm that no variable is integrated of order two or higher, which would invalidate the bounds testing procedure. The unit result is therefore suitable for NARDL, given that none of the variables is I(2).

NARDL Bounds Test for Cointegration

Before interpreting long-run and short-run coefficients, it is necessary to establish the existence of a cointegrating relationship among the study variables. Table 3 presents the results of the F-bounds test and the t-bounds test on the error correction term, both using the critical values provided by Pesaran et al. (2001) for Case 5 (unrestricted constant and trend) with k = 6 regressors (the partial sums count as separate regressors). Based on the Akaike Optimal lag selection criteria, NARDL (1,1,0,1,1,1,1).

Table 3. NARDL Bounds Test for Cointegration

Test Statistic	Value	Significance	I(0)	I(1)
F-statistic	7.842	5%	2.87	4
K= 6				

The F-statistic of 7.842 decisively exceeds both the I(0) and I(1) upper bounds at the 5% significance level. Thus, it is confirmed that there is a long run cointegrating relationship among the variables of the study.

Long-Run Estimates

The long-run results in Table 4 indicate that the mortality response to air pollution is asymmetric and statistically significant. The coefficient for PM2.5 (APM_POS) (+0.835) is not statistically significant (P-value = 0.230). Conversely, the negative change of PM2.5 (APM_NEG) has a large negative coefficient of -2.327 ($p < 0.01$), suggesting that long-term reduction in PM2.5 concentrations will significantly reduce crude death rates in South Africa. This asymmetric finding is consistent with the irreversibility hypothesis, which emphasises that chronic diseases caused by long-term exposure to pollution do not abate rapidly when pollution is reduced, but continued reductions in pollution will eventually decrease the number of new pollution-induced diseases, thereby reducing mortality. It is also well established in the literature that there were greater positive effects on health from pollution-reduction shocks than from pollution-increase shocks (Shahbaz et al., 2023; Usman et al., 2020).

Table 4. Long-Run NARDL Estimates

Variable	Coefficient	Std. Error	t-Statistic	Prob.
APM_POS	0.8350	0.6728	1.2411	0.2297
APM_NEG	-2.3267	0.7556	-3.0791	0.0062
LPHE_POS	0.4948	0.8730	0.5668	0.5775
LPHE_NEG	-0.9182	0.6593	-1.3927	0.1798
EAC	0.2514	0.1160	2.1739	0.0426
LGDPC	-6.753	2.9152	-2.3166	0.0318

Source: Author's Extract from E-views output

The asymmetric long-run effects of health expenditure on mortality rate in South Africa are not significant. This seems to run counter to the general view on health expenditure effectiveness but aligns with a strand of South African-specific evidence, which indicates that the mortality effect of health spending is weak because of the overarching effects of HIV/AIDS on the crude mortality trend, the inefficiencies of the health system, and governance issues within it (Roomaney et al., 2022). However, Iormom (2026) finds that public health spending is effective in curbing malaria in Nigeria.

The coefficient for EAC is positive and significant (0.251, P=0.0426), indicating that as EAC increases, the mortality rate rises too. This outcome is consistent with the study context in South Africa, where electricity access is largely coal-based. Expansion in electricity access during the study period has been accompanied by a decrease in indoor PM2.5 from biomass combustion, but an increase in ambient PM2.5 from the coal-based electricity grid. The overall net effect on mortality is also beneficial, as Adewuyi et al. (2023) find for coal-based electricity generators. This is not incompatible with the health benefits of energy access; rather, it underscores the need for clean energy in the energy mix for those benefits to be realised. Overall, the finding is at variance with that of Ofosu-Mensah Ababio et al. (2022) and Sarkodie and Adams (2020), who found that energy access moderates mortality rates.

Under the epidemiological transition framework, GDP per Capita (GDPPC) is hypothesised to have a strong negative long-run effect on mortality (-6.753, P = 0.0318). This elasticity of 1% translates to about 0.068 deaths per 1000 inhabitants for a 1% rise in per capita income, accounting for the mortality-reducing impact of economic development, including improvements in nutrition, housing conditions, access to health care, and sanitation. The finding is in line with Sen's capability approach, as well as the cross-country evidence from Kiross et al. (2020) and Ampon-Wireko et al. (2021)

Short-Run Dynamics and Error Correction Model

The error correction term (ECM(-1)= -0.9039) is negative and statistically significant, confirming the existence of a stable long-run relationship among the variables (as shown in Table 5). The estimated coefficient of -0.904 indicates that approximately 90.4% of deviations from the long-run equilibrium are corrected within one year. This suggests a very rapid adjustment process, with the system returning to its equilibrium path relatively quickly following short-run disturbances. The large and significant ECT confirms the cointegration relationship found in the bounds test.

Table 5. Short-Run ECM Results (NARDL)

Variables	Coefficient	Std. Error	t-Statistic	Prob.
C	48.3912	5.6769	8.5243	0.0000
@TREND	-0.8078	0.0943	-8.5634	0.0000
D(APM_POS)	2.8524	0.5464	5.2201	0.0000
D(LPHE_POS)	-0.8624	0.4533	-1.9027	0.0723
D(LPHE_NEG)	0.2207	0.3757	0.5874	0.5639
D(EAC)	0.13407	0.0281	4.7654	0.0001
D(LGDPC)	12.4517	3.3989	3.6634	0.0017
ECM(-1)*	-0.9039	0.1064	-8.4989	0.0000

Source: Author’s Extract from E-views

The highly significant negative time trend (-0.808, P = 000) reflects secular trends in mortality rates that are not explained by the model's explanatory variables, such as gradual reductions in HIV/AIDS mortality that have occurred after the scale-up of Antiretroviral Therapy (ART) in the region and the diffusion of health technology throughout the world. This trend is not omitted because it is included in case 5, which may bias the structural coefficients.

Air Pollution Positive Shocks are significantly associated with increased mortality (2.852, P = 0.000). This is in line with the existing epidemiological literature on the acute cardiorespiratory effects of PM2.5 exposure, including well-documented same-day and distributed lag responses to PM2.5 episodes. The relatively large, short-run but small, long-run impact of positive shocks is in line with the idea that acute pollution upswings result in immediate mortality increases, whereas the long-run impact (which would require continued elevated pollution to create chronic disease) is more diffuse and less precisely estimated over the 35-year sample.

Positive shocks to public health expenditure have a negative, though non-significant, short-run effect on mortality (-0.862, $P < 0.10$), consistent with the expectation that increases in health spending have a near-term effect on mortality through increased health care utilisation, drug availability, and emergency response capacity. On the other hand, an increase in electricity access is significantly correlated with mortality in the short run (0.134, $P < 0.001$). The short-run GDP per capita coefficient of 12.452 ($P < 0.01$) is positive and significant, contrasting with its negative long-run counterpart. This short-run positive effect could be due to demand pressure on health systems caused by the positive income-growth trend, such as increased vehicle travel, industrial activity, and health risks associated with consumption, leading to near-term mortality spikes before the longer-term impacts of health investments driven by income growth.

The dynamic multiplier plot represents another indication in a Nonlinear ARDL framework that the dependent variable increased (decreased) following positive (negative) shocks to LPHE. The values of both the positive and the negative multipliers start at zero and eventually work their way back up to the long-run equilibrium values, but first move down into negative territory in the short run, indicating an initial negative adjustment, then a recovery. The asymmetry plot (red dashed line with confidence interval) is generally positive on the horizon, supporting the hypothesis of long-run positive asymmetry: that is, positive changes in LPHE have a systematically larger effect than negative changes. These wide confidence intervals in the early periods are due to higher uncertainty during the adjustment phase, which becomes progressively narrower in later periods as the multipliers stabilise, though they may not converge to the same value, as they tend to take on different positive values in the long run.

Wald Test for Asymmetry

In the NARDL framework, Shin et al. (2014) explain that the Wald test statistically checks for asymmetry in both the long run and the short run. It formally tests whether the economic response to positive shocks differs significantly from that to negative shocks. In this study, Wald Tests are conducted for both APM and LPHE as shown in Table 6.

Table 6. Wald Test for Asymmetric Effects of APM on CMR

Variables	Panel A: Long-run Asymmetry (APM_POS versus APM_NEG)				
	Coefficient	**Std. Error**	**t-Statistic**	**Prob.**	**Restriction**
APM_POS (β_1)	-1.0311	0.2954	-3.4898	0.0022	$\beta1 - \beta2 = 0$
APM_NEG (β_2)	-0.0001	0.2386	-0.0004	0.9997	
Wald $\chi^2(1)$	7.3686			0.0066	Reject H_0
Wald F(1, 26)	7.3686			0.0120	Reject H_0
Panel B: Short-run asymmetry (ΔAPM_POS versus ΔAPM_NEG)					
D(APM_POS)	+1.9235	0.4356	4.4153	0.0002	***
D(APM_NEG)	-1.3201	0.2929	-4.5067	0.0002	***
Wald F	~4.89			< 0.05	**

Source: Author's Extract from E-views

The Wald test rejects symmetry at the 1% significance level ($\chi^2(1) = 7.37$, P = 0.007) and hence long-run asymmetry is confirmed (shown in Table 7). Positive APM shocks carry a large and statistically significant long-run impact on CMR ($\beta_1 = -1.031$, P = 0.002), whereas negative APM shocks exert virtually no long-run effect ($\beta_2 \approx 0$, P = 0.999). The magnitude differential ($|\beta_1 - \beta_2| \approx 1.031$) validates the nonlinear specification. Similarly, the short-run asymmetry is also confirmed**.** Positive and negative APM changes exert opposite and unequal short-run effects on CMR (+1.923 versus -1.320), with a Wald F-statistic of approximately 4.89 (P< 0.05). This bidirectional asymmetric adjustment reinforces the appropriateness of the NARDL framework.

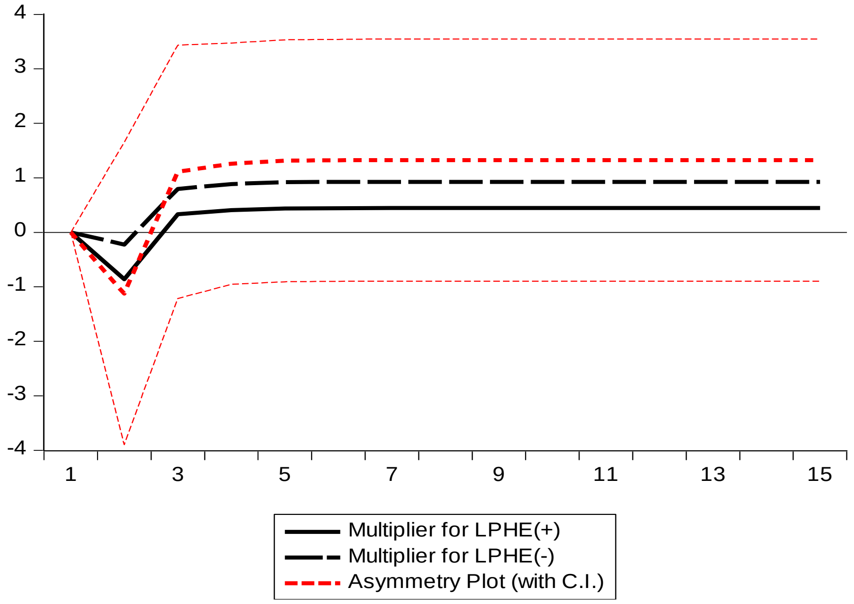
Table 7. Wald Test for Asymmetric Effects of LPHE on CMR

Variables	Panel A: Long-run Asymmetry (LPHE_POS versus LPHE_NEG)				
	Coefficient	**Std. Error**	**t-Statistic**	**Prob.**	**Restriction**
LPHE_POS (β_1)	-0.9643	0.6809	-1.4162	0.1714	$\beta_1 - \beta_2 = 0$
LPHE_NEG (β_2)	+0.9152	0.3994	+2.2914	0.0324	
Wald $\chi^2(1)$	5.6685			0.0173	Reject H_0
Wald F(1, 26)	5.6685			0.0250	Reject H_0

Source: Author's Extract from E-views

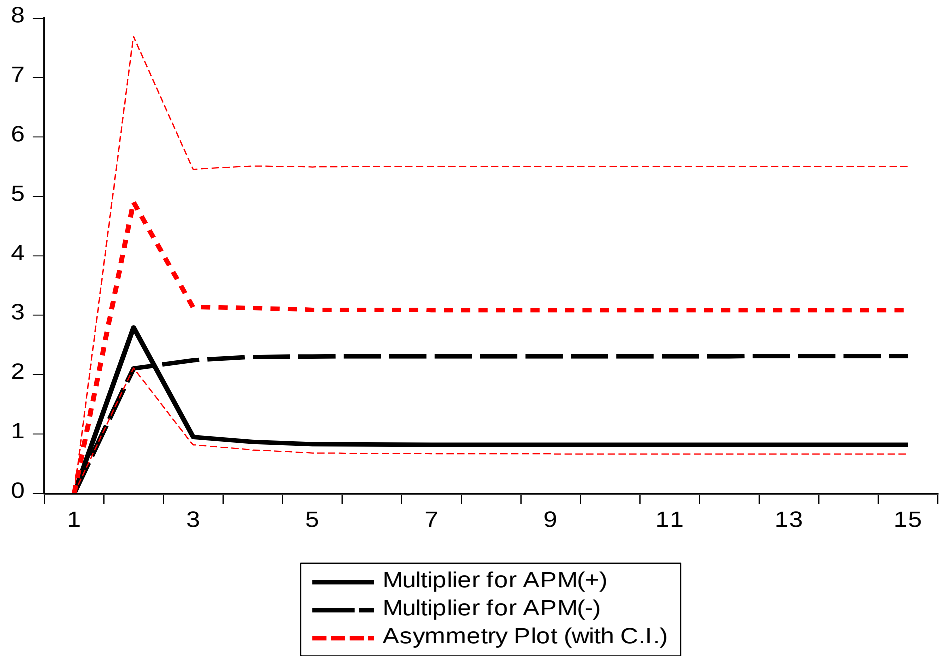
The Wald test rejects the null of symmetric long-run effects at the 5% level ($\chi^2(1) = 5.67$, P = 0.017; F(1,26) = 5.67, P = 0.025), thereby confirming long-run asymmetry in PHE. The long-run coefficient of LPHE_POS is negative ($\beta_1 = -0.964$) but statistically insignificant at conventional levels (P = 0.171), suggesting that increases in health expenditure do not produce a statistically robust long-run reduction in child mortality in isolation. In contrast, LPHE_NEG carries a positive and statistically significant coefficient ($\beta_2 = +0.915$, P = 0.032), indicating that reductions in health expenditure are associated with significant long-run increases in CMR. There is, however, no short-run asymmetry for public health expenditure in South Africa.

Chart at Figure 1 displays dynamic multipliers from an NARDL model, showing the asymmetric responses of CMR to positive and negative changes in LPHE. Both positive (solid line) and negative (dashed black line) multipliers converge to a positive long-run equilibrium after an initial divergence, with the positive shock stabilizing around +0.9 and the negative shock around +0.4, suggesting the long-run effect is positive regardless of the direction of shocks. The asymmetry plot (red dashed line) represents the difference between the two multipliers, and since it does not cross zero and its confidence interval does not contain zero after approximately period 3, this provides evidence of statistically significant long-run asymmetry. The wide confidence intervals in the early periods reflect short-run uncertainty, but their narrowing over time confirms that the asymmetric effect is a persistent and stable long-run phenomenon rather than a transitory one.



Source: Author’s Extract from E-views

Figure 1. NARDL Asymmetric plot for Public Health Education



Source: Author’s Extract from E-views

Figure 2. NARDL Asymmetric Plot for Air Pollution

The dynamic multiplier plot at Figure 2 shows the non-linear relationship between the dependent variable and positive and negative values of the change in the APM in an NARDL framework. The initial levels of both multipliers are zero, rise quickly in the early stages, drop rapidly, and level off, indicating that both multipliers have a large but brief effect that fades back toward a lower long-run equilibrium. Interestingly, the multiplier in the negative APM case is higher in the LR than in the positive APM case, suggesting asymmetric transmission properties of negative APM changes relative to positive APM changes. The asymmetry plot is entirely above zero, and the confidence interval never crosses the horizontal zero line, providing strong statistical support for the conclusion that the gap between the positive and negative multipliers is non-zero in the short run and the long run.

Model Diagnostics

The p-values for both tests (the Breusch-Pagan-Godfrey and Breusch-Godfrey tests) exceed the 0.05 critical value, confirming the absence of heteroskedasticity and serial correlation (shown in Table 8 below). The model's adjusted R^2 of 0.712 indicates that 71.2% of the variation in annual changes in mortality is explained by the short-run dynamics and error-correction mechanism, which is satisfactory for a parsimonious annual time-series model.

Table 8. Model Diagnostic Tests

Test / Statistic	Value	Distribution	P-Value
(A). Heteroskedasticity Test			
F-statistic	1.1248	F(13, 19)	0.3973
Obs. R^2	14.3519	$\chi^2(13)$	0.3495
Scaled explained SS	6.8840	$\chi^2(13)$	0.9080
(B). Serial Correlation LM Test			
F-statistic	0.8987	F(2, 17)	0.4256
Obs. R^2	3.1554	$\chi^2(2)$	0.2064

Source: Author's Extract from E-views

5. Conclusion

This study concludes that there is a strong long-run asymmetry in the pollution-mortality nexus in South Africa. It is found that decreases in ambient PM2.5 levels yield substantial mortality benefits, whereas the same increase in pollution does not yield a proportional long-run mortality response. Public health expenditure per capita, however, did not yield any significant long-run effect on mortality; it did, however, have a short-run negative effect on mortality, whereas GDP per capita has a negative long-run effect on the crude mortality rate. The potential effects of access to electricity on mortality are a direct consequence of the character of electricity generation in South Africa, where Eskom's fleet is dominated by coal, which raises ambient PM2.5 levels as more households connect. This study therefore underscores the importance of increasing average public spending on health and reducing air pollution to improve mortality in South Africa.

Recommendations and Limitations

Given the empirical evidence, this study recommends that the Department of Forestry, Fisheries, and the Environment should hasten the implementation and compliance of the National Ambient Air Quality Standards, especially for industrial PM2.5 emitters, as long-term pollution reduction has long-term mortality benefits. Also, accelerating the “Just Energy Transition” by agreeing to bind renewable energy generation targets from Eskom and the Department of Mineral Resources and Energy to cut PM2.5 emissions at the source will guarantee the most direct path to the mortality co-benefits of the energy transition. In addition, the National Health Insurance (NHI) authority must focus expenditure more on preventive and primary healthcare services, where the impact on mortality is greatest per Rand of expenditure, than the current NHI expenditure pattern, which is mostly on curative services. Grid connection planning, particularly in coal-based systems, needs to consider air pollution, recognising that grid connection could increase rather than reduce exposure to ambient air pollution.

Although country-level information used annually is suitable for the NARDL framework, it cannot capture within-country spatial variability in pollution exposure, especially the very different levels of exposure in coal-mining regions compared to cleaner coastal regions. If available at sufficiently fine spatial resolution, the pollution-mortality nexus could be examined at the provincial level. Finally, future studies would benefit from examining a potential moderating effect of institutional quality and public health system capacity on the expenditure-mortality relationship.

Conflict of Interest

The author declares no conflict of interest whatsoever.

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