



The asymmetric nexus between air pollution and COVID-19: Evidence from a non-linear panel autoregressive distributed lag model

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ABSTRACT

The emergence of a new coronavirus (COVID-19) has become a major global concern that has damaged human health and disturbing environmental quality. Some researchers have identified a positive relationship between air pollution (fine particulate matter PM_{2.5}) and COVID-19. Nonetheless, no inclusive investigation has comprehensively examined this relationship for a tropical climate such as India. This study aims to address this knowledge gap by investigating the nexus between air pollution and COVID-19 in the ten most affected Indian states using daily observations from 9th March to September 20, 2020. The study has used the newly developed Hidden Panel Cointegration test and Nonlinear Panel Autoregressive Distributed Lag (NPARDL) model for asymmetric analysis. Empirical results illustrate an asymmetric relationship between PM_{2.5} and COVID-19 cases. More precisely, a 1% change in the positive shocks of PM_{2.5} increases the COVID-19 cases by 0.439%. Besides, the estimates of individual states expose the heterogeneous effects of PM_{2.5} on COVID-19. The asymmetric causality test of Hatemi-J's (2011) also suggests that the positive shocks on PM_{2.5} Granger-cause positive shocks on COVID19 cases. Research findings indicate that air pollution is the root cause of this outbreak; thus, the government should recognize this channel and implement robust policy guidelines to control the spread of environmental pollution.

1. Introduction

Along with mounting public health concerns, pandemics wreak havoc on the socio-economic fabric of disease-stricken countries (Elavarasan et al., 2021). In the past few years, human civilization has been afflicted by a number of pandemics (Yang et al., 2021), resulting in massive deaths (Khan et al., 2021), illnesses (Yu et al., 2021), and costs trillions of dollars worldwide (Iqbal et al., 2021). By the end of 2019, the world was challenged by a novel pandemic known as COVID-19 (Linillos-Pradillo et al., 2021). Regardless of the Chinese government's

attempts to isolate Wuhan city from other regions, all continents were rampant in the outbreak, and it was declared as a worldwide pandemic by the World Health Organization (Razzaq et al., 2020). COVID-19 has not been completely eradicated, and even certain regions continue to observe an upward tendency, mostly due to the lack of disease-resistant vaccination and treatment (Lai et al., 2020).

India, which shares a border with China, is also battling new coronavirus. The country reported just three COVID-19 incidences through March 2, 2020 (Irfan et al., 2021a). During the next month, however, the confirmed COVID-19 instances grew to thousands all over the country.

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The COVID-19 patients are still growing rapidly, and the scenario is deteriorating. According to government figures, the COVID-19 cases totalled 37.4 M in India, with 486,482 deaths (Worldometers, 2021). India's most serious concern is combating COVID-19, which has lately attracted worldwide attention. To prevent the spread of COVID-19, the Indian government has implemented a number of action plans, including isolation facilities, designated healthcare facilities, testing laboratories, case tracking, and contingency planning. Additionally, the government is attempting to fortify states by providing a prompt and efficient response to any coronavirus-related crises. Several policies have been implemented in this vein, such as lockdown, quarantine, and social isolation (Ghosh et al., 2020).

With increase in energy consumption (Abbasi et al., 2022; Akram et al., 2022; Dagar et al., 2021; Fang et al., 2022), air pollution is increasing globally (Akram et al., 2020; Islam et al., 2022; Sun et al., 2021; Tanveer et al., 2021) and research exposed that it/ is a carrier of SARS-CoV-2 (Marquès et al., 2021). Researchers argued that air pollutants have a detrimental effect on cardio-pulmonary and immunological systems by reducing hosts' susceptibility to viral and bacterial infections. For instance, Taghizadeh-Hesary et al. (2021) scrutinized the energy-pollution-health nexus among low and middle-income Asian countries using the generalized method of moments estimation technique. The study results revealed that fossil fuel consumption increases air pollution, which leads to lung and respiratory diseases. In another study, Taghizadeh-Hesary and Akbari (2020) examined the parameters influencing the immune system's response to COVID-19. The authors exposed that SARS-CoV-2 weakens the immune system by increasing IFN-1 yield. This process culminates in the accumulation of inflammatory monocytes/macrophages and neutrophils, contributing to lung immunopathology. Later, the cytokine storm further weakens the immune system through IFN-1-mediated T cell apoptosis. Higher concentrations of air pollutants are linked with higher occurrences of respiratory viral infections, particularly when the viral infection occurs simultaneously with a transient increase in air pollution exposure (Rasoulinezhad et al., 2020). Air pollution may be associated to an increase in COVID-19 intensity and fatality owing to its effect on chronic conditions such as cardiovascular disease and diabetes (Bourdrel et al., 2021). Air pollution also contributes to the development of cardiometabolic conditions such as heart disease and insulin sensitivity.

According to research, roughly 38% of COVID-19 patients in China had hypertension or coronary heart disease, whereas approximately 19% had diabetes. Further, these individuals exhibited higher mortality from COVID-19 infection (Zhou et al., 2020).

Air pollution aggravates the intensity of COVID-19 pneumonia by deteriorating the respiratory system (Irfan et al., 2021). Poor air quality mainly, $PM_{2.5}$ is one of the key reasons for excessive mortality (Ali and Islam, 2020). Taghizadeh-Hesary and Taghizadeh-Hesary (2020) studied the impact of air pollution on human health in Southeast Asian countries and found that $PM_{2.5}$ and CO_2 are major risk factors for lung cancer in the region. Abundant medical studies revealed that elevated $PM_{2.5}$ levels lead to serious chronic health conditions, such as bronchitis and emphysema, breathlessness, itchy throat, respiratory infections, and asthma by increasing the lungs' susceptibility to infection (Pozzer et al., 2020). These conditions are comparable to those associated with SARS-CoV-2 (Ameri et al., 2020). Air pollution ($PM_{2.5}$) can provoke the COVID-19 pandemic in two ways. *First*, by making people more vulnerable to COVID-19 infection through increasing their vulnerability to chronic diseases and pushing COVID-19 infected individuals at acute danger and even death. *Second*, by increasing the risk of exposure to COVID-19 since it can be transmitted by microscopic particles or combined with ultrafine aerosols (Annesi-Maesano et al., 2021). The situation is explained in Fig. 1.

Previous research has mostly focused on disease control and prevention mechanism (Gao and Yu, 2020; Kang et al., 2020). The first set of research considered the epidemiology of infections (Nkenfou et al., 2021; Shah et al., 2020). The second set of research determined the effect of various factors on epidemic prevention (Ahmad et al., 2021; Yang and Ren, 2020; Irfan et al., 2021). The third set of research examined the current state of disease profiles to develop effective preventative action plans (Irfan et al., 2021b; Rawat et al., 2021). Finally, the fourth set of research scrutinized individuals' perceptions of the importance of preventing epidemics (Ahmad et al., 2020a; Chughtai and Khan, 2020; Irfan et al., 2021). Despite the significance of past investigations, the propensity to investigate the relationship between air pollution and COVID-19 is a prime agenda. The current work responds to this literature gap by addressing the following research issues: (i) what is the nexus between $PM_{2.5}$ and COVID-19 spread in India? (ii) Does COVID-19 a climate savior or a climate devil? Though

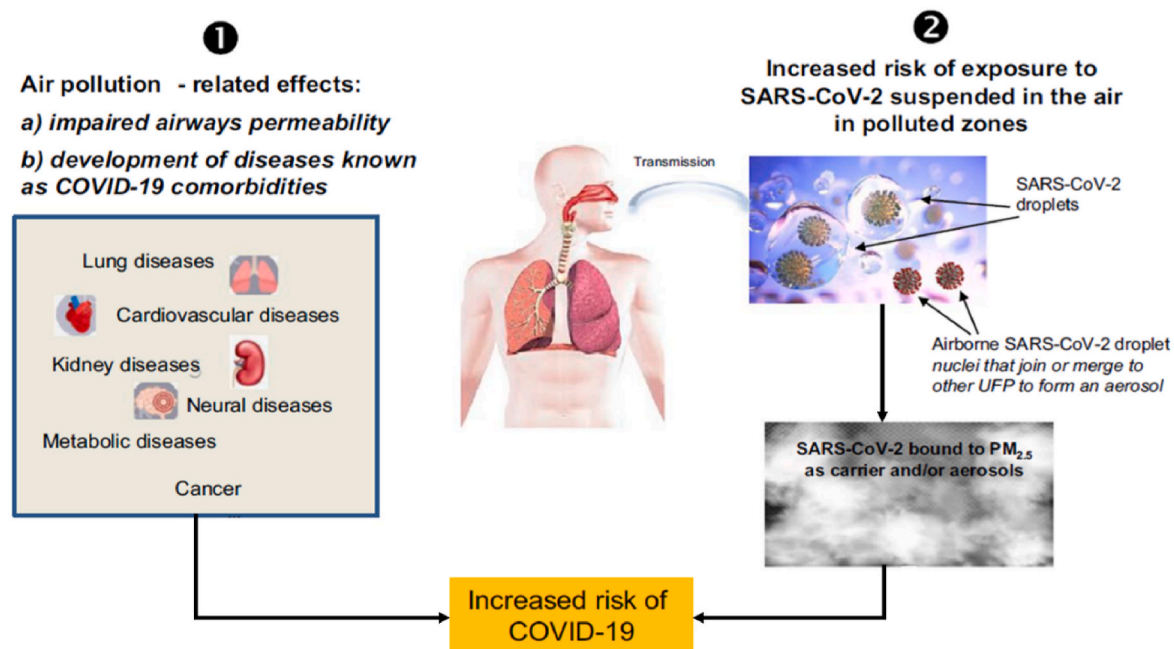


Fig. 1. Air pollution and COVID-19 transmission. Data source: (Annesi-Maesano et al., 2021).

multipollutant analyses are worthy of consideration, we focus on PM_{2.5}, which is very popular in air pollution epidemiology studies (Heal and Beverland, 2017). The fundamental rationale of selecting PM_{2.5} includes evidence in the former studies about chronic health issues and the growing risks of morbidity and respiratory infections. Besides, we chose PM_{2.5} as compared to PM₁₀ because the former is more associated with human illness and correlates with greater health impacts than PM₁₀. From the current air pollution literature, the most valid evidence points to PM_{2.5} regarding respiratory mortality impacts as compared to other air pollutants (Coker et al., 2020).

Along these lines, following are the contributions of the study to the existing literature: *Firstly*, the study examines and elaborates on the effect of air pollution (PM_{2.5}) on COVID-19 transmissibility in India using the comprehensive framework. Former researchers have been limited in their analysis of contentious findings and have concentrated exclusively on the consequences of atmospheric circumstances. *Secondly*, the regional investigation is much more credible and valid in estimating the air pollution impact on COVID-19 transmissibility by taking into account the Indian states and their apparent climate variations. *Thirdly*, by recognizing crucial factors, the danger of COVID-19 and the severity of forthcoming outbreaks can be minimized. *Finally*, a detailed understanding of the connection between air pollution and COVID-19 can be accomplished in clinical practice through the execution of infection control policy development and public health procedures.

The structure of the remaining study is given as follows: section 2 provides data description. Section 3 elaborates the methodology of the study. Section 4 reports research results and discussion. Finally, section 5 presents concluding remarks, policy implications, and study limitations.

2. Data

This paper used the daily data of PM_{2.5} concentrations and COVID-19 cases in the ten most infected Indian states. The National Air Quality Index database has been accessed to obtain the daily mean data of PM_{2.5} emissions from March 9, 2020 to September 20, 2020 (National Air Quality Index, 2020), whereas COVID-19 data is accessed from (COVID-19 India, 2021). For the analysis, all variables were transformed into their natural logarithm. The capital cities of all states were chosen for PM_{2.5} input since they contain the largest population and provide efficient medical facilities. Consequently, population density is higher here than in other cities. Likewise, each capital city contains an international airport, signifying that viral infection is considerable danger.

3. Methodology

The research has incorporated PM_{2.5} pollution as the primary indicator to describe COVID-19 cases and realized the potential non-linear linkage between them, which have not been previously analyzed. In this way, this is the pioneering study to reveal the asymmetrical ties between PM_{2.5} pollution and COVID-19 cases among the chosen states in the Indian context. The following econometric methods have been employed to fulfil the study objectives. (i) The CD test of Pesaran (2004) is performed after developing the model to investigate the cross-sectional dependence (CSD). (ii) The Pesaran (2007) CIPS and CADF unit root tests are applied to test CSD and serial correlation. (iii) Next, asymmetric cointegration is conducted after verifying unit root (Ahmad et al., 2020b). (iv) An in-depth discussion of the NPARDL method is provided. (v) Finally, asymmetric causality is tested between PM_{2.5} and COVID-19 spread. The descriptive statistics are provided in Table 1.

3.1. Analysis of cross-sectional dependence and unit root test

CSD is commonly present in panel data. Overlooking CSD can cause inefficient and unreliable estimates of regression (Ahmad et al., 2020b;

Table 1
Descriptive statistics.

Variables	Observations	Mean	Std. Dev.	Min	Max
log PM _{2.5}	196	2.883	.81	0	5.17
log COVID-19	196	5.876	2.557	0	10.122
Madhya Pradesh					
log PM _{2.5}	196	2.544	.518	1.099	4.159
log COVID-19	196	5.198	1.985	0	7.866
Tamil Nadu					
log PM _{2.5}	196	2.179	.679	0	3.689
log COVID-19	196	6.521	2.603	0	8.853
Delhi					
log PM _{2.5}	196	3.546	.655	1.099	4.796
log COVID-19	196	6.051	2.248	0	8.406
Gujarat					
log PM _{2.5}	196	3.5	.336	2.639	4.205
log COVID-19	196	5.608	2.028	0	7.267
Telangana					
log PM _{2.5}	196	3.088	.337	1.792	4.511
log COVID-19	196	5.19	2.438	0	8.012
Karnataka					
log PM _{2.5}	196	3.187	.25	2.485	3.871
log COVID-19	196	5.655	2.904	0	9.2
West Bengal					
log PM _{2.5}	196	2.083	.584	.693	3.871
log COVID-19	196	5.406	2.626	0	8.094
Uttar Pradesh					
log PM _{2.5}	196	2.854	.758	1.099	4.844
log COVID-19	196	5.917	2.424	0	8.856
Maharashtra					
log PM _{2.5}	196	2.294	1.039	0	5.17
log COVID-19	196	7.43	2.425	.693	10.122
Andhra Pradesh					
log PM _{2.5}	196	3.554	.367	2.197	4.511
log COVID-19	196	5.778	2.935	0	9.29

Note: PM_{2.5} = Air pollution, COVID-19 = COVID-19 cases.

Akram et al., 2020a). The chosen Indian states have certain common features of PM_{2.5} pollution due to industrialization. We, therefore, start the empirical investigation employing Pesaran’s CSD test (2004).

The unit root tests focusing on the econometrics of first-generation mostly overlook CSD. Nevertheless, the unit root tests of CADF and CIPS examine stationarity and check panel data’s heterogeneity (Pesaran, 2007). Using a standard framework, Pesaran (2007) established the improved root unit tests of CADF and CIPS. Consequently, researchers have widely adopted these tests that allow CSD (Akram et al., 2020b; Aydin, 2019).

On the one hand, the unit root tests help in deciding whether the shocks to PM_{2.5} pollution and COVID-19 cases remain temporary or permanent and, on the other hand, indicate whether the variables should be decomposed or not. However, a long-run linkage is present between the studied variables, and any system disruptions would have a temporary deviation in the case of a unit root. Instead, in the absence of cointegration, any external shock can have a permanent effect and must be treated accordingly.

3.2. Analysis of asymmetric cointegration

The newly developed Hatemi-J’s (2020) test of Hidden Panel Cointegration is employed to check asymmetric cointegration between the +ve and -ve components of variables. This test assumes that the variables are not cointegrated in their genuine form, but cointegration may exist between the hidden components (i.e., +ve and -ve). One possible reason is that the presence of possible unknown trends in a non-cointegrated relationship drives the parts of the variables rather than the variables themselves.

The following steps have been carried out during the analysis. Firstly, the existence of a unit root between the variables is examined. The test of Hatemi-J (2020) presumes that series are stationary at the first difference. After stationarity check, we estimate the relevant equations

using the particular variables of this research as:

$$C19_{it}^+ = \alpha_i^+ + \beta_i^+ NO2_{it}^+ + \varepsilon_{it}^+ \tag{1}$$

$$C19_{it}^- = \alpha_i^- + \beta_i^- NO2_{it}^- + \varepsilon_{it}^- \tag{2}$$

Here C19 denotes COVID-19 cases. The variable can be further decomposed as follows:

$$C19_{it}^+ = \sum_{j=1}^t \Delta C19_{ij}^+ = \sum_{j=1}^t \max(\Delta C19_{ij}, 0) \tag{3}$$

$$C19_{it}^- = \sum_{j=1}^t \Delta C19_{ij}^- = \sum_{j=1}^t \max(\Delta C19_{ij}, 0) \tag{4}$$

Besides, the same decomposition can be used for the independent variable as:

$$NO2_{it}^+ = \sum_{j=1}^t \Delta NO2_{ij}^+ = \sum_{j=1}^t \max(\Delta NO2_{ij}, 0) \tag{5}$$

$$NO2_{it}^- = \sum_{j=1}^t \Delta NO2_{ij}^- = \sum_{j=1}^t \max(\Delta NO2_{ij}, 0) \tag{6}$$

Finally, ε_{it}^+ and ε_{it}^- residuals must be stationary to allow the cointegration of the series. To tackle this condition, we have used the unit root test of Pesaran (2007) with CSD.

3.3. Non-linear panel ARDL model

The majority of researchers have applied the linear structure, i.e., ARDL specification to investigate the relationship among variables (Dong et al., 2018; Rehman et al., 2019). This trend shows the importance of the ARDL method to test the complex relationships among variables. On the flip side, researchers have also applied the NARDL method in a time-series context to explain the non-linear relationship between COVID-19 and other related variables. (Sarfraz et al., 2020; Vuong et al., 2019). Generally, the +ve and -ve components of the independent variables in the NARDL method are described by using a single equation.

The panel structure of NARDL is also the same as studied in the time-series framework. NPARDL model is a non-linear depiction of panel data that examines panel data's heterogeneous nature and fits panels with large T, as is the sample of this research. Following the Salisu and Isah (2017) and Kouton (2019) specifications, we have used one independent variable to explain non-linear effects best suited for this study. Using Shin et al. (2014) model, we integrate the non-linear effects in the panel context, as follows:

$$\Delta C19_{it} = \alpha_0 + \alpha_1 C19_{it-1} + \alpha_2^+ NO2_{it-1}^+ + \alpha_2^- NO2_{it-1}^- + \sum_{j=1}^K \beta_j \Delta C19_{it-j} + \sum_{j=0}^{m1} (\gamma_j^+ \Delta NO2_{it-j}^+ + \gamma_j^- \Delta NO2_{it-j}^-) + \mu_i + \varepsilon_{it} \tag{7}$$

Here, lag orders are denoted by k and m , states specific impacts are represented by μ_i , and the standard error term is denoted by ε_{it} . The coefficients α_2^+ and α_2^- compute long-run symmetries, whereas, and γ_j^+ and γ_j^- compute short-run asymmetries, respectively. This equation is represented in an error correction system in the following way.

$$\Delta C19_{it} = \alpha_0 + \sigma \varepsilon_{it-1} + \sum_{j=1}^k \beta_j \Delta C19_{it-j} + \sum_{j=0}^{m1} (\gamma_j^+ \Delta NO2_{it-j}^+ + \gamma_j^- \Delta NO2_{it-j}^-) + \mu_i + \varepsilon_{it} \tag{8}$$

Here, ε_{it-1} represents the NPARDL model's long-term equilibrium. σ

represents the speed-adjustment parameter, which measures the time needed to achieve long-run equilibrium after any shock. Following null hypothesis "no cointegration," the cointegration relation is confirmed as:

$$H_0 : \alpha_1 = \sum_{i=2}^5 \alpha_i^+ = \sum_{i=2}^5 \alpha_i^- = 0 \tag{9}$$

PMG method is used to estimate the NPARDL model since it offers heterogeneous short-run coefficients and homogenous long-run coefficients for all states (Rumbia et al., 2020). The primary reason for employing the PMG method is that the correlation between PM_{2.5} pollution and COVID-19 cases could be different in the short-run. On the contrary, similar behaviour is possible for the selected variables in the long-run. It is important to mention that the cointegration association's estimation can also be done using other methods like FMOLS and DOLS. However, only the long-run relationship between the variables could be examined in these methods without capturing the short-run dynamics (Akram et al., 2020a).

3.4. Asymmetric panel causality testing

This paper also discusses the causality between PM_{2.5} pollution and COVID-19. For this purpose, we employ the Hatemi-J's (2011, 2012) test of asymmetric panel causality to examine the asymmetric causality between PM_{2.5} pollution and COVID-19 cases. Consideration of asymmetry is essential in causality analysis as it improves the inference (Hatemi-J, 2012). It is possible to investigate the causality between the +ve and -ve constituents of the variables, which is the central property of (Hatemi-J, 2012) test.

The test involves the following steps: First of all, the series of the study is divided into positive and negative components. Then we estimate the following VAR-SUR model.

$$\begin{bmatrix} x_{it}^+ \\ y_{it}^+ \end{bmatrix} = \begin{bmatrix} \alpha_{i0} \\ \beta_{i0} \end{bmatrix} + \begin{bmatrix} \sum_{j=1}^p \alpha_{ij} \sum_{j=1}^p \alpha_{izj} \\ \sum_{j=1}^p \beta_{ij} \sum_{j=1}^p \beta_{izj} \end{bmatrix} * \begin{bmatrix} x_{it-j}^+ \\ y_{it-j}^+ \end{bmatrix} + \begin{bmatrix} \varepsilon_{it}^+ \\ \varepsilon_{it}^- \end{bmatrix} \tag{10}$$

To check the causality from Y_{it}^+ to X_{it}^+ the following null hypothesis is constructed:

$$H_0 : \alpha_{izj} = 0, \forall j, \text{ and } j = 1, \dots, p$$

4. Results and discussion

The empirical results are discussed in this section as follows: The results of CSD and unit root tests are compiled in the first subsection. The results of asymmetric cointegration analysis are presented in the second subsection. The results of NPARDL and its robustness are discussed in the third subsection, while the fourth section illustrates the results of asymmetric panel causality.

4.1. Results of cross-sectional dependence analysis and unit root

Suitable unit root tests are selected by analyzing CSD, which considers the CSD in panel data. The results of the CSD test are compiled in Table 2. It is clear that CSD occurs in our chosen states, so the null hypothesis of "no CSD" is rejected. The findings stipulate significant proof of CSD in PM_{2.5} pollution and COVID-19, although at different levels (the correlation coefficient for all variables is not the same). Moreover,

Table 2
Cross-sectional dependence test.

Variable	CD-test	p-value	corr	abs(corr)
log PM _{2.5}	10.510	0.000	0.112	0.159
log COVID-19	86.330	0.000	0.920	0.920

Notes: Under the null hypothesis of cross-section independence CD ~ N(0, 1).

the findings validate that the impact of shock from any panel state also affects other states. Once CSD is verified, the unit root tests of CIPS and CADF are employed, which allow serial correlation. Besides unit root testing, both tests also demonstrate the heterogeneity of variables. The findings are reported in Table 3, indicating that all variables have a unit root at the level. However, at the first difference, all variables are stationary. Firstly, all of the series are I(1), indicating that Hatemi-J's (2020) asymmetric cointegration is possible to examine the long-run relationship between variables. Secondly, this finding shows that the first prerequisite of NPARDL estimation has been met. We confirmed that none of the order two variables I(2) is incorporated to estimate the NPARDL. Finally, any shock on PM_{2.5} pollution would have a permanent environmental effect. Research conducted in Italy, France, Germany, and Spain found a significant linkage between PM_{2.5} concentrations and the COVID-19 infected patients (Ogen, 2020). In the same vein, Iqbal et al. (2021) studied the association between COVID-19 infections and variations in air pollution levels in China and exposed that PM_{2.5} is the primary cause of COVID-19 transmissibility and fatality in the country. The findings reveal that a 1% increase in PM_{2.5} concentration is associated with an 11.67% increase in COVID-19 cases and an 18% increase in COVID-19 fatalities.

4.2. Results of asymmetric cointegration

We move further with hidden cointegration and employ Hatemi-J's (2020) test of asymmetric cointegration. The results of asymmetric cointegration are compiled in Table 4. Results demonstrate the asymmetric structure in the cointegration relationship between the series for the selected states. The results further illustrate a hidden or non-linear cointegration between PM_{2.5} pollution and COVID-19, which is in line with the recent research findings of (Zoran et al., 2020). In another study, Frontera et al. (2020) found that COVID-19 mortality was twice as high in regions with the highest PM_{2.5} concentrations compared to the areas with low PM_{2.5} concentrations. The explanation for using non-linear cointegration analysis is that the linear models cannot catch periodic variations, while non-linear models consider these variations (Kouton, 2019).

4.3. Results of the non-linear panel ARDL model

After confirming the asymmetric cointegration between PM_{2.5} and COVID-19 cases, we proceed with NPARDL. We follow Kouton (2019) and Akram et al. (2020b) for panel representation of NARDL. PMG estimation method has been employed to obtain the results of NPARDL (see Table 5). A significant negative error correction term indicates that it will convert to a long-run symmetry state following a shock. This process demonstrates non-linear cointegration as estimated above and implies that the long-run equilibrium between PM_{2.5} pollution and COVID-19 cases is asymmetric.

Research results expose the asymmetric association between PM_{2.5} and COVID-19 in the panel of ten Indian states. Positive shocks of PM_{2.5}

Table 3 Pesaran's (2007) unit root test.

Variables	Level		1st difference		Integration order
	Intercept	Intercept & trend	Intercept	Intercept & trend	
Pesaran CIPS					
PM _{2.5}	-1.89	-2.36	-5.622***	-5.947***	1(1)
COVID-19	-1.98	-2.06	-3.582***	-4.134***	1(1)
Pesaran CADF					
PM _{2.5}	-2.001	-1.476	-5.020***	-5.458***	1(1)
COVID-19	-1.765	-1.486	-2.113***	-2.323***	1(1)

Table 4 Hatemi-J's (2020) asymmetric cointegration.

Variables	Residuals CD test	Residuals Unit root test	Decision regarding the residuals
Y ⁺ , X ⁺	93.71 (0.000)	-7.0987 (0.000)	Stationary
Y ⁺ , X ⁻	92.65 (0.000)	-5.022 (0.000)	Stationary
Y ⁻ , X ⁺	90.96 (0.000)	-4.829 (0.000)	Stationary
Y ⁻ , X ⁻	92.92 (0.000)	-5.378 (0.000)	Stationary

Notes: Y = PM_{2.5} pollution, X = COVID-19 cases. p-values are provided in ().

Table 5 Non-linear panel ARDL analysis.

Variables	Dependent variable: COVID-19 cases
ECT	-0.123*** (0.0274)
ΔPM _{2.5} pollution _t ⁺	0.112** (0.0554)
ΔPM _{2.5} pollution _t ⁻	-0.0348 (0.0369)
PM _{2.5} pollution _t ⁺	0.439*** (0.144)
PM _{2.5} pollution _t ⁻	-0.694*** (0.144)
Constant	-3.807*** (1.201)
log likelihood	-1192.222
Cointegration F-test	209.50** [0.0507]
Long-run asymmetry Wald test	586.62***[0.0000]
Short-run asymmetry Wald test	5.26**[0.0218]

Note: Significance level (***p < 0.001, **p < 0.05, *p < 0.01). Standard error values are reported in brackets (), while p-values are reported in parentheses [] for long and short-run asymmetry. PMG method is employed for the estimation of the model.

emissions cause an increase, and negative shocks of PM_{2.5} emissions lead to a decrease in COVID-19 cases in long-run. In particular, a 1% change in the positive shocks of PM_{2.5} pollution increases the COVID-19 cases by 0.439%. Wu et al. (2020) obtained similar findings and showed a positive linkage between long-term PM_{2.5} and mortality from COVID-19 in the USA. (Cole et al., 2020) investigated the influence of PM_{2.5} on COVID-19 cases, hospitalizations, and fatalities throughout the Netherlands' 355 municipalities. The authors noted that a 1 μg m⁻³ rise in long-run PM_{2.5} levels is related to an extra nine cases, three hospitalizations, and two fatalities. Notably, this research showed a significant association between air pollution and COVID-19 in rural locations as well, suggesting direct air pollution–COVID-19 linkage irrespective of the density or crowding of the urban context. On the contrary, the negative shock of PM_{2.5} pollution cause to decline in COVID-19 cases because a 1% fluctuation in the negative shocks of PM_{2.5} pollution reduces the COVID-19 cases by 0.694% in the long-run. These outcomes verify an asymmetric relationship between PM_{2.5} pollution and COVID-19, given that the positive and negative PM_{2.5} shocks exhibit dissimilar effects on COVID-19 cases. The Wald test statistics for short and long-run asymmetries are also significant and verify the non-linear association between PM_{2.5} pollution and COVID-19.

Moreover, the short-run effect of PM_{2.5} on coronavirus dispersion is also asymmetric. More specifically, a 1% variation in the positive shock on PM_{2.5} pollution increases COVID-19 cases by 0.112%, while a 1% variation in the negative shock on PM_{2.5} pollution decreases COVID-19 cases by 0.0348%. Among the research examining the short-term impacts of air pollution, Frontera et al. (2020) found a significant relationship between PM_{2.5} and pandemic spread in Italy. The effects of PM_{2.5} and PM₁₀ on daily verified COVID-19 patients were evaluated in China. The COVID-19 patients were related to short-term lagged growths in PM_{2.5}, with the magnitude of the impact being larger for

PM_{2.5} than for PM₁₀ (Wang et al., 2020). Another research examined the short-term impact of six distinct pollutants in 120 Chinese cities to establish its connection with the COVID-19 cases. Daily COVID-19 instances increased by approximately 2% for every 10 μg m⁻³ rise in PM_{2.5} and PM₁₀ during two weeks (Zhu et al., 2020). Though the positive shocks of PM_{2.5} pollution in the short and long-run positively affect COVID-19 cases; however, the positive impact is stronger in the long-run. It implies an improvement in air quality during the lockdown period (in the short-run) due to less PM_{2.5} emissions. However, as the government lifted the lockdown restrictions, the air quality deteriorated due to an escalated amount of PM_{2.5} concentrations.

Furthermore, previous literature verified that the high concentrations of PM_{2.5}, when inhaled, cause severe health problems, including shortness of breath, chest pain, throat irritation, coughing, and lung infection (Rovira et al., 2020). It can also exacerbate chronic respiratory conditions such as asthma and impair the body's capacity to combat respiratory diseases (Copat et al., 2020). COVID-19 also has similar symptoms (Manisalidis et al., 2020), suggesting that an upsurge in air pollution (PM_{2.5} concentration) escalates the tendencies and vulnerabilities of COVID-19 cases (Cole et al., 2020; Wu et al., 2020).

Experiments have shown that air pollution lowers immune response, allowing viruses to spread and reproduce more easily. Air pollution induces lung infection, which can have short-term and long-term consequences, including asthma and fibrosis (Guan et al., 2016). An increase in PM_{2.5} has been attributed to an 11% increase in cardiovascular mortality each year. A spike in PM_{2.5} over a short period has also been accompanied by an upsurge in severe cardiac incidents (Nawrot et al., 2011). Another research explains that overcrowding of medical facilities and high fatality due to coronavirus experienced in several European countries could be connected to peaks in PM_{2.5} and specific weather conditions that promoted the virus's spread (Annesi-Maesano et al., 2021).

Poor air quality mainly, PM_{2.5} is one of the key reasons for a substantial number of excess mortality (Ali and Islam, 2020). Long-term contact with air pollution significantly affects life expectancy more than any contagious disease. COVID-19 mortality is impacted by comorbidities such as arterial hypertension, diabetes mellitus, obesity, pre-existing coronary artery disease, and respiratory illnesses such as asthma, influenced by air pollution. Apart from their direct contact with the human body, respiratory infections have complex interfaces in the air, which might affect the virus's persistence (Pozzer et al., 2020).

As a step further, we run the NPARDL model using the MG technique to perform a robustness check to verify the validity of the proposed model. The findings presented in Table 5 are supported by the results of Table A1 (see Appendix A). Sensitivity analysis further validates that the research results are robust, and the effect of PM_{2.5} on COVID-19 is asymmetric in the selected states. Meo et al. (2021) explored the effect of PM_{2.5} on daily COVID-19 cases and deaths in London. The authors opined that PM_{2.5} has a positive association with COVID-19, as a 1 μm upsurge in PM_{2.5} concentration leads to an increase of 1.1% COVID-19 cases and 2.3% COVID-19 deaths, respectively. In a study conducted in the United States to understand the relationship between air pollution and COVID-19 mortality, Wu et al. (2021) found that a 1 μg/m³ increase in PM_{2.5} is related to an 8% increase in COVID-19 mortality. COVID-19 mortality counts for over 3000 counties across the United States were obtained for this study (representing 98% of the population).

Next, we concentrate on state-wise characteristics and evaluate each state's estimates (see Table A2 in Appendix A). The results highlight that every state responds differently to positive and negative shocks. The asymmetric short-run impact has been found in Madhya Pradesh, Gujrat, Tamil Nadu, Uttar Pradesh, Telangana, and Maharashtra states, specifying a significant influence of PM_{2.5} pollution on the transmissibility of coronavirus. This finding indicates that these states are more vulnerable to short-run shocks on PM_{2.5} pollution. Similarly, Delhi, Karnataka, Andhra Pradesh, and West Bengal states also exhibit asymmetric short-run effects and the negative shock on PM_{2.5} emissions. Each state

responds differently to short-run positive and negative shocks because of the different air pollution levels in each state. The short-run analysis also confirms the heterogeneity in the selected states and validates the asymmetric relationship between PM_{2.5} pollution and COVID-19 cases.

4.4. Results of asymmetric panel causality

Examining asymmetric causality will likely lead to accurate results if the variables respond differently to positive and negative shocks. Therefore, we performed Hatemi-J's (2011) test to examine asymmetric causality. Findings are shown in Table A3 (see Appendix A), specifying that the positive shocks on PM_{2.5} pollution Granger-cause positive shocks on COVID-19 cases. An asymmetric causality is also running from the negative shocks of PM_{2.5} to the negative shock of COVID-19 cases. It implies that positive shocks of PM_{2.5} emissions escalate the intensity of the COVID-19 case, while the negative shocks of PM_{2.5} emissions decrease the COVID-19 cases. Pata (2020) used an asymmetric Fourier causality test to investigate the effect of the COVID-19 epidemic on PM_{2.5} emissions in USA states. According to study findings, positive shocks in COVID-19 fatalities negatively affect PM_{2.5} levels in San Diego, New York, and San Jose states. While positive shocks in COVID-19 result in negative changes in PM_{2.5} levels in Chicago, Los Angeles, Phoenix, San Antonio, San Jose, and Philadelphia states, respectively.

5. Conclusions and policy implications

This paper systematically explores the nexus between air pollution (PM_{2.5}) and COVID-19 in the affected Indian states. We performed the asymmetric relationship between variables using the newly introduced "Hidden Panel Cointegration test of Hatemi-J (2020)" and the NPARDL model. The subsequent analyses of individual states endorse the heterogeneous effect of PM_{2.5} on coronavirus among the selected Indian states. The empirical findings from the NPARDL model verify the asymmetric relationship between PM_{2.5} and COVID-19 cases. Research results expose that positive shocks of PM_{2.5} concentrations escalate COVID-19 spread. In particular, a 1% change in the positive shocks of PM_{2.5} pollution increases the COVID-19 cases by 0.439%. The Hatemi-J (2011) asymmetric causality analysis also suggests positive shocks on PM_{2.5} pollution Granger-cause positive shocks on COVID-19 cases. An asymmetric causality is also running from the negative shocks of PM_{2.5} pollution to the negative shock of COVID-19 cases.

Research findings verify that a higher level of environmental contamination in heavily polluted regions cause respiratory syndromes, weakens the residents' immunity, and influence the susceptibility of COVID-19. The magnitude of these negative consequences on humans and the environment varies across states, primarily due to the diverse demographic features, social distancing, and lockdown steps implemented by the Indian states. Other probable explanations for the spread of COVID-19 in these states include the lack of adequate healthcare facilities and a failure to follow anticipated human actions during the pandemic, such as adherence to face mask usage, sanitizing, social stratification, and separation from affected people.

Environmental pollution is a result of human actions, leading to environmental degradation. It is expected that public awareness of environmental problems will increase due to the COVID-19 pandemic. However, an abrupt growth in global unemployment is deforming the socio-economic harmony and is very harmful to our lives, communities, and economies due to coronavirus. It is crucial to create employment opportunities and sustainably develop the healthcare infrastructure, which might help provide the groundwork for a sustainable recovery, particularly if additional government promises to environmental sustainability are made. Numerous initiatives have been created in developing economies like Nepal and Pakistan to assist the government's "Green Wagers Scheme" for monetary support and green employment creation through tree plantation and ecosystem restoration. Additionally, the forest society may contribute by collecting timber and other

resources responsibly, focusing on forestry initiatives.

The findings of this study have several practical policy recommendations. Air pollution indicators are critical and vital when it comes to avoiding and forecasting the development of the coronavirus. Air pollution has a substantial impact on coronavirus propagation and is critical for developing mitigation plans that will help forecast and control the emergence of future outbreaks. Energy generation from fossil fuels is the primary cause of air pollution. Other causes include gasoline-fuelled vehicles, residential and industrial heating. Therefore, India should accelerate its transition from fossil fuels to renewable energy by reinforcing public health policy. Likewise, if this epidemic persists in humans for an extended period of time, the governments should implement anti-epidemic strategies. Globally, quick action is required to halt climate degradation, alter ecosystems, and reorganize international collaboration. This is also a fact that individuals spend most of their time indoors, where pollutants' concentrations are sometimes higher than outdoors. Consequently, it is critical to maintain a healthy home environment. Using an air purifier can be beneficial in this endeavour, as indoor air quality has been shown to significantly influence the transmission of viral infections such as COVID-19 (Fermo et al., 2021). Given the crucial nature of better indoor air quality to contain the spread of the COVID-19 pandemic, air purifier devices could be successfully applied in particularly crowded areas and critical environments. Hospitals are obliged to develop a self-protocol to improve patient management during the COVID-19 pandemic by considering existing logistics and resources (Rakhsha et al., 2020). However, it is also true that the current and future epidemics cannot be treated alone by medical research and practice; multidisciplinary scientific research based on environmental and sustainable science must be done in this regard.

The study also has some limitations. *Firstly*, we only focused on India's top ten infected states and did not consider other regions. *Secondly*, we only found the effect of PM_{2.5} on COVID-19 cases and neglected other air pollutants. *Thirdly*, we did not examine the influence of lockdown on atmospheric pollution and its linkage with sustainable development. *Finally*, there are also significant confounding factors associated with air pollution and COVID-19. The transmissibility of virus varies significantly among states, depending on (i) population density, (ii) socio-economic composition, (iii) access to healthcare, (iv) virus introduction time, and (v) the implementation of epidemic prevention policies (i. e., social distancing, mask-wearing obligations, testing policies, or lockdown restrictions. All of these above-mentioned factors have an effect on the disease's dynamics, which can be assessed by daily new cases. Therefore, subsequent researchers should include these potential confounders to strengthen their analyses.

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 paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envres.2022.112848>.

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