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Analysis of spatiotemporal distribution of air quality index (AQI) in the state of West Bengal, India from 2016 to 2021

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Abstract

The ambient air quality is progressively declining, especially in emerging countries, due to increased urbanization, high demands of energy, and industrialization. High risks to human health and environmental degradation are associated with air pollution. The analysis of the Air Quality Index (AQI) serves as a valuable tool for simplifying the communication of air quality in a specific region, making it easily comprehensible to the general public. The United States Environmental Protection Agency (USEPA) and Indian air quality regulations recommend mathematical functions to compute sub-indices for calculating the AQI. The main objectives of this study were to evaluate the AQI status from a different point of view (monthly, seasonal, and annual variations and association of AQI with meteorological factors) and estimate the future AQI. The monthly AQI values in West Bengal vary from "Satisfactory to Moderate" level from 2016 to 2021. In district-wise, the highest AQI was observed in Kolkata (189), Bardhaman (178), and Murshidabad (167) in the year 2016; Kolkata (180), Bardhaman (155), and Howrah (155) in 2017; Howrah (180), Kolkata (179) and Hoogly (166) in 2018; Howrah (170), Kolkata (156) and Bardhaman (156) in 2019; Howrah (150), South 24 Parganas (137), and Kolkata (136) in 2020 and Howrah (161), Kolkata (139), and South 24 Parganas (139) in 2021 respectively in Winter season. The association between meteorological parameters, such as temperature ($r = -0.605$, $p < 0.001$), relative humidity ($r = -0.647$, $p < 0.001$), and precipitation ($r = -0.821$, $p < 0.001$) and AQI shows a significant strong negative correlation ($p < 0.05$). In addition, the relative influence of temperature, precipitation, and relative humidity was 53.13%, 36.69%, and 10.18%, respectively, on AQI variation. Temperature plays a significant role in association with AQI distribution in the atmosphere than RH and precipitation. The distribution of AQI in the whole state of West Bengal showed a higher AQI observed in the Southern part compared to the northern part of the state. The study's conclusions and recommendations can help stakeholders and policymakers' to control and improve the deterioration of air quality caused by concerns about AQI and human health.

Keywords Air pollution · Air quality index (AQI) · Meteorology · Spatiotemporal distribution

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1 Introduction

In the modern era, air pollution has become a significant environmental problem worldwide due to the increasing industrialization, urbanization, and developmental projects [1]. The number of deaths driven by modern forms of air and toxic chemical pollution has increased by 66% over the previous 20 years. More than 6.5 million deaths are brought on by air pollution each year, which is rising [2]. The unplanned and uncontrolled growth activity, excess fossil fuel combustion, and lack of adequate national or international policy led to a decline in the air quality of the atmosphere; about 90% of air pollution-related mortality occurs in low- and middle-income nations [2, 3]. Poor air quality greatly threatens human health [4, 5]. According to WHO [6], 99% of the world's population resided in areas where the WHO air quality guidelines levels were violated, and the combined effects of ambient air pollution and household air pollution are linked to 6.7 million premature deaths annually, while only outdoor air pollution is estimated to have caused 4.2 million premature deaths globally in 2019. The majority of premature fatalities, about 89% (among 90%), occur in low- and middle-income nations, particularly in South-East Asia and the Western Pacific. The global air quality was worsening daily due to rapid industrialization, urbanization, higher energy consumption, and overcrowding [7–9]. To comprehend the current situation of air quality, air pollution must be continuously monitored in the atmosphere. The study of multiple pollutants is quite tricky, so here developed a multi-pollutant single index, i.e., Air Quality Index (AQI). AQI is a tool created to reflect the public point of view of AQI and its associated health risk. Understanding the "good" and "bad" air quality is straightforward. The AQI levels depend on various pollutant concentrations. The Central Pollution Control Board (CPCB), India uses eight pollutants to calculate AQI, i.e., particulate matter [PM_{10} (μg/m^3)], particulate matter [$PM_{2.5}$ (μg/m^3)], nitrogen dioxide [NO_2 (μg/m^3)], sulphur dioxide [SO_2 (μg/m^3)], carbon monoxide [CO (mg/m^3)], ground-level ozone [O_3 (μg/m^3)], ammonia [NH_3 (μg/m^3)] and lead [Pb (μg/m^3)]. Most of the research on air quality forecasting currently available in the literature has been done for specific air contaminants. The AQI is influenced by a multitude factors, such as the concentration of pollutants, meteorological conditions, seasonal variations, emissions from both anthropogenic and natural sources, regulatory measures, urbanization, geographical locations, and long-range transport [10–13]. The concentration of air pollutants, including particulate matter (PM_{10} and $PM_{2.5}$), ground-level ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and carbon monoxide (CO), is the significant air pollutants for AQI calculations [14]. The meteorological factors, such as temperature, wind speed and direction, relative humidity, and atmospheric stability, significantly influence the dispersion and accumulation of pollutants in an area [13]. Temperature inversions have the ability to trap pollutants near to the ground surface as a result of raising AQI levels [15]. The numerous studies have consistently noted that the cold seasons exhibit higher AQI levels when compared to the summer and rainy seasons [10, 13, 15, 16]. Long-distance pollutant transfer by wind patterns can have an impact on the AQI in nearby areas. Comprehending the correlations between meteorological parameters and air quality index (AQI) is crucial for precise air quality monitoring and forecast. Furthermore, AQI levels vary from one country to another due to the presence of individual national ambient air quality standards (NAAQS). The AQI is an essential tool with widespread importance. In AQI analysis, converting complex air pollution data into straightforward and understandable information helps to be the cornerstone for protecting public health. This information allows people and communities, especially vulnerable groups, to adopt preventive actions.

The main objective of the current study was to investigate the distribution of AQI on an annual, monthly, and seasonal basis in different districts of West Bengal. Additionally, from 2016 to 2021, the distribution of the AQI across the entire state of West Bengal was studied for the first time, and all districts were ranked based on average AQI. Then, we studied the meteorological effects on AQI distribution and focused on the marginal impact on the AQI variations. Furthermore, predicting the future status of AQI from the observed value (using the Expert Modeler, ARIMA and linear trend model).

2 Materials and methods

2.1 Study area

The state of West Bengal is nationally important due to its cultural and natural diversity. The state of West Bengal offers a distinctive flavour to the richness of India's diversity with its synthesis of various languages, religions, customs, traditions, cuisines, and lifestyles. West Bengal is the economic hub of Eastern India [17, 18]. The state primarily depends on agriculture, tourism, and high, medium, and small-sized industries across the state [18]. West Bengal has various industries, such as iron and steel, thermal power plants, coal mining, leather, jute, tea, IT, car manufacturing, and gems and jewellery. The districts such as Alipurduar, Bankura, Birbhum, Bardhaman (both Purba and Paschim Bardhaman), Cooch Behar, Dakshin Dinajpur, Darjeeling, Hooghly, Howrah, Jalpaiguri, Jhargram, Kalimpong, Kolkata, Malda, Murshidabad, Nadia, North 24 Parganas, Paschim Medinipur, Purba Medinipur, Purulia, South 24 Parganas, and Uttar Dinajpur were considered in this study. The general description of the study area is shown on a map (Fig. 1). If we divide the districts in West Bengal with respect to environmental concerns southern part has the high population density, and are the place of large and medium-scale industries. Such districts are Bankura, Paschim Bardhaman, Purba Bardhaman, Purulia, Nadia, West Midnapore, Jhargram, East Midnapore, Hooghly, Howrah, Kolkata, North 24 Parganas and South 24 Parganas. The central part of West Bengal districts, such as Murshidabad, Maldah, Birbhum, Dakshin Dinajpur, and Uttar Dinajpur, mainly depend on agricultural activitities and small-scale industry, and northern part districts, such as Darjeeling, Jalpaiguri, Cooch Behar Alipurduar and Kalimpong primarily relies on tourism and agricultural activities. Among all the districts, Kolkata, Howrah, South 24 Parganas, and Hooghly were considered urban agglomeration cities, and Bankura and Bardhaman were considered large-scale industrial complexes. This study is designed to comprehensively evaluate the air quality in the diverse districts of West Bengal during 2016 to 2021. The study area includes 22 districts (81 monitoring stations) characterized by distinct environmental concerns and economic activities. This comprehensive study protocol is designed to provide valuable insights into air quality and its correlations with environmental factors and health issues in West Bengal to contribute to evidence-based decision-making and air quality improvement efforts in the region.

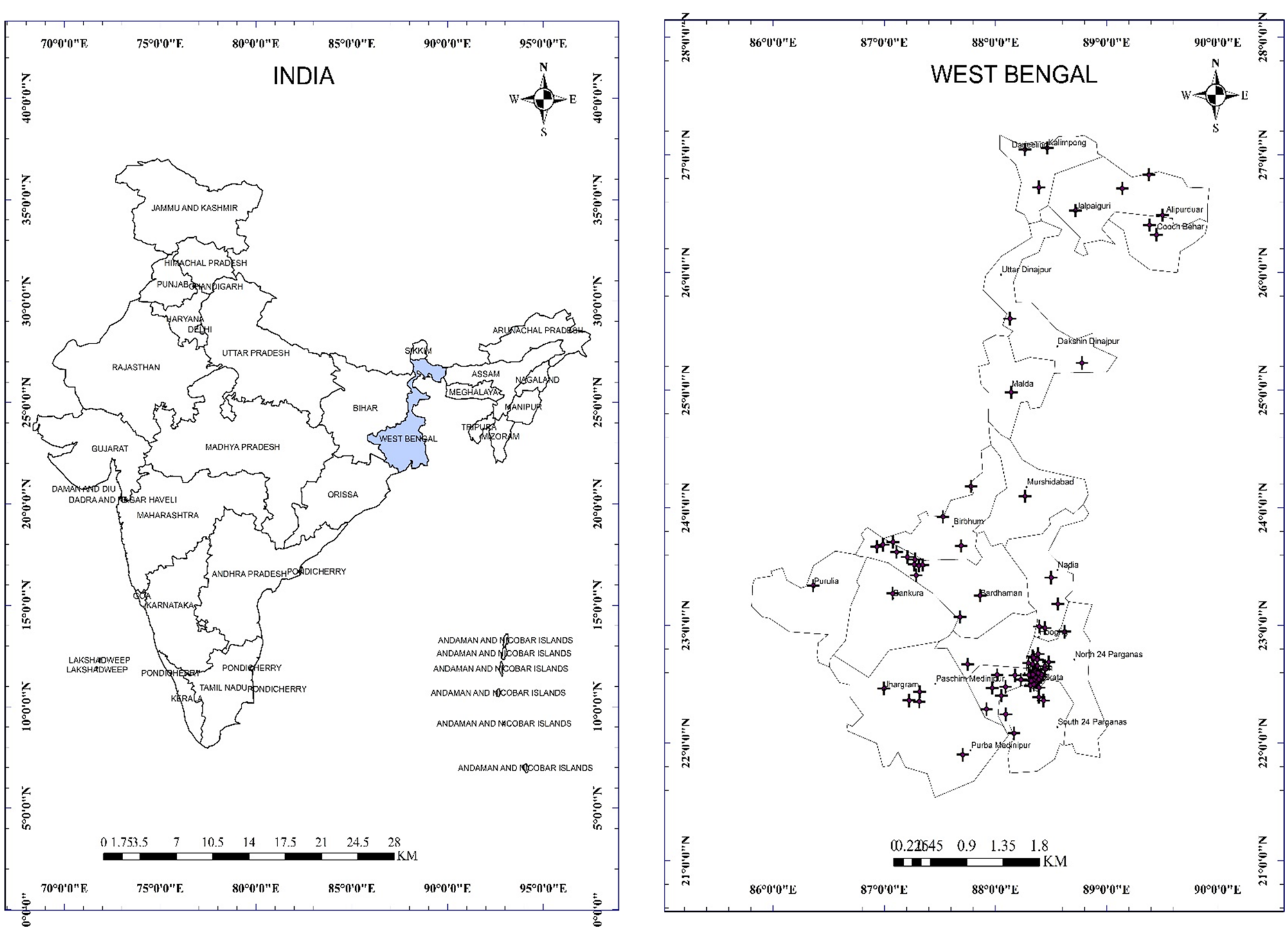


Fig. 1 Study area map of West Bengal and monitoring stations

2.2 Data collection

Three criteria pollutants, particulate matter (PM_{10}), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2), were used to calculate the air quality index (AQI) as per Central Pollution Control Board (CPCB) guideline. The data on air pollutants were obtained from the West Bengal Pollution Control Board (WBPCB), which is under the regulation of CPCB, India, and the meteorological data such as temperature (°C), relative humidity (%), and precipitation (mm/day) was collected from READY NOAA (national oceanic and atmospheric administration). Over the course of study period from 2016 to 2021, the data on the selected pollutants and meteorological parameters were collected from 81 monitoring stations situated across the 22 districts of West Bengal, India, through 24 h monitoring.

2.3 Air quality index (AQI) analysis

The Air Quality Index (AQI) is a mechanism for clearly explaining the air quality status to the general public. It simplifies the complicated information about the air quality caused by different contaminants into a single number (index value), nomenclature, and colour. The CPCB guidelines for computing AQI state that the sub-indices for particular pollutants at a monitoring station are calculated using the pollutants health breakpoint concentration range and 24-hourly average concentration value (except for CO and O_3). At least three pollutants were required to calculate the AQI, where one PM must be used, either $PM_{2.5}$ or PM_{10}. The CPCB provided a total of eight pollutant break points such as particulate matter PM_{10} and $PM_{2.5}$, nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), ammonia (NH_3) and lead (Pb). The breaking point of particular pollutants and its AQI categories are tabulated in Table S1. The sub-index for each pollutant has been assessed using the following Eq. (1):

$$I_i = \frac{(I_{Hi} - I_{LO})}{(BP_{Hi} - BP_{LO})} \times (C_P - BP_{LO}) + I_{LO} \tag{1}$$

where, I_i = AQI for the ith pollutant. BP_{Hi} = Breakpoint concentration greater or equal to the given concentration. BP_{Lo} = Breakpoint concentration smaller or equal to given concentration. I_{Hi} = AQI value corresponding to BP_{Hi}. I_{Lo} = AQI value corresponding to BP_{Lo}. Cp = Pollutant concentration.

An AQI system based on the AQS (Air Quality Standard) and pollutant dose–response relationships in order to effectively represent air quality in terms that are related to health effects. Equation 2 illustrates the aggregate AQI in terms of the highest sub-AQI index value for all contaminants considered for the study.

$$AQI = \max\{I_1, I_2, I_3 \dots In\} \dots\dots\dots\dots\dots\dots\dots\dots n;\ denotes\ n\ pollutants \tag{2}$$

The Indian AQI (IND-AQI) index values represent six divisions, viz., Good (0–50), satisfactory (51–100), Moderate (101–200), Poor (201–300), Very Poor (301 400), and Severe (401–500) to represent the state of air quality as well as its effects on human health in the Indian perspective.

2.4 Statistical analysis

MS-Excel, SPSS v26, Minitab v20 and JASP v0.16.4.0 were used to conduct the statistical analysis. Data screening and AQI table with colour coding (yearly, seasonal, and monthly variations) was done using MS Excel. At the same time, JASP was employed for correlation and regression analysis between AQI and meteorological parameters. The Expert Modeler (exponential smoothing and autoregressive integrated moving average (ARIMA) models) were performed through SPSS v26 to forecast future variations of AQI of the study area and Minitab v20 utilised for the analysis of time series linear trend model. On the other hand, Arc-GIS v10.3 was applied to prepare a clear observable yearly AQI map for better understanding the changes of AQI over the year of the study area.

3 Results and discussion

3.1 Spatiotemporal distribution of AQI

The current study examines the air quality index at 81 monitoring sites in 22 districts of West Bengal, India from 2019 to 2021. Table 1 demonstrate the annual variations of AQI in the state of West Bengal on a monthly basis. The year-wise monthly and annual distribution of AQI exhibits statistically significant variations ($p < 0.05$, 95% confidence interval) in the state of West Bengal. The months of January, February, November, and December have "moderate" AQI distributions, whereas the remaining months observed "satisfactory" distributions. The highest AQI value of 142 and the lowest AQI value of 56 were recorded during the months of January 2016 and July 2017, respectively. The highest observed seasonal fluctuations of the AQI were found during the winter months (January, February, and December). Conversely, the lowest variations were detected during the monsoon season (July, August, and September) and the summer season (April, May, and June), respectively. The AQI distribution across the seasons in West Bengal indicates that the highest AQI values were observed during the winter season, accounting for approximately 43.59% of the total AQI observations. In contrast, the summer and monsoon season contributes to around 30.51% and 25.90% of the overall AQI measurements. In district-wise study, the maximum AQI was observed in Kolkata (189), followed by Bardhaman (178), and Murshidabad (167) in 2016; Kolkata (180), Bardhaman (155), and Howrah (155) in 2017; Howrah (180), Kolkata (179) and Hoogly (166) in 2018; Howrah (170), Kolkata (156) and Bardhaman (156) in 2019; Howrah (150), South 24 Parganas (137), and Kolkata (136) in 2020 and Howrah (161), Kolkata (139), and South 24 Parganas (139) in 2021 respectively in Winter season. The details about AQI's seasonal variations were illustrated in Tables 2, 3, and 4 for winter, summer, and monsoon, respectively. A combination of human and meteorological factors can be responsible for the higher and lower AQI observations in the study area. During the winter (January, February, and December), temperature inversions (stable condition) are more prevalent, trapping pollutants near the ground

Table 1 Year wise monthly variations of AQI in West Bengal from 2016 to 2021

	2016	2017	2018	2019	2020	2021	ANOVA
January	142	114	112	106	116	115	$p < 0.05$
February	132	115	104	102	113	115	$p < 0.05$
March	120	95	93	107	99	114	$p < 0.05$
April	97	78	81	88	95	103	$p < 0.05$
May	79	67	74	82	88	83	$p < 0.05$
June	66	62	78	78	63	73	$p < 0.05$
July	62	56	71	73	63	74	$p < 0.05$
August	58	60	72	78	67	74	$p < 0.05$
September	60	62	76	74	65	73	$p < 0.05$
October	85	68	88	97	71	81	$p < 0.05$
November	102	86	114	113	100	103	$p < 0.05$
December	114	97	113	116	107	117	$p < 0.05$
Annual	95	85	92	95	85	95	$p < 0.05$
AQI colour code	Good (0–50)	Satisfactory (51–100)	Moderate (101–200)	Poor (201–300)	Very poor (301–400)	Severe (401 – 500)	95% CI

Table 2 AQI variations in winter season of all studied districts of West Bengal from 2016 to 2021

District	Winter					
	2016	2017	2018	2019	2020	2021
Alipurduar	NA	NA	NA	96	109	119
Bankura	163	134	114	133	118	109
Birbhum	NA	109	106	104	86	88
Bardhaman	178	155	131	156	131	119
Cooch Behar	NA	66	49	96	112	120
Dakshin Dinajpur	91	49	51	107	131	130
Darjeeling	73	50	54	90	104	109
Hooghly	153	141	166	110	93	93
Howrah	162	155	180	170	150	161
Jalpaiguri	100	56	49	95	112	108
Jhargram	NA	NA	NA	81	111	118
Kalimpong	NA	NA	NA	67	76	90
Kolkata	189	180	179	157	136	139
Malda	110	75	63	107	131	136
Murshidabad	167	139	134	100	90	87
Nadia	149	133	160	111	94	90
North 24 Parganas	145	136	131	125	110	108
Paschim Medinipur	114	108	104	107	117	123
Purba Medinipur	113	118	114	113	118	124
Purulia	126	103	78	96	84	87
South 24 Parganas	166	153	148	136	137	139
Uttar Dinajpur	90	42	51	90	119	125
AQI colour code	Good (0–50)	Satisfactory (51–100)	Moderate (101–200)	Poor (201–300)	Very poor (301–400)	Severe (401 – 500)

due to a layer of warmer air above cooler surface air. As a result, there is less vertical air mixing and more accumulation of contaminants, which raises the AQI levels. Additionally, high energy consumption for industrial processing and residential activities releases pollutants into the atmosphere. On the other hand, agricultural practices such as crop residue burning during the post-harvest season also contribute to higher pollutant concentrations. In winter, weaker wind velocity and less atmospheric turbulence limit the pollutant dispersion. In contrast, the summer (April, May and June) and monsoon (July, August, and September) seasons have lower AQI levels because of their higher

Table 3 AQI variations in summer season of all studied districts of West Bengal from 2016 to 2021

District	Summer					
	2016	2017	2018	2019	2020	2021
Alipurduar	NA	NA	NA	60	55	71
Bankura	134	119	103	141	78	102
Birbhum	NA	94	76	109	76	74
Bardhaman	170	134	120	163	82	112
Cooch Behar	NA	58	69	59	61	98
Dakshin Dinajpur	75	45	74	65	66	108
Darjeeling	61	57	56	57	51	84
Hooghly	61	52	51	102	60	76
Howrah	62	56	58	100	58	107
Jalpaiguri	63	49	71	62	58	94
Jhargram	NA	NA	NA	60	52	97
Kalimpong	NA	NA	NA	53	44	62
Kolkata	75	105	71	69	56	71
Malda	83	65	71	89	76	103
Murshidabad	89	92	143	99	54	67
Nadia	72	69	99	99	61	71
North 24 Parganas	72	73	70	99	69	73
Paschim Medinipur	81	91	79	58	56	97
Purba Medinipur	100	93	88	60	58	97
Purulia	108	93	70	108	61	71
South 24 Parganas	71	70	62	79	63	89
Uttar Dinajpur	77	46	74	71	56	98
AQI colour code	Good (0–50)	Satisfactory (51–100)	Moderate (101–200)	Poor (201–300)	Very poor (301–400)	Severe (401–500)

temperatures, more rainfall, and stronger winds, which promote pollution dispersion and improve the air quality [19, 20]. The air quality index (AQI) is an easy-to-understand approach to display information on air pollution levels and their potential health hazards [21]. The sub-index values play an important role in the AQI calculation of the multi-pollutant index. The Indian AQI range varies from 0 to 500, which are six divisions, i.e., "0 – 50", "51–100", "101–200", "201–300", "301–400" and "401 to 500" that represent "Good", "Satisfactory", "Moderate", "Poor", and "Severe" [22, 23]. The rank-wise investigation of average (from 2019 to 2021) AQI data in several West Bengal districts indicate a wide range in air quality variations (Fig. 2). While some areas have generally acceptable air quality, such as Kalimpong, which has an AQI of 58, others, like Bardhaman, which has an AQI of 129, have higher pollution levels due to industrial activity. This variation can be linked to several factors, such as weather patterns, emissions from transportation-related industrial operations, and topographical features. The information highlights the difference between urban

Table 4 AQI variations in monsoon season of all studied districts of West Bengal from 2016 to 2021

District			Monsoon			
	2016	2017	2018	2019	2020	2021
Alipurduar	NA	NA	NA	71	80	97
Bankura	68	100	101	108	81	95
Birbhum	NA	64	72	81	68	66
Bardhaman	137	114	119	119	81	108
Cooch Behar	NA	48	69	71	55	72
Dakshin Dinajpur	54	50	75	73	55	73
Darjeeling	48	NA	49	59	51	66
Hooghly	36	38	42	91	62	81
Howrah	44	47	45	97	59	81
Jalpaiguri	50	57	67	67	55	70
Jhargram	NA	NA	NA	60	53	74
Kalimpong	NA	NA	NA	55	49	50
Kolkata	50	71	55	55	70	60
Malda	53	56	71	98	60	76
Murshidabad	62	74	120	88	61	73
Nadia	66	56	84	86	62	83
North 24 Parganas	60	58	64	84	64	78
Paschim Medinipur	72	74	71	67	57	74
Purba Medinipur	96	83	82	65	58	77
Purulia	80	61	88	76	70	64
South 24 Parganas	48	63	45	55	74	75
Uttar Dinajpur	51	55	75	63	55	72
AQI colour code	Good (0 – 50)	Satisfactory (51 – 100)	Moderate (101 – 200)	Poor (201 – 300)	Very poor (301 – 400)	Severe (401 – 500)

and rural locations, with metropolitan places like Kolkata (AQI 101) experiencing greater pollution levels due to urban transportations [24]. The elevated AQI levels have adverse health effects and put vulnerable groups at more risk, emphasizing the urgency of solving air quality issues [25]. Across West Bengal districts, Bardhaman (AQI = 129), Bankura (AQI = 112), Paschim Medinipur (AQI = 105), Howrah (AQI = 104), South 24 Parganas (AQI = 101), and Kolkata (AQI = 101) consistently exhibited the elevated AQI levels throughout the study period, while Dakshin Dinajpur (AQI = 77), Cooch Behar (AQI = 75), Uttar Dinajpur (AQI = 75), Jalpaiguri (72), Darjeeling (AQI = 66), and Kalimpong (58) recorded lower AQI values. These areas tend to experience elevated AQI levels primarily because of industrial activity, the presence of thermal power plants, mining operations, substantial vehicle emissions, extensive urban development, and notably high population density. The cumulative impact of these factors results in increased pollutant concentrations and, consequently, elevated AQI values [26–28]. On the other hand, if we could distribute the

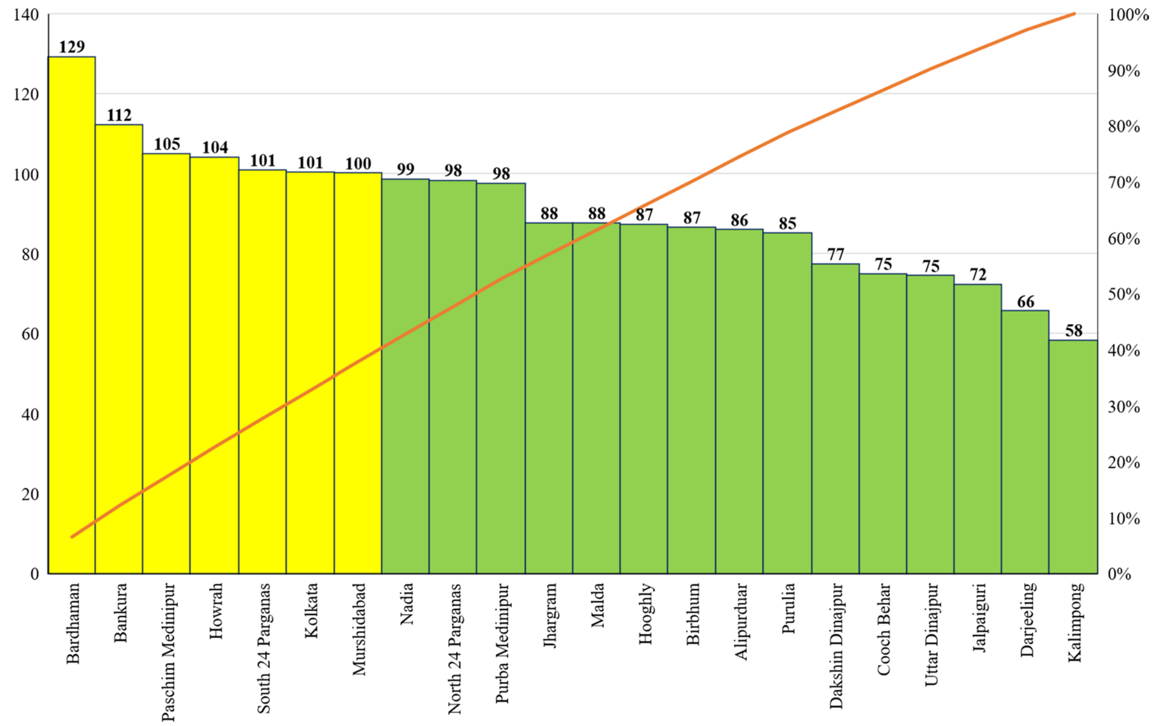


Fig. 2 Rank-wise districts AQI distribution of West Bengal state

districts of West Bengal into two parts, namely southern and northern, the AQI distribution was found to be higher in the southern half of West Bengal and somewhat lower in the northern part of West Bengal (Fig. 3). This is due to the presence of the majority of industrial activity, thermal power plants, important transportation, mining, administrative workflow, and high population density in the southern region of Bengal as compared to the northern part.

The diverse levels of AQI demonstrate the significant consequences for health, as indicated in Table S2, which provides information on AQI and its corresponding health effects. The AQI categories, namely "Good," "Satisfactory," "Moderate," "Poor," "Very Poor" and "Severe" correspond to varying levels of air quality and associated health impacts. The "Good" AQI signifies a minimal impact on individuals' health. The "Satisfactory" AQI suggests that sensitive people may experience minor breathing discomfort. The "Moderate" AQI indicates that individuals with lung diseases such as asthma, as well as children and older adults with heart disease, may experience breathing discomfort. Lastly, the "Poor" AQI signifies breathing discomfort for individuals exposed to poor air quality for an extended period and discomfort for those with heart disease. The "Very Poor" AQI represents respiratory illness in people on prolonged exposure. The effect may be more pronounced in people with lung and heart problems, and negative effects on health could be felt even when engaging in light exercise. The "Severe" AQI indicates the potential respiratory effects on individual healthy people and the significant adverse effects on those with pre-existing lung or heart diseases [23]. In this study, the state AQI vary from "Satisfactory to Moderate," meaning minor breathing discomfort for sensitive people to breathing discomfort of people for those who suffered from lung diseases like asthma, as well as discomfort for children and older adults with heart disease [22].

The Expert Modeller was used to analyse previous data and forecast future data in a time series using exponential smoothing and autoregressive integrated moving average (ARIMA) models. The AQI observed/predicted from 2016 to 2021 was 93/95, 80/82, 90/88, 93/93, 87/88, and 94/93; when the model was used to predict data from 2022 to 2024, it projected mean AQI 95 (min. 50–max. 139). The R^2 and root mean square error (RMSE) are 0.916 and 6.039 for the goodness-of-fit model. On the other hand, the time series linear trend model was also employed to analyse the future trend of AQI in the study area. The linear trend model shows a Mean Absolute Percentage Error (MAPE) of 21.456 and Mean Absolute Deviation (MAD) of 18.092, indicating its potential suitability for this analysis. The model performance measures demonstrate a satisfactory degree of precision and reliability in the model's forecasts. The anticipated values from both the model express that no significant trends were observed in West Bengal AQI (Fig. 4 for Expert Modeller and Fig. 5 for time series linear trend model). The AQI values predicted and observed are situated beyond satisfactory levels, which may cause breathing discomfort to people.

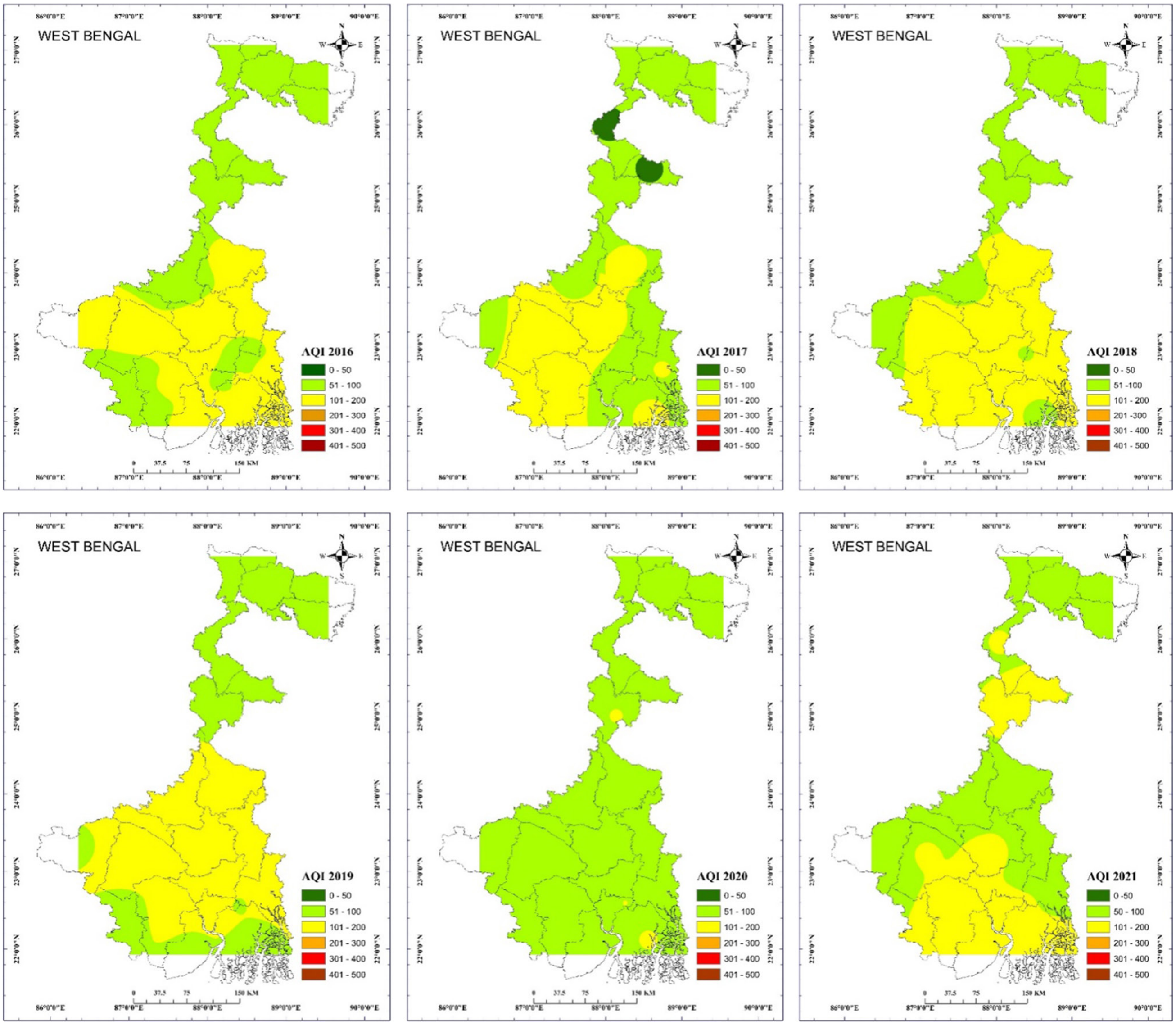


Fig. 3 AQI variations map of all over studied West Bengal districts from 2016 to 2021

3.2 AQI and meteorology

The meteorological parameters such as temperature, relative humidity, wind speed and direction, mixing height, and precipitation play an important role in variations of regional, local, and global scale AQI [29]. In this study, the statistical correlation was done between climatic factors such as temperature, relative humidity, precipitation, and AQI see in Fig. 6. The studied meteorological parameter demonstrates a significant negative correlation between temperature, relative humidity, and precipitation with AQI. In comparison to temperature, relative humidity, and precipitation, the precipitation has shown a significantly strong negative correlation (-0.821), where temperature (-0.605) and relative humidity (− 0.647) also shows a significant negative correlation [30, 31]. This observation indicates that precipitation significantly influences on the air quality improvement. However, temperature and relative humidity demonstrate milder associations with improving AQI, and the findings revealed a complex relationship between meteorological variables and air quality dynamics. The results emphasize the significance of considering these climatic factors for evaluating and controlling air quality in the study area. On the other hand, the multiple linear regression coefficients of temperature, relative humidity, and precipitation are tabulated in Table 5. The results of this investigation, highlight the importance of the influence of weather conditions on air quality as measured by the AQI. The negative coefficients for temperature, relative humidity,

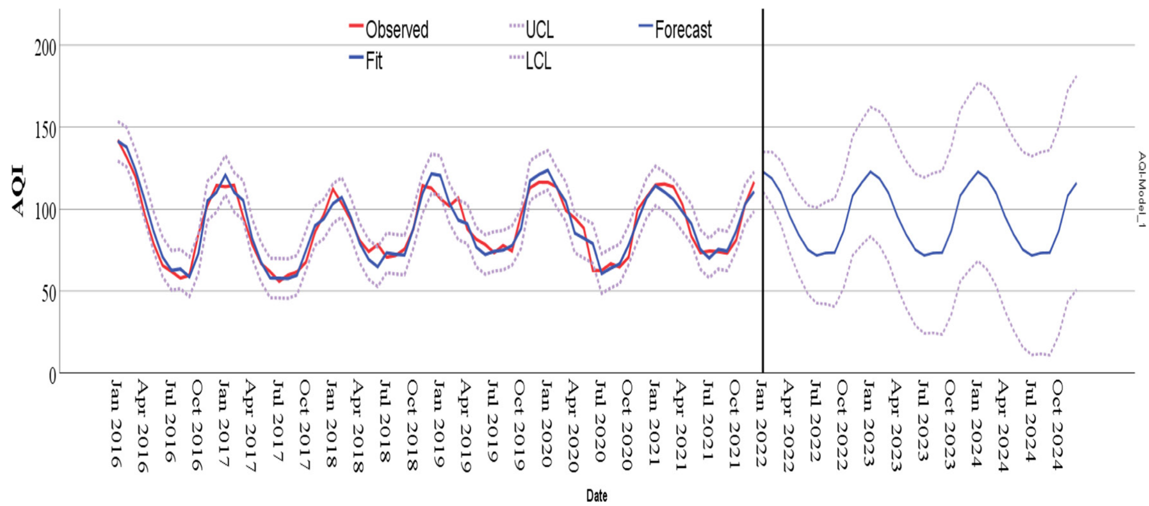
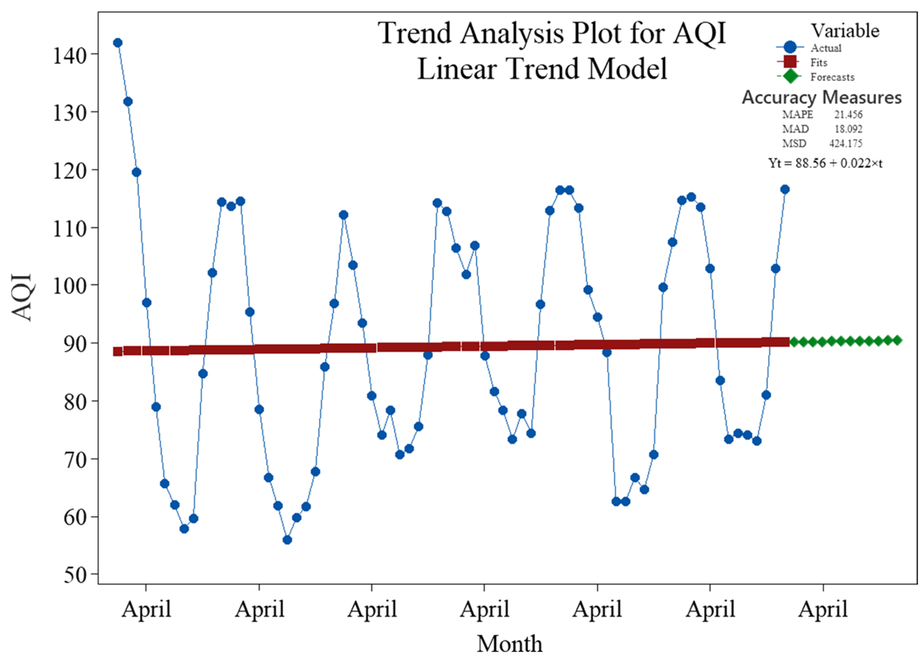


Fig. 4 Future prediction of AQI from past data using Expert Modeler (exponential smoothing and ARIMA models). *UCL* upper confidence level, *LCL* Lower confidence level

Fig. 5 Linear trend analysis of AQI from January 2016 to December 2021



and precipitation imply that favourable weather contributes to improved air quality. A significant factor affecting air quality is temperature, which is widely recognized. The strong negative coefficient (β = − 0.569, $p < 0.001$) implies that higher temperatures are linked to lower AQI values [19]. This may be explained by the improved dispersion and dilution of pollutants at higher temperatures, as well as the possibility of an increase in chemical processes that result in the breakdown of pollutants [32, 33]. Another important factor is precipitation, which has a negative value (β = − 0.457, $p < 0.05$). The higher precipitation levels are expected to encourage the removal of gaseous and particle pollutants from the atmosphere through washout [34]. This connection supports the widely held notion that with rainy day frequently result in better air quality [35]. Although relative humidity (RH) also shows negative impact (β = − 0.184, $p < 0.001$) on AQI, it continues to exert a considerable influence on the AQI distribution. The wet deposition is a process that can significantly lower the levels of contaminants present in the atmosphere, as a result improved the AQI. The marginal effects of temperature (TEMP), relative humidity (RH) and precipitation (PPT) on AQI shows negative trends, it signifies that the AQI improved with increasing the temperature, precipitation and relative humidity (Fig. 7). The relative influence of temperature, precipitation, and relative humidity was 53.13%, 36.69%, and 10.18%, respectively, on AQI distribution.

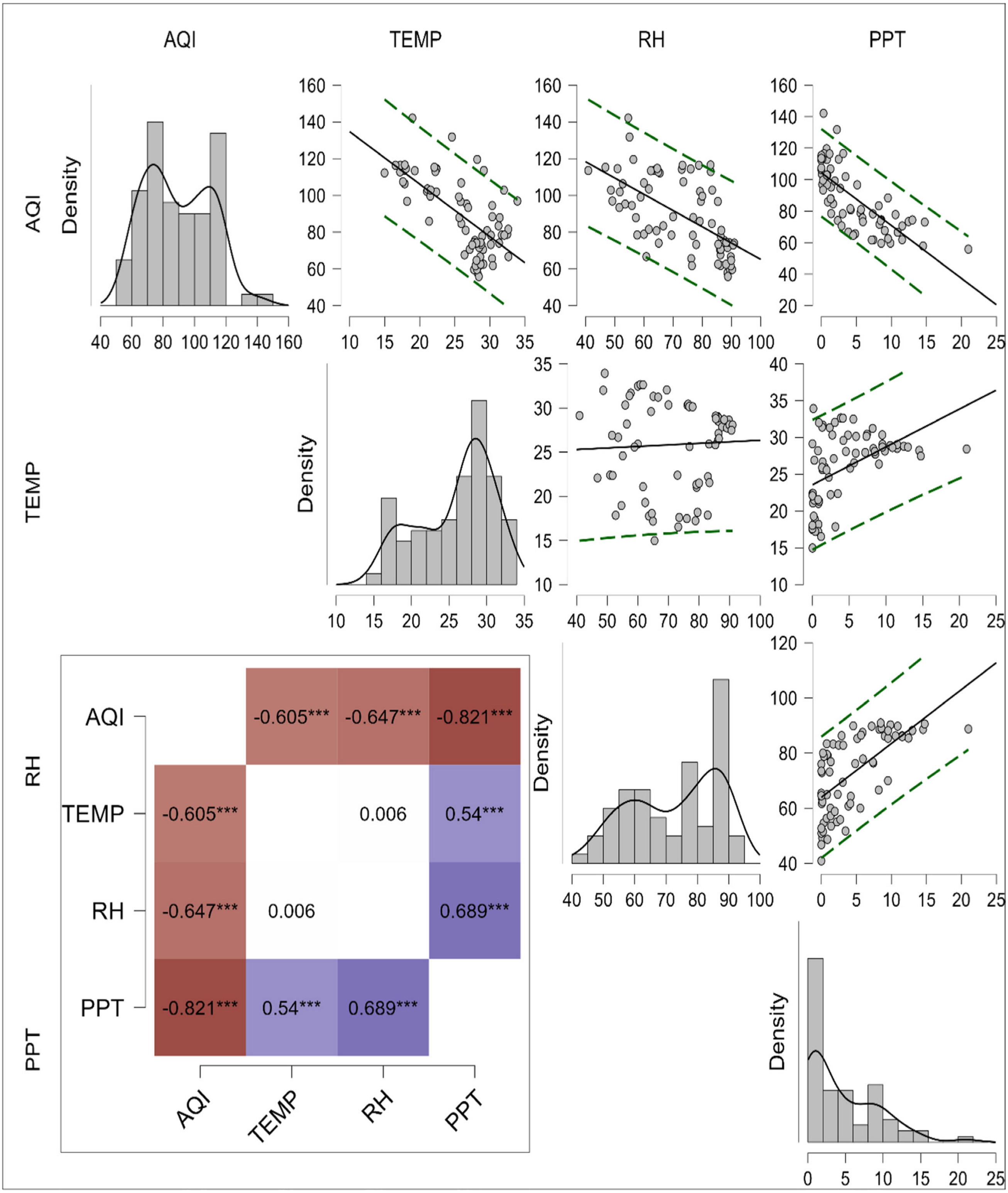


Fig. 6 Spearman's Rho correlation analysis between meteorological parameters (*TEMP* Temperature, *RH* Relative humidity and *PPT* precipitation) and AQI. * p < .05, ** p < .01, *** p < .001

The observation showed temperature plays a great role in association with AQI distribution in the atmosphere than RH and precipitation [10, 20]. The empirical evidence from multiple studies consistently supports this study's findings that temperature, relative humidity, and precipitation were inversely related to the AQI [34–37]. The elevated temperatures

Table 5 Multiple linear regression analysis between meteorological factors (Independent variables) and AQI (Dependent variables)

Parameters	Coefficient		
	Standardized coefficient beta	t	*P* value
Temp	– 0.569	– 8.494	< 0.001
RH	– 0.457	– 5.959	< 0.001
PPT	– 0.184	– 2.097	< 0.05

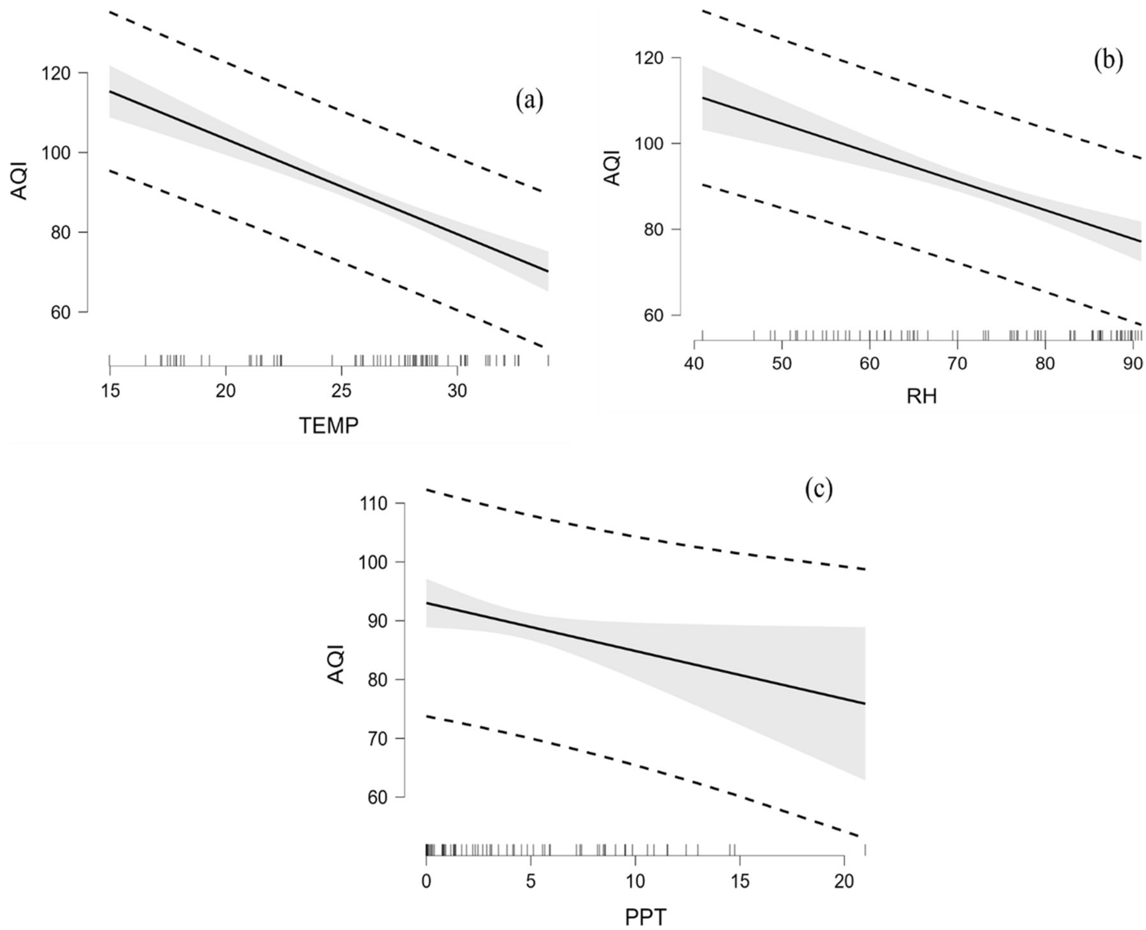


Fig. 7 Marginal effects of temperature **a**, relative humidity **b** and precipitation **c** on AQI

have been found to be linked with enhanced dispersion and dilution of pollutants, along with enhanced chemical reactions that facilitate the degradation of contaminants. Furthermore, higher amounts of precipitation play a pivotal role in cleaning the atmosphere by eliminating gaseous and particulate pollutants. Relative humidity, although exhibiting a lesser influence than rainfall and temperature, but plays an essential role in enhancing air quality through wet deposition [31, 32, 34, 36, 37].

4 Conclusions

The air quality index (AQI) in West Bengal varied from satisfactory to moderate from 2016 to 2021. Across the West Bengal districts, Bardhaman, Bankura, Paschim Medinipur, Howrah, South 24 Parganas, and Kolkata consistently exhibited elevated AQI levels throughout the study period. In West Bengal, the southern part observed a higher AQI and the Northern part showed a lower AQI. The seasonal AQI varies tremendously in winter, summer, and monsoons. The winter period AQI was very high (114) as compared to summer (80) and monsoon (68). Over the study period, the winter season contributes to 43.59% of the total AQI observations, the summer season accounts for 30.51%, and the monsoon season comprises 25.90%. Among all the seasons, the monsoon period shows the least AQI due to seasonal washout, which is a good indication for improving AQI in the atmosphere. In addition, the temperature greatly influences AQI distribution than precipitation and relative humidity. West Bengal being an extremely diverse agro-climatically state of India, a distinct variation in AQI were observed in different regions, particularly between southern and northern parts. According to the anticipated values obtained from both the Expert Modeller and linear trend model, it can be concluded that there were no significant trends seen in the AQI in the region of West Bengal. The projected and actual AQI values exceed satisfactory levels, which potentially leading to respiratory discomfort among individuals. The satisfactory to moderate AQI of the studied area indicates that the locals experience a range of breathing problems and respiratory issues. Based on the present study's findings, we may suggest specific measures for reducing the AQI level in ambient air, such as reducing vehicular pollution, use public transport instead of private, improving fuel quality, less operations of industrial activities in winter season, consume less energy which derived from fossil fuel burning, and replacing old engines to upgraded ones. Overall, this study offers valuable information that can be utilized by policymakers and environmental professionals in their endeavours to safeguard human health and maintain environmental integrity in various regions of West Bengal. The government must make significant policies to improve the AQI for well-being. The findings of the study, particularly the meteorological influences on air quality index, can not only be limited to national level but also can be used at international level for addressing the problems of air pollution.

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Author contribution BG contributed to the concept, writing the original draft, statistical analysis, and study design. HCB collected, managed, and cleaned the data. PKP helped write the initial draft, review, and edit. The published version of the manuscript has been read and approved by all authors.

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Data availability The datasets are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors confirm that they have no known financial or interpersonal competing that would have appeared to impact the research presented in this study.

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