Quest Journals
Journal of Research in Environmental and Earth Sciences
Volume 11 ~ Issue 6 (June 2025) pp: 34-46
ISSN(Online) :2348-2532
www.questjournals.org

Research Paper

Assessment of Air Quality and Identification of Possible Sources in and Around Angul-Talcher Area of Odisha, India

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ABSTRACT: *A work was undertaken to study the air quality, pollution load and its possible sources in and around Angul-Talcher, an industrial area of Odisha, India during March 2022 to February 2023 at six sampling stations, of which three are in Angul area, viz. Jindal Steel & Power Limited (JSPL), Industrial Estate (IE) and National Aluminium Company Limited (NALCO), and three are in Talcher area, viz. Talcher Thermal Power Station (TTPS), Mahanadi Coalfields Limited (MCL) and National Thermal Power Corporation (NTPC). Particulate (PM_{10} and $PM_{2.5}$) and gaseous pollutants (SO_2 and NO_2) were sampled and analysed following the guidelines of the Central Pollution Control Board [24], while Air Pollution Index API was calculated using the formula quoted by Ziauddin and Siddiqui [25] and Principal Component Analysis (PCA) and Cluster Analysis (CA) was performed, using SPSS (version-19) statistical package. The results revealed that particulate matter is significantly higher than the NAAQS [29] recommended standard of 100 µg/m^3 (PM_{10}) and 60 µg/m^3 ($PM_{2.5}$) at all the six stations. Among the gaseous pollutants, the NO_2 level is also above the allowable limit of 80 µg/m^3, but the SO_2 level is within the limit of 80 µg/m^3. Further, all the stations are coming under Severe Air Pollution (SAP >100) category. Principal Component Analysis (PCA) identified potential causes of air pollution to be wide spread industrial emissions, mining activities, vehicular emissions, seasonality, and meteorological conditions like temperature inversions in winter.* ***As*** *all the stations showed a high degree of similarity (97.92%) in sharing a common source of pollution, it is recommended to implement region-wide pollution control measures to address the pollution sources effectively.*

KEY WORDS: *Air Quality, Particulate Matter, Gaseous Pollutant, Air Pollution Index, Principal Component Analysis, Cluster Analysis, Angul-Talcher Area*

Received 15 June., 2025; Revised 27 June., 2025; Accepted 29 June., 2025

I. INTRODUCTION

Air pollution has become a major concern, particularly in urban environments worldwide [1]. In India, around 55% of the total population lives in urban areas. Unfortunately, during the last few decades, the ambient air quality of urban areas in India have been mostly declined due to unplanned and excessive use of natural resources, coupled with growing cities, rapid population explosion, increasing traffic, expanding industrialization, speedy economic development and high amplitude of energy consumption [2, 3].

Urban areas in India emit more than half of the total air pollutants, such as particulate matter, gaseous, organic, and inorganic pollutants, of which 80% do not meet WHO air quality criteria [4, 5]. Additionally, the air pollution index (API), a collective value of different pollutants, highlights and authenticates the air pollutants that are mostly responsible for the deterioration of air quality [6, 7]. A variety of factors, including geography, land-use patterns, meteorological conditions (such as temperature, relative humidity, wind speed, wind direction, precipitation), dispersion and long-range transport patterns, local sources etc., also influence the pollutant concentrations in the atmosphere [8, 9].

With the increase in air pollution in different urban areas of India, source apportionment analyses, using different receptor model techniques, have been conducted to identify potential sources of pollutants and to implement effective air quality management [10]. Some of the most popularly used receptor model techniques are Factor analysis (FA), Principal Component Analysis (PCA), edge analysis (Unmix), chemical mass balance (CMB) and Positive Matrix Factorization (PMF) [11, 12, 13]. Out of these, Principal component analysis (PCA) is the most frequently used technique, but there are some cases of application of the chemical mass balance (CMB) model [14].

The greatest menaces of air pollution, is not only due to its impact on global warming and climate change, but also for its effect on materials, plants, animals including human beings [5, 15]. The consequences of air pollution have been extensively studied, and as perceived by the environmentalists and decision-makers, air pollution is the most significant factor negatively affecting human health ranging from morbidity to serious illness and mortality [16, 17, 18].

The Central Pollution Control Board has identified many industrial clusters in India, of which three (namely Angul-Talcher, Ib-valley, and Jharsuguda) are recognised as critically polluted areas in the State of Odisha [19]. Among the three, Angul-Talcher is a well-known industrial cluster located in the eastern zone of India and the central part of Odisha. Minerals like coal, chromite, graphite, mica, kyanite, granite, laterite, sand (stow), and quartz are found in this area. In consequence, many allied mining and industrial activities have proliferated significantly, causing severe air pollution in and around the area [20].

Many studies have been done to assess the air quality and to identify the possible sources in different towns, cities, and industrial clusters of India [3, 21]. Comparatively, little is known about the source apportionment of air pollution in Angul- Talcher industrial cluster area [20, 22]. Based on the above backdrop, a work was envisaged to study the air quality (through the measurement of PM_{10}, $PM_{2.5}$, SO_2, and NO_2), assess the overall pollution status (through computation of Air Pollution Index) and detect the possible sources in and around Angul-Talcher, an industrial area of Odisha, India.

II. STUDYSITE AND MATERIALS AND METHODS

Study Site

Angul and Talcher are the two major industrial- cum- mining areas in the district of Angul, Odisha. The district, with 4.09% of the State area, has 4 subdivisions (Angul, Talcher, Pallahra and Athamallik), covering an area of 6232 sq. km, out of which Angul and Talcher occupy 3175 sq. km (50.95 % of the district). Geographically, Angul is located at 20^0 84'North Latitude and 85^0 15' East Longitude, and Talcher is located at the coordinates of 20^0 95' North Latitude and 85^0 21' East Longitude. Both areas (subdivisions) are situated at an average elevation of 876 meters above the mean sea level (MSL). They are surrounded to the north by Keonjhar and Sundargarh, east by Cuttack and Dhenkanal, south by Boudh, and west by Sambalpur and Deogarh district. The total population of district is 12.74 lakhs (as per the 2011 census), out of which Angul and Talcher areas share approximately 10.0% [23].

Topography and Climate

Topographically, the district Angul has been divided into three natural tracks. First is a chain of hills running along the northeastern boundary of the district covering Pallahara. Another chain of hills runs along the south-west boundary, covering Athamallik and Angul. The third natural division is a valley of Brahmani River running along the boundary of Talcher through Kaniha, touching Pallahara.

The climate conditions of the district are generally hot and high humidity from March to mid-June, and cold during October to February. The monsoon breaks during the second fortnight of June and continues till the end of September.

Sampling Stations and Sampling Frequency

Monitoring of ambient air quality was carried out from March 2022 to February 2023 (for one year) at six sampling stations, out of which three are in Angul area (Jindal Steel & Power Limited, Industrial Estate and National Aluminium Company Limited) and three are in Talcher area (Talcher Thermal Power Station, Mahanadi Coalfields Limited and National Thermal Power Corporation). The locations, abbreviations, and geographical coordinates of the sampling stations are shown in Figure - 1 and Table - 1. Several factors, such as accessibility to the area, steady electricity supply, and a platform for installing the instruments, were considered while choosing the sample stations. The sampling was conducted in every station during the last week (4^{th} week) of the month for 24 hours.

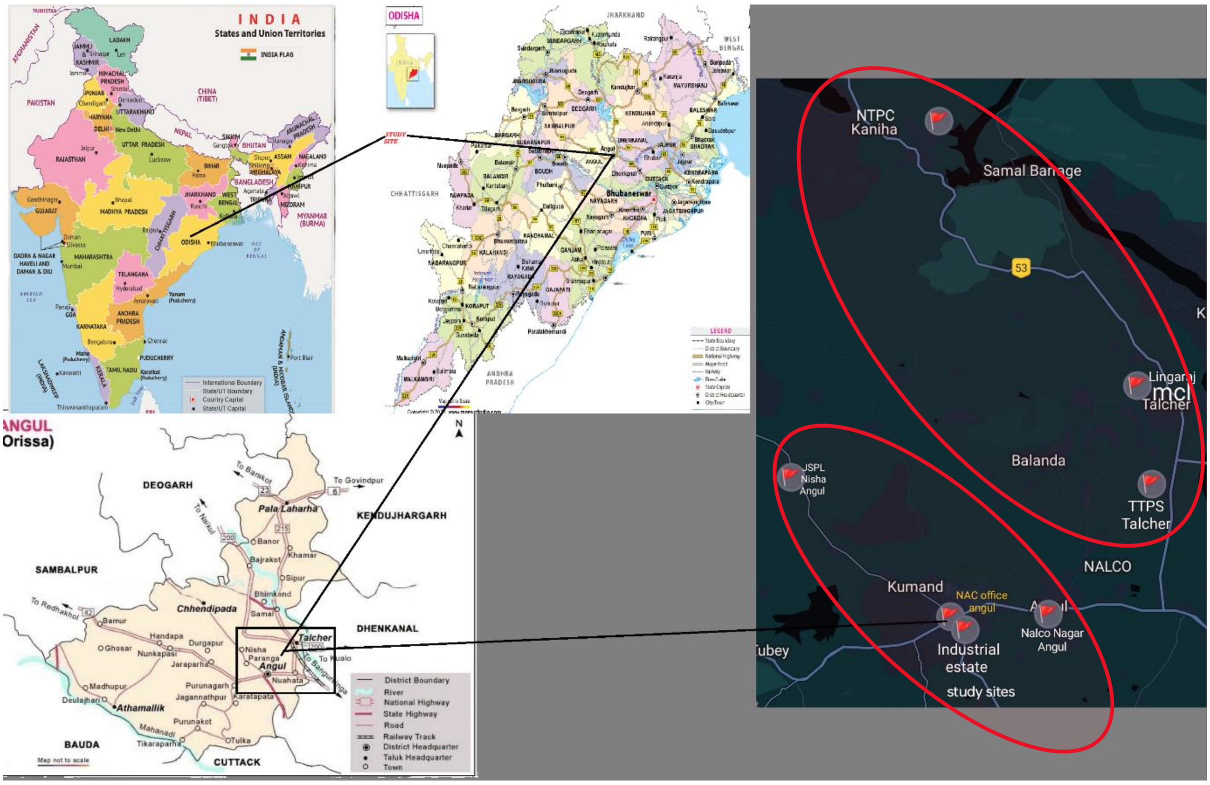

Figure -1: Location of Sampling stations in and around Angul -Talcher Area

Table -1: Details of the sampling stations of Angul -Talcher area

Sl. No.	Name of the sampling station	Abbreviation	Name of the location	Geographical coordinates
1	Jindal Steel & Power Limited	JSPL	Nisha	20.9051N, 85.0137E
2	Industrial Estate	IE	Hakimpada	20.8328N, 85.1043E
3	National Aluminium Company Limited	NALCO	Nalco Nagra	20.8410N, 85.1509E
4	Talcher Thermal Power Station	TTPS	Thermal	20.9090N, 85.2088E
5	Mahanadi Coalfields Limited	MCL	Dera	20.9604N, 85.2007E
6	National Thermal Power Corporation	NTPC	Kaniha	21.0940N, 85.0534E

Sampling and Analysis of Air Quality Parameters

Particulate (PM_{10} and $PM_{2.5}$) and gaseous pollutants (SO_2 and NO_2) were sampled and analysed following the guidelines of the Central Pollution Control Board [24]. A respirable dust sampler (RDS) was used to collect PM_{10}, SO_2, and NO_2 samples, whereas $PM_{2.5}$ samples were collected by a fine particulate sampler (FPS). To completely rule out the possibility of sample contamination from dust produced by foot traffic and uplift from the ground, the samplers were positioned 6–8 meters above the ground.

Following the manual of the instrument, the sampling was done for 24 hours (4 hours in each run × 6 times) at a steady air flow rate of 1.0 to 1.3 m^3/h for PM_{10} and gaseous pollutants, and at a rate of 1.0 m^3/h for $PM_{2.5}$. The particulate matter analysis was carried out gravimetrically using the initial and final weights of the filter sheets (Whatman for PM10 and Polytetrafluoroethylene for $PM_{2.5}$). The gaseous pollutants were analysed by subjecting the air to the proper absorbing reagents (sodium tetrachloromercurate for SO_2 and a mixture of sodium hydroxide and sodium arsenate for NO_2). The improved West and Geake method and modified Jacob and Hochheiser method were followed for colorimetric analysis of SO_2 and NO_2 [24]. The concentration of particulate ($PM_{2.5}$ and PM_{10}) and gaseous (SO_2 and NO_2) pollutants in ambient air was expressed in $\mu g/m^3$.

Computation of Air Pollution Index

API was calculated from the actual and standard concentrations of the particulate (PM_{10} and $PM_{2.5}$) and the gaseous pollutants (SO_2 and NO_2) using the formula quoted by Ziauddin and Siddiqui [25].

$$\text{Air Pollution Index (API)} = \frac{1}{4}\left(\frac{IPM_{10}}{SPM_{10}} + \frac{IPM_{2.5}}{SPM_{2.5}} + \frac{INO_2}{SNO_2} + \frac{ISO_2}{SSO_2}\right)\times 100$$

Where IPM_{10}, $IPM_{2.5}$, ISO_2, and INO_2 are the determined values of PM_{10}, $PM_{2.5}$, SO_2, and NO_2, respectively, and SPM_{10}, $SPM_{2.5}$, SSO_2, and SNO2 are their respective 24-hourly standard values specified in NAAQS (2009).

Principal Component Analysis (PCA) and Cluster Analysis (CA)

The principal component analysis (PCA) was performed, using SPSS (version-19) statistical package, to identify the probable sources of air pollutants (PM_{10}, $PM_{2.5}$ NO_2 and SO_2). PCA is a crucial technique used to decrease the number of dimension and detect patterns in data sets. The eigen values, which quantify the variance captured by each main component, play a crucial role in uncovering the intrinsic structure of the data. The cluster analysis (CA) was also done to classify the separate groups among the observed stations.

Windrose Diagram, Analysis of Variance and Correlation Matrix

Windrose diagram has been prepared using software available in the website, http://windrose.xyz. Two-way ANOVA and correlation matrix were performed using MS- Excel 2019 software.

III. RESULTS

Meteorological parameters

Table - 2 gives the meteorological data of Angul-Talcher area during the study period. From the table it is evident that the rainfall, baring six months (0 mm), varied from 46.6 (October 2022) to 445.8mm (August 2022), with a total annual precipitation of 1159 mm. The relative humidity oscillated between 51% (March 2022) and 97% (June 2022) throughout the year. The wind speed fluctuated from a minimum of 2 - 4 km/h to a maximum of 6 - 22 km/hr during the study period. The lowest temperature (8.6 °C) was recorded in January 2023, and the highest (44.7 °C) in April 2022. The minimum (416.55X10 KJ/m^2) and maximum (700.74X10 KJ/m^2) solar radiation were received during August and May 2022, respectively.

Table - 2: Meteorological parameters of the Angul – Talcher Area during March 2022 to February 2023

Month	Rainfall (mm)	Relative Humidity (%)			Wind Speed (Km/hr)			Wind direction	Temperature (^{0}C)			Solar Radiation (KJ/m^2)
		Min	Max	Avg	Min	Max	Avg		Min	Max	Avg	
Mar. 22	0	51	91	71	5	13	9	NW	16.6	40.1	28.35	625.47
Apr. 22	0	55	89	72	6	12	9	NW	23.6	44.7	34.15	654.27
May 22	86	54	96	75	6	14	10	SE	21	42.1	31.55	700.74
Jun. 22	160.6	73	97	85	6	18	12	SE	21.6	42.1	31.85	463.39
Jul. 22	333.8	76	96	86	4	16	10	NW	23	35.7	29.35	463.26
Aug.22	445.8	74	96	85	4	22	14	SW	21.6	35.6	28.6	416.55
Sep. 22	86.2	75	95	85	2	10	6	SE	22.8	33.9	28.35	428.23
Oct. 22	46.6	74	96	85	2	8	5	SE	15.6	33.1	24.35	490.52
Nov. 22	0	74	96	85	3	15	9	NW	12	32.1	17.05	445.81
Dec. 22	0	77	95	86	3	9	6	NW	10.6	32.1	21.35	425.63
Jan. 23	0	69	91	80	4	10	7	NW	8.6	32.1	20.35	473.65
Feb. 23	0	64	94	89	4	12	8	NW	10.6	37.1	23.85	498.83

Windrose

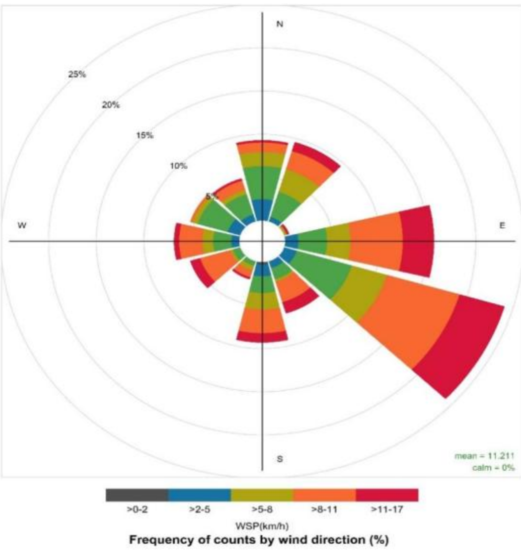

Figure – 2: Windrose Diagram for the study period

The Figure – 2 depicts the annual Windrose diagram for Angul - Talcher area during March 2022 to February 2023. It is apparent from the diagram that wind blew from the South–East and East direction on most occasions. So, the areas located in the North–West and West play an important role in the dispersion of pollutants.

Ambient Air Quality

The monthly concentration of PM_{10} (μg/m^3) at various stations of Angul -Talcher area with their minimum, maximum, and average value during the study period has been given in Table - 3. From the table, it is evident that the concentration of PM_{10} varied from 190.56 (Aug. 22, JSPL) to 370.42 (Jan. 23, NALCO) μg/m^3 in Angul area and from 148.27 (Aug. 22, NTPC) to 478.95 (Feb. 23, MCL) μg/m^3 in Talcher area, with their average concentrations fluctuating from 275.66 to 326.87 μg/m^3 and 261.02 to 358.32 μg/m^3, respectively. Irrespective of stations, the average PM_{10} concentration varied from 209.96 (Aug. 22) to 375.06 (Feb. 23) μg/m^3 with an average value of 299.00 μg/m^3 in Angul -Talcher Area.

Table - 3: Monthly concentration of PM_{10} (μg/m^3) at various stations of Angul -Talcher Area with their minimum, maximum, and average value during the study period (March 2022 to February 2023)
*For details of sampling station abbreviation see Table -1

Month	Angul Area			Talcher Area			Average
Station	JSPL*	IE*	NALCO*	TTPS*	MCL*	NTPC*	
Mar. 22	284.32	271.66	340.25	301.33	410.52	265.38	312.24
Apr. 22	286.12	280.11	345.29	288.62	380.37	318.78	316.55
May 22	288.61	272.55	339.41	272.52	378.54	298.55	308.36
Jun. 22	282.6	268.63	321.47	225.62	370.51	285.24	292.35
Jul. 22	265.7	230.52	265.74	215.74	321.52	210.12	251.56
Aug. 22	190.56	200.3	260.63	205.36	254.62	148.27	209.96
Sep. 22	210.36	278.39	318.47	220.63	240.66	198.52	244.51
Oct. 22	222.16	276.85	328.75	264.74	285.36	210.74	264.77
Nov. 22	298.35	322.63	340.88	317.62	335.75	235.17	308.40
Dec. 22	318.32	335.29	338.49	333.17	380.63	310.12	336.00
Jan. 23	332.36	345.36	370.42	381.28	462.36	318.22	368.33
Feb. 23	328.45	338.84	352.63	418.31	478.95	333.18	375.06
Minimum	190.56	200.30	260.63	205.36	240.66	148.27	209.96
Maximum	332.36	345.36	370.42	418.31	478.95	333.18	375.06
Average	275.66	285.10	326.87	287.08	358.32	261.02	299.00
SD	±43.97	±42.19	±31.35	±64.57	±71.55	±56.75	± 44.59

Table - 4 gives the monthly concentration of $PM_{2.5}$ (μg/m^3) at various stations of Angul -Talcher area with their minimum, maximum, and average value during the study period. From the table it is apparent that, the concentration of $PM_{2.5}$ ranged from 76.12 (Aug. 22, IE) to 142.28 (Dec. 22, NALCO) μg/m^3 in Angul area and from 91.76 (Oct. 22, NTPC) to 149.16 (May 22, MCL) μg/m^3 in Talcher area with their average concentrations varying from 97.85 to 128.20 μg/m^3 and 100.44 to 131.97μg/m^3, respectively. Regardless of stations, the average $PM_{2.5}$ concentration ranged from 96.35 (Aug. 22) to 129.75 (Feb. 23) μg/m^3 with an average value of 115.74 μg/m^3 in Angul -Talcher area.

Table - 4: Monthly concentration of $PM_{2.5}$ (μg/m^3) at various stations of Angul -Talcher Area with their minimum, maximum, and average value during the study period (March 2022 to February 2023)

Month	Angul Area			Talcher Area			Average
Station	JSPL*	IE*	NALCO*	TTPS*	MCL*	NTPC*	
Mar. 22	123.15	95.37	126.45	111.08	134.63	107.15	116.31
Apr. 22	124.18	97.73	136.18	110.66	138.32	106.18	118.88
May 22	132.15	98.12	112.18	128.13	149.16	107.36	121.18
Jun. 22	109.31	78.62	122.36	126.18	148.19	98.66	113.89
Jul. 22	115.26	82.65	138.49	131.29	136.26	96.87	116.80
Aug. 22	97.18	76.12	108.18	101.18	101.08	94.35	96.35

Sep. 22	98.36	81.36	101.17	99.78	109.12	93.88	97.28
Oct. 22	111.18	92.12	136.35	112.38	112.13	91.76	109.32
Nov. 22	103.28	109.16	138.39	138.18	136.28	101.13	121.07
Dec. 22	120.39	115.28	142.28	131.12	138.12	102.22	124.90
Jan. 23	122.32	112.22	139.16	121.39	141.16	102.39	123.11
Feb. 23	129.66	135.39	137.18	133.75	139.15	103.36	129.75
Minimum	97.18	76.12	101.17	99.78	101.08	91.76	96.35
Maximum	132.15	135.39	142.28	138.18	149.16	107.36	129.75
Average	115.54	97.85	128.20	120.43	131.97	100.44	115.74
SD	± 1.75	± 17.66	± 4.03	± 3.01	± 15.62	± 5.33	±4.24

*For details of station abbreviation see Table -1

Table – 5: Monthly concentration of SO_2 ($\mu g/m^3$) at various stations in and around Angul Talcher Area with their minimum, maximum, and average value during the study period (March 2022 to February 2023).

*For details of station abbreviation see Table-1

Month	Angul Area			Talcher Area			Average
Station	JSPL*	IE*	NALCO*	TTPS*	MCL*	NTPC*	
Mar. 22	61.33	61.21	65.53	63.46	68.47	60.12	63.35
Apr. 22	62.76	60.59	64.61	64.14	69.94	63.32	64.23
May 22	62.82	60.13	62.97	66.42	73.75	61.18	64.55
Jun. 22	60.78	56.28	59.34	60.86	59.79	59.12	59.36
Jul. 22	55.59	52.46	55.62	58.95	57.17	58.48	56.38
Aug. 22	53.51	47.64	53.15	52.29	51.18	50.41	51.36
Sep. 22	57.54	52.38	56.61	56.27	55.35	56.18	55.72
Oct.22	63.58	62.07	62.18	59.22	56.45	59.26	60.46
Nov.22	62.41	65.28	65.66	67.17	61.54	61.36	63.90
Dec.22	68.25	72.58	71.33	69.19	71.47	67.42	70.00
Jan. 23	69.41	69.87	72.27	67.28	73.81	62.55	69.20
Feb. 23	62.26	66.67	68.77	68.12	69.97	60.23	66.00
Minimum	53.51	47.64	53.15	52.29	51.18	50.41	51.36
Maximum	69.41	72.58	72.27	69.19	73.81	67.42	70.00
Average	61.69	60.60	63.17	62.78	64.07	59.97	62.05
SD	±4.39	±7.14	±5.85	±5.07	±7.66	±3.94	± 2.86

The monthly concentration of SO_2 ($\mu g/m^3$) at various stations of Angul -Talcher area with their minimum, maximum, and average values during the study period has been presented in Table - 5. It is obvious from the table that, the concentration of SO_2 fluctuated from 47.64 (Aug. 22, IE) to 72.58 (Dec. 22, IE) $\mu g/m^3$ in Angul area and from 50.41 (Aug. 22, NTPC) to 73.81 (Jan. 23, MCL) $\mu g/m^3$ in Talcher area with their average concentrations ranging from 60.60 to 63.17 $\mu g/m^3$ and 59.97 to 64.07 $\mu g/m^3$, respectively. Further, across all the stations the average SO_2 concentration fluctuated from 51.36 (Aug. 22) to 70.00 (Dec. 22) $\mu g/m^3$ with an average value of 62.05 $\mu g/m^3$ in Angul -Talcher area.

Table - 6 gives the monthly concentration of NO_2 ($\mu g/m^3$) at various stations of Angul -Talcher area with their minimum, maximum, and average values during the study period. From the table, it is clear that the concentration of NO_2 was in the range of 102.65 (Aug. 22, IE) to 173.95 (Dec. 22, IE) $\mu g/m^3$ in Angul area and 108.60 (Aug. 22, NTPC) to 187.88 (Jan. 23, MCL) $\mu g/m^3$ in Talcher area, with their average concentrations varying from 148.60 to 168.10 $\mu g/m^3$ and 150.13 to 166.34 $\mu g/m^3$, respectively. Despite stations, the NO_2 average concentration ranged from 122.95 (Aug. 22) to 173.00 (Jan. 23) $\mu g/m^3$ with an average value of 158.27 $\mu g/m^3$ in Angul -Talcher area.

Table – 6: Monthly concentration of NO_2 ($\mu g/m^3$) at various stations in and around Angul- Talcher area with their minimum, maximum, and average values during the study period (March 2022 to February 2023)
*For details of station abbreviation see Table -1

Month	Angul Area			Talcher Area			Average
Station	JSPL*	IE*	NALCO*	TTPS*	MCL*	NTPC*	
Mar. 22	170.25	167.15	171.95	170.35	172.10	168.18	170.00
Apr. 22	169.19	160.96	170.56	170.15	172.30	160.25	167.24
May 22	171.3	154.90	171.14	169.98	173.18	162.65	167.19
Jun. 22	160.85	108.50	168.25	135.28	120.12	155.80	141.48
Jul. 22	163.7	103.58	158.04	129.16	148.50	138.35	140.20
Aug. 22	104.05	102.65	155.40	113.38	153.60	108.60	122.95
Sep. 22	125.38	146.02	166.09	167.25	170.93	138.75	152.40
Oct. 22	152.8	154.64	168.56	172.14	169.13	139.18	159.40
Nov. 22	159.55	165.95	169.73	173.61	175.83	139.20	163.98
Dec. 22	163.38	173.95	171.46	173.88	178.26	158.26	169.87
Jan. 23	168.28	173.58	173.15	172.25	187.88	162.98	173.00
Feb. 23	170.12	171.31	172.85	171.18	174.24	169.40	171.50
Minimum	104.05	102.65	155.40	113.38	120.12	108.60	122.95
Maximum	171.30	173.95	173.15	173.88	187.88	169.40	173.00
Average	156.57	148.60	168.10	159.88	166.34	150.13	158.27
SD	±20.79	±27.65	±5.71	±21.10	±17.89	±17.72	± 12.26

Air Pollution Index

The monthly concentration of API at different stations of Angul -Talcher area with their minimum, maximum, and average values for the study period has been depicted in Table - 7. It is apparent from the table that the concentration of API varied from 128.76 (Aug. 22, IE) to 227.28 (Jan. 23, NALCO) in Angul area and 126.07 (Aug. 22, NTPC) to 256.18 (Jan. 23, MCL) in the Talcher area, with their average concentrations ranging from 185.26 to 207.40 and 172.76 to 216.57, respectively. Irrespective of stations, in Angul -Talcher area, the average API concentration varied from 147.11 (Aug. 22) to 222.05 (Feb. 23) with an average value of 299.00.

Table -7: Monthly value of Air Pollution Index (API) at various stations in and around Angul -Talcher area with their minimum, maximum, and average values during the study period (March 2022 to February 2023)

Month	Angul Area			Talcher Area			Average
Station	JSPL*	IE*	NALCO*	TTPS*	MCL*	NTPC*	
Mar. 22	194.76	179.02	211.96	194.68	233.90	182.33	199.44
Apr. 22	195.76	179.98	216.55	191.48	228.43	193.80	201.00
May 22	200.38	176.22	204.75	195.39	233.95	189.32	200.00
Jun. 22	185.46	151.41	202.47	170.27	210.60	179.58	183.30
Jul. 22	182.98	140.83	190.91	167.42	201.43	154.40	173.00
Aug. 22	137.37	128.76	175.40	145.27	169.77	126.07	147.11
Sep. 22	150.74	165.50	191.37	166.58	176.34	149.66	166.70
Oct. 22	169.48	175.32	211.11	185.31	188.55	152.93	180.45
Nov. 22	186.98	198.40	216.44	212.22	214.90	163.61	198.76
Dec. 22	202.13	208.90	219.78	213.89	230.75	190.61	211.01
Jan. 23	208.33	209.18	227.28	220.75	256.18	192.70	219.07
Feb. 23	208.76	215.49	220.82	235.09	254.03	198.12	222.05
Minimum	137.37	128.76	175.40	145.27	169.77	126.07	147.11

Maximum	208.76	215.49	227.28	235.09	256.18	198.12	222.05
Average	185.26	177.41	207.40	191.52	216.57	172.76	299.00
SD	±21.49	±26.50	±14.47	±25.06	±27.04	±21.87	± 15.16

*For details of station abbreviation see Table -1

Analysis of Variance and Correlation Matrix

A two-way ANOVA was computed for different air quality parameters to assess the significance of the sources of variance concerning sampling stations and months. The results showed significant variation between stations ($F_1 \geq 3.08$, $p < 0.05$) as well as months ($F_2 \geq 7.34$, $p < 0.05$) (Table - 8).

Further, to understand the relationship between the meteorological and air quality parameters, a correlation matrix was worked out and is presented in Table - 9. It is clear from the table that all the individual pollutants (PM_{10}, $PM_{2.5}$, SO_2 and NO_2) as well as API showed significant positive correlations among themselves ($r \geq 0.733$, $p < 0.05$). These parameters showed significant negative correlations with rainfall ($r \geq -0.597$, $p < 0.05$), temperature ($r \geq -0.532$, $p < 0.05$), and wind speed ($r \geq -0.511$, $p < 0.05$). However, relative humidity and solar radiation showed insignificant negative relationships with all the air quality parameters ($p > 0.05$).

Table – 8: Two- way ANOVA among various stations and sampling months in respect of air quality parameters

Parameter	Source of Variation	SS	DF	MS	Cal. F	Tab. F at 0.05	S/NS
PM_{10}	Stations	66768.05	5	13353.61	15.89	2.40	S
	Months	160771.26	10	16077.13	19.14	2.03	S
$PM_{2.5}$	Stations	11125.25	5	2225.05	23.37	2.40	S
	Months	6989.53	10	698.95	7.34	2.03	S
SO_2	Stations	116.50	5	23.30	3.08	2.40	S
	Months	2045.85	10	204.59	27.02	2.03	S
NO_2	Stations	4110.08	5	822.02	4.73	2.40	S
	Months	15594.59	10	1559.46	8.98	2.03	S
API	Stations	15712.16	5	3142.43	28.33	2.40	S
	Months	32434.94	10	3243.49	29.24	2.03	S

Table 9. Correlation matrix between various meteorological and air quality parameters

Parameter	PM_{10}	$PM_{2.5}$	NO_2	SO_2	Rainfall	Temp	WS	RH	SR	API
PM_{10}	1									
$PM_{2.5}$	0.890*	1								
NO_2	0.848*	0.733*	1							
SO_2	0.929*	0.863*	0.905*	1						
Rainfall	-0.770*	-0.597*	-0.939*	-0.824*	1					
Temp	-0.584*	-0.532*	-0.568*	-0.547*	0.370	1				
WS	-0.573*	-0.642*	-0.665*	-0.511*	0.703*	0.459	1			
RH	-0.170	-0.108	-0.379	-0.242	0.301	-0.448	-0.087	1		
SR	-0.279	-0.319	-0.457	-0.300	-0.336	0.522*	0.068	-0.855*	1	
API	0.987*	0.917*	0.904*	0.961*	-0.815*	-0.593*	-0.541*	-0.218	0.341	1

*p<0.05

Principal Component Analysis (PCA)

Principal Component with eigen value and proportion of variance for interpretation of air pollution data in and around Angul-Talcher area has been given in Table - 10. The data set shows that the first principal component (PC1), with an eigenvalue of 5.8416, explains 97.4% of the total variance, while the remaining five components explains 2.6% of the variance only. This suggests that PC1 alone is largely sufficient to capture the overall pollution trends across stations.

Principal component loadings (eigen vectors) reflect the degree to which each original variable (station) contributes to a principal component. Higher absolute values indicate a stronger influence. Principal Component loadings of different variables (stations) for interpretation of air pollution data in and around Angul-Talcher area are given in Table - 11. It is apparent from the table that, in PC1 all stations have similar loadings (~0.40), suggesting a common pollution pattern affecting all stations uniformly. In contrast, PC2 highlights a contrast between Industrial Estate (-0.571) and NTPC (0.568), while PC3 distinguishes TTPS (-0.764) from NALCO (0.528). PC4 separates MCL (-0.653) and NALCO (-0.434) from NTPC (0.442), and PC5 differentiates JSPL (-0.839) from NTPC (0.489), indicating some site-specific pollution influences at these locations.

Table 10. Principal Component with eigen value and proportion of variance for interpretation of air pollution data in and around Angul-Talcher area

Component	Eigen Value	Proportion of Variance	Cumulative Variance
PC1	5.8416	97.4%	97.4%
PC2	0.0563	0.9%	98.3%
PC3	0.0433	0.7%	99.0%
PC4	0.0296	0.5%	99.5%
PC5	0.0159	0.3%	99.8%
PC6	0.0134	0.2%	100%

Table 11. Principal component loadings of different variables (stations) for interpretation of air pollution data in and around Angul-Talcher area

Variable (Station)	PC1	PC2	PC3	PC4	PC5
JSPL	0.410	0.257	0.186	0.155	-0.839
Industrial Estate	0.408	-0.571	0.075	0.396	0.149
NALCO	0.408	-0.378	0.528	-0.434	0.092
TTPS	0.407	-0.199	-0.764	0.094	-0.041
MCL	0.409	0.321	-0.232	-0.653	0.155
NTPC	0.407	0.568	0.206	0.442	0.489

The unrotated factor loadings and communalities from the factor analysis, presented in Table - 12, also shows that Factor 1 accounts for 97.4% of the total variance, indicating that a single dominant factor (likely a common pollution source) drives the air pollution trends across all monitoring stations. In contrast, Factors 2 and 3 contribute only marginally (0.9% and 0.7%, respectively), suggesting that localized pollution influences are minimal compared to the overarching trend captured by Factor 1.

Table 12. Factor analysis for interpretation of air pollution data in and around Angul-Talcher area

Variable (Station)	Factor 1	Factor 2	Factor 3	Communality
JSPL	0.991	0.061	0.039	0.988
Industrial Estate	0.986	-0.135	0.016	0.991
NALCO	0.986	-0.090	0.110	0.991
TTPS	0.985	-0.047	-0.159	0.997
MCL	0.988	0.076	-0.048	0.984
NTPC	0.985	0.135	0.043	0.990
Variance	5.8416	0.0563	0.0433	5.9411
% Variance Explained	97.4%	0.9%	0.7%	99.0%

Cluster Analysis (CA)

In this study, cluster analysis was applied to data on air pollutants (PM_{10}, $PM_{2.5}$, SO_2 and NO_2), utilizing Euclidean distance and complete linkage. This technique provides a detailed view of the hierarchical relationships between air pollutants at different sampling stations, and the results of the present study in this regard are displayed in a dendrogram (Figure - 3).

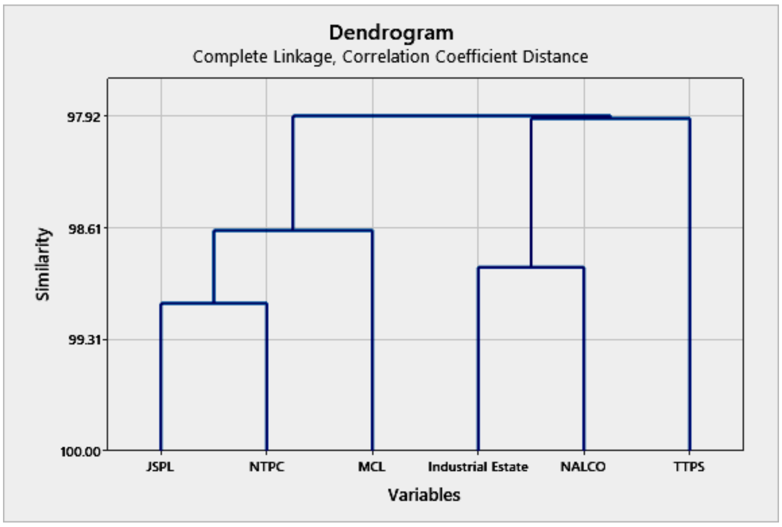

Figure - 3: Dendrogram showing the categorization of sampling stations in different groups in and around Angul-Talcher area

The dendrogram illustrates the hierarchical clustering of monitoring stations (JSPL, NTPC, MCL, Industrial Estate, NALCO, and TTPS) based on the pollution levels. The y-axis represents the similarity index, with higher values indicating greater similarity, while the x-axis shows the monitoring stations. The first major cluster includes JSPL and NTPC, with a similarity of over 99.3%, suggesting nearly identical pollution levels. MCL later joins this cluster, indicating similar pollution patterns to JSPL and NTPC, with slight variations. The second major cluster consists of Industrial Estate and NALCO, which are also highly correlated (over 98.9%) but later merge with TTPS, showing minor differences. Ultimately, both clusters merge at a 97.92% similarity, highlighting that while there are two distinct groups, the overall pollution trends across all stations remain closely related.

IV. DISCUSSION

Ambient Air Quality

The data for air quality (PM_{10}, $PM_{2.5}$, SO_2, and NO_2) across various stations and months, given in Table - 3 to 6, revealed significant seasonal and geographical variations in pollution levels. Particulate matter (PM_{10} and $PM_{2.5}$) levels were at their peak during winter months (November to February), with the highest PM_{10} concentration recorded at MCL in February 2023 (478.95 μg/m³), which might be due to temperature inversions that trap pollutants closer to the ground. In contrast, monsoon months (July and September) showed the lowest PM concentrations, due to the settling down of airborne particles. Among the stations, MCL consistently recorded the highest pollution levels, indicating either higher industrial activity or poor dispersion conditions [26]. NO_2 levels remained relatively steady, but MCL again registered the highest readings, suggesting significant vehicular and industrial emissions [27]. SO_2 levels were comparatively lower, indicating controlled sulfur emissions, possibly due to regulatory measures [9]. Industrial Estate and NTPC tend to have relatively lower pollution levels, suggesting better emission control and relatively less work density [28]. Overall, the air quality data suggested a clear seasonal impact on pollution, with worsening situation during winter and relatively less acute during monsoon.

Moreover, the concentration of air quality variables recorded in the Angul-Talcher area, has been compared with their respective NAAQ Standards, and it is given in Table - 13. It is clear from the data that during the study period, all the six stations in Angul-Talcher area recorded higher levels of particulate matter (PM_{10} and $PM_{2.5}$). The particulate matter was significantly higher than the NAAQS [29] recommended standard of 100 μg/m³ (PM_{10}) and 60 μg/m³ ($PM_{2.5}$). Among the gaseous pollutants, the NO_2 level was also above the allowable limit of 80 μg/m³, whereas the SO_2 level was within the limit of 80 μg/m³. Further, the concentration of all the studied parameters were not only differed significantly between stations and months (Table - 8), but also found to be higher in Talcher as compared to Angul area (Table - 13).

A variety of activities are responsible for the greater emission of particulate and gaseous pollutants into the atmosphere of Angul-Talcher area. These activities are mostly drilling, blasting, crushing, mining, loading and transportation of coal and other ores; burning of coal and garbage; construction and demolition activities; suspended dust due to movement of vehicles and automobile exhausts, domestic cooking and heating, and manufacturing and production activities in industries with energy consumption and emissions [20]. Of the two areas, mining activities are rigorous in the Talcher area and industrial activities are pronounced in the Angul area, in addition to other stated activities. This is consistent with the results reported for other such areas and towns in India [3, 21, 22, 30, 31, 32].

Table - 13: Comparison of ambient air quality parameters with that of NAAQ Standards

Area	Station	PM10 (μg/m3)		PM2.5 (μg/m3)		NO2 (μg/m3)		SO2 (μg/m3)	
		Observed value	NAAQ Stand.	Observed value	NAAQ Stand.	Observed value	NAAQ Stand.	Observed value	NAAQS (2009)
Angul	JSPL	275.66	100	115.54	60	156.57	80	61.69	80
	IE	285.10	100	97.85	60	148.60	80	60.60	80
	NALCO	326.87	100	128.20	60	168.10	80	63.17	80
	Average	297.87	100	113.87	60	157.76	80	61.82	80
Talcher	TTPS	287.08	100	120.43	60	159.88	80	62.78	80
	MCL	358.32	100	131.97	60	166.34	80	64.07	80
	NTPC	261.02	100	100.44	60	150.13	80	59.97	80
	Average	302.14	100	117.61	60	158.78	80	62.27	80
Grand Average		299.00	100	115.74	60	158.27	80	62.05	80

Meteorology and Windrose

The meteorological parameters play an important role so far emission and dispersion of pollutants are concerned [9]. In the present study the highest recorded temperature of 44.7°C was in the summer and lowest temperature of 8.6°C was in the winter. Further, 88.6% (1026.4 mm) rainfall occurred during the monsoon season. Wind speeds were highest during the summer and lowest during the winter season and the direction of the wind in most of the occasion, as observed from Windrose diagram, was either from the South – East or East direction (Table - 2 and Fig. - 2). As a consequence, a strong inverse relationship was obtained in the present study between the meteorological (like rainfall, wind temperature and speed) and air quality parameters with greater dispersion of pollutants in North – West to West direction [33, 34].

Air Pollution Index

The pollution status of the different sampling stations in and around Angul-Talcher area, as evident from air pollution index (API), has been shown in Table - 14. It is clear from the table that, all the stations in Angul-Talcher area are coming under Severe Air Pollution (SAP >100) category. API of a location also reflects its human health issues to varied degrees (Table -15). The API score of > 100 in the present study, divulges the possibility of severe aggravation of heart and lung diseases, as well as increased risk of death in children.

Table -14: Pollution status of the different sampling stations in and around Angul -Talcher area as evident from air pollution index (API)

Area	Sataion	Air Pollution Index (API)			Pollution Status
		Minimum	Maximum	Average	
Angul	JSPL	137.37	208.76	185.26	Severe Air Pollution
	IE	128.76	215.49	177.41	Severe Air Pollution
	NALCO	175.40	227.28	207.40	Severe Air Pollution
Talcher	TTPS	145.27	235.09	191.52	Severe Air Pollution
	MCL	169.77	256.18	216.57	Severe Air Pollution
	NTPC	126.07	198.12	172.76	Severe Air Pollution

Table - 15: Range of the API index, quality of air and its related health concerns [25]

API Range	Quality of Air	Health Concerns
0-25	Clean Air	None /minimal health effects
26-50	Light Air Pollution (LAP)	Possible respiratory or cardiac effect for the most sensitive group
51-75	Moderate Air Pollution (MAP)	Increasing symptoms of respiratory or cardiovascular illness
76-100	Heavy Air Pollution (HAP)	Aggravation of heart and lung diseases
>100	Severe Air Pollution (SAP)	Serious aggravation of heart and lung diseases. Risk of death in children.

Analysis of Variance and Correlation Matrix

A significant variation with respect to different stations and months ($F_1 \geq 3.08$, $F_2 \geq 7.34$, $p < 0.05$), which was observed in this study, indicates substantial difference in the concentration of particulate and gaseous pollutants from stations to stations and months to months in Angul -Talcher area (Table - 8). Our observations corroborate the findings of Sahu and Sahu [7] and Patel et al. [22] for Sambalpur and Jharsuguda towns, respectively.

Particulate pollutants (PM_{10} and $PM_{2.5}$), gaseous pollutants (SO_2 and NO_2), as well as the API in this study, showed positive correlation among themselves ($r \geq 0.733$, $p < 0.05$), but correlations with environmental parameters like rainfall, temperature and wind speed were significantly negative ($r \geq -0.511$, $p < 0.05$), (Table - 9). This postulates that an intricate relationship exists between air pollution intensity and various environmental factors for governing the air quality of an area [20, 34, 35].

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was employed in the present study, by means of SPSS version 19, using Varimax rotation with Kaiser Normalization, to identify potential sources of air pollutants [13]. It helps reducing the dimensionality of multivariate data by generating a smaller number of linear combinations (known as principal components) that capture most of the variability in the original dataset. This approach enables a clearer identification of distinct sources contributing to air pollution [36].

In this study, PC1, with an eigen value greater than one, explained a significant portion (97.4%) of the total variance, indicating the influence of common pollution drivers such as seasonality, widespread industrial emissions, mining activities, vehicular emissions, and meteorological conditions like temperature inversions in winter [37]. The almost equal loadings (~0.40) of PC1 across all stations suggest a widespread pollution pattern affecting all locations similarly. Smaller contributions from PC2 to PC5 point to localized pollution variations, potentially influenced by station-specific factors like industrial density, traffic emissions, or topographical differences [38]. The loading and factor analysis further support the conclusion that PC1 reflects broad pollution sources, while PC2 captures minor location-specific pollution differences.

Cluster Analysis (CA)

Cluster Analysis (CA) is a technique used to categorize objects based on their similarities, ensuring that items within the same group are more alike than those in different groups [39]. The clustering pattern, as revealed from the dendrogram in the present study, divulges that JSPL, NTPC, and MCL share a common pollution source, mostly from industrial and power plant emissions and mining activities, while Industrial Estate, NALCO, and TTPS share altogether different sources, such as localized industrial activities and hefty traffic emissions**.** Since all the stations exhibit high similarity (97.92%), region-wide pollution control strategies would be more effective, but localized interventions should be tailored for each cluster to address site-specific variations in pollution sources [40].

V. CONCLUSION

Angul-Talcher area is located in the central part of Odisha and rich in minerals like coal, chromite, graphite, mica, kyanite, granite, laterite, sand (stow), and quartz. As a result of which many mining, industrial and allied activities have proliferated over time in and around this area, and it is identified as an important industrial cluster in India. The present study revealed that, the PM_{10}, $PM_{2.5}$ and NO_2 level is significantly higher than the recommended standard of NAAQS at all the six stations (JSPL, IE and NALCO in Angul area, and TTPS, MCL and NTPC in Talcher area), but coincidentally SO_2 level is in the border line. The cumulative effects of air pollutants have brought the Angul-Talcher area under Severe Air Pollution category (API value 299). Principal Component as well as Cluster Analysis indicated more or less common pollution source affecting all stations uniformly. Therefore, it is suggested to implement region-wide pollution management programs in order to combat the sources of pollution successfully.

ACKNOWLEDGEMENT

The Authors thank the Head, P. G. Department of Environmental Sciences, Sambalpur University for providing the necessary facilities to carry out this study. The authors are also thankful to the State Pollution Control Board, Bhubaneswar, Odisha for providing necessary support during the course of this work.

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