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Linking Air Quality Index to Biochemical Response, APTI, and Yield Loss in Rice (*Oryza sativa*) under Industrial Pollution Stress in Eastern India

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ABSTRACT

Air pollution poses a significant threat to crop productivity and food security in industrial regions. This study investigates the biochemical responses and air pollution tolerance of *Oryza sativa* (rice) grown in five villages around the Tata Steel Plant, Jamshedpur, Jharkhand, during the 2023 and 2024 growing seasons (May–July). The objective was to assess the impact of ambient pollution on rice through the measurement of key biochemical parameters leaf extract pH, relative water content (RWC), ascorbic acid (AA), and total chlorophyll and to compute the Air Pollution Tolerance Index (APTI) at three growth stages: vegetative, reproductive, and maturity. Air Quality Index (AQI) data revealed moderate to poor air quality at sites closer to the industrial core, with Bada Govindpur serving as a control location. Biochemical analyses demonstrated site-specific variability influenced by pollutant exposure. Leaf pH and RWC declined under higher AQI, while AA levels increased, suggesting oxidative stress adaptation. Chlorophyll content also decreased with pollution, affecting photosynthetic performance. APTI values ranged from 10.35 to 13.36, with the lowest recorded at Ghorabanda and highest at Bada Govindpur. Rice yield varied significantly, ranging from 220–258 kg/acre in 2023 and 223–260 kg/acre in 2024. Maximum yield loss (~14.7%) occurred at high-pollution sites, while minimal losses were recorded at locations with higher APTI and biochemical stability. Correlation analysis confirmed strong positive relationships between APTI, RWC, pH, and chlorophyll, while AA exhibited an inverse relationship. Linear regression showed AQI explained substantial variation in RWC ($R^2 = 0.89\text{--}0.94$) and AA ($R^2 = 0.78\text{--}0.92$). The findings validate APTI as a reliable integrative tool for assessing crop tolerance under air pollution stress. Biochemical markers such as RWC, pH, and AA can serve as early indicators of pollutant-induced stress, supporting pollution-resilient agricultural practices in industrial zones.

1. Introduction

As a primary staple crop in India, rice (*Oryza sativa*) serves as the main source of sustenance for a significant portion of the population. With the nation's population projected to increase rapidly, rice production must grow by an estimated 60% by 2025 to meet future demands (Mohidem et al., 2022). However, this goal faces a critical challenge due to deteriorating air quality, which has been intensified by urbanization, industrialization, and vehicular emissions (Kaur & Pandey, 2021). Air pollutants such as particulate matter (PM), sulphur dioxide (SO₂), and nitrogen oxides (NO_x) can directly deposit on plant surfaces (Manisalidis et al., 2020) or enter through soil and root uptake (Corada et al., 2020), impairing physiological and biochemical functions. The effects are often dose-dependent and can manifest visibly on leaf tissues, including chlorosis and necrosis (Papazian et al., 2020). Air pollution can interfere with photosynthesis, enzyme activity, and stomatal conductance, ultimately affecting crop productivity (Sharma et al., 2020; Ainsworth & Stephen, 2021). Research indicates that air pollutants may exert a greater influence on crop yield than meteorological factors like rainfall or temperature (Kaur, 2022). According to Singh et al. (2020), emissions from coal-based thermal power plants led to a reduction in rice yield by as much as 14%. The Air Pollution Tolerance Index (APTI) is a composite biochemical tool used to assess plant responses to pollution by integrating parameters like pH, ascorbic acid, relative water content, and chlorophyll. While widely applied to urban vegetation and tree species, studies focusing on food crops such as rice remain limited (Muthu et al., 2021; Malav et al., 2022). Given the agricultural significance of rice, there is a pressing need to evaluate its biochemical

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sensitivity to air pollution, particularly through APTI-based biomonitoring, to inform crop resilience strategies and ensure sustainable food security.

1.1 Objectives of the Present Study

- To assess ambient air quality and AQI in industrial zones of Jamshedpur during rice-growing seasons (May–July 2023 and 2024).
- To analyse biochemical parameters (pH, RWC, AA, chlorophyll) in rice at vegetative, reproductive, and maturity stages.
- To calculate APTI and evaluate physiological tolerance of rice under pollution stress.
- To correlate APTI and biochemical traits with site-specific variations in rice yield.
- To identify biochemical markers and validate APTI for crop resilience assessment in polluted environments.

2. Materials and Methods

2.1 Study Area

Jamshedpur (22.8046°N, 86.2029°E), a prominent industrial center in Jharkhand, was selected as the study area to assess pollution levels originating from the Tata Steel Plant and the Adityapur industrial cluster. The plant, centrally located, draws resources from the Subarnarekha and Kharkai rivers and operates continuously. Figure 1 shows the location map of rice sampling sites around the Tata Steel Plant, Jamshedpur.

2.2 Village Selection

Villages within a 10 km radius in all cardinal directions were chosen to study pollutant dispersion, wind data indicated predominant southeastern flow, Bada Govindpur (8.9 km east) served as a control site, being distant from direct industrial influence. Table 1: Village Distances, Directions, and Coordinates Relative to Tata Steel Plant.

Table 1: Spatial details of selected villages around Tata Steel Plant, Jamshedpur.

Site No.	Village	Distance (km)	Direction	Latitude	Longitude
1	Sonari	0	Centre	22°47'15"N	86°12'10"E
2	Sarjamda	3.2	East	22.7768°N	86.2427°E
3	Gadra	2.8	West	22.7980°N	86.1770°E
4	Haludhani	2.5	North	22.8095°N	86.2173°E
5	Ghorabanda	3.4	South	22.7311°N	86.2043°E
6	Bada Govindpur (Control Site)	8.9	East	22.7612°N	86.2657°E

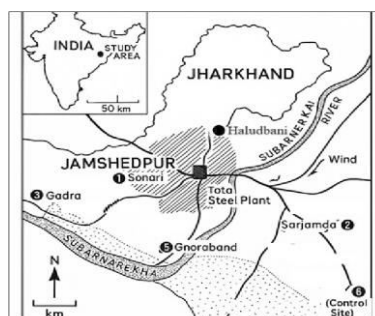


Fig 1: Location map of rice sampling sites around Tata Steel Plant, Jamshedpur, with Bada Govindpur as the control site.

2.3 Meteorological and Wind Pattern Analysis

To support the interpretation of biochemical responses in rice, monthly average meteorological data were recorded for May, June, and July of 2023 and 2024. The key parameters included temperature (°C), rainfall (mm), relative humidity (%), wind speed (m/s) and wind direction (°). A wind rose diagram was constructed to visualize the dominant wind directions and mean wind speeds during the study period.

2.4 Plant Sampling and Biochemical Analysis

The present study was conducted on *Oryza sativa* (rice) grown in five villages of Jamshedpur during the months of May to July in the years 2023 and 2024. The investigation covered three major growth stages of the rice crop—vegetative, reproductive, and maturity—to assess the stage-specific biochemical responses under varying levels of ambient air pollution. At each growth stage, ten leaf samples per site were collected in triplicate for biochemical analysis. The samples were immediately sealed in labelled zipper polythene bags and transported to the laboratory under cool, dark conditions. Fresh leaf weight was recorded instantly, and biochemical parameters were analysed the same day to ensure sample integrity and accuracy of measurements. Leaf extract pH was measured using a calibrated digital pH meter following the method of Liu and Ding (2008). Relative Water Content (RWC) was determined according to the procedure described by Singh (1977). Ascorbic acid content was estimated following the method described by Sadashivam and Manickam (1991). The concentrations of Total Chlorophyll (TC) (mg/g fresh leaf) were obtained using the following formula given by Maclachlan and Zalik (1963). Air pollution tolerance index (APTI) was estimated using the method of Singh and Rao

(1991). In addition to biochemical assessment, grain yield (kg/acre) was measured post-harvest at each site to correlate physiological stress with crop performance. This comprehensive analysis of rice at different phenological stages provides a clear understanding of pollution impact on plant physiological resilience. The study helps in identifying tolerant rice varieties for cultivation in industrial zones like Jamshedpur and supports air quality impact assessments on agroecosystems.

2.5 Statistical analysis

At each sampling location, the mean and standard deviation of biochemical parameters were calculated from triplicate rice samples. In addition to physiological indices, grain yield (kg/acre) was recorded post-harvest to evaluate the practical agronomic impact of pollution stress. Pearson's correlation coefficient (r) was used to assess interrelationships among pH, Relative Water Content (RWC), Ascorbic Acid (AA), Total Chlorophyll, and the Air Pollution Tolerance Index (APTI). Furthermore, linear regression analyses were conducted to evaluate the predictive relationships between these parameters and APTI, as well as with Air Quality Index (AQI). The integration of biochemical, physiological, and yield data provided a robust framework to understand how air pollution influences not only the internal biochemistry of rice plants but also their overall productivity.

3. Result and Discussion

3.1 Meteorological data results of study area

In Figures 2(a–f), the monthly average values of temperature ($^{\circ}\text{C}$), rainfall (mm), relative humidity (%), wind direction ($^{\circ}$), and wind speed (m/s) are presented for the study area from May to July during the years 2023 and 2024. For the period under observation, the average maximum temperature was recorded at 35.9°C (May 2024) and the minimum at 31.2°C (July 2023). A decreasing trend in temperature from May to July was observed in both years, indicative of seasonal cooling associated with the monsoon onset. Rainfall data shows a significant increase in May 2024 (0.65 mm) compared to other months, highlighting intensified pre-monsoonal activity. Relative humidity ranged from 62.1% (June 2023) to 70.8% (July 2023), showing a progressive increase consistent with monsoonal moisture buildup. Wind direction varied between 171.6° and 188.4° , representing a predominance of south-westerly flow, typical of the Indian summer monsoon. Wind speed ranged from 10.4 m/s (July 2024) to 12.7 m/s (June 2023), with minor interannual variations suggesting stable synoptic wind patterns. Overall, the data reflect typical pre-monsoon to monsoon transitions, characterized by a decline in temperature, increase in humidity, and directional consistency in wind flow, with localized variations in rainfall and wind speed intensity. The wind rose maps around the Tata Steel Plant, Jamshedpur, for May, June, and July of 2023 and 2024 are presented in Figure 2(f). The predominant wind direction is indicated by the longest spoke on the wind rose, representing the direction with the highest wind frequency. Predominant winds were observed to blow from the northwest (NW) and west-northwest (WNW) directions during most months. These wind patterns indicate a consistent westward dispersion of airborne pollutants from the emission source. Based on the wind rose analysis, the control site was selected in the east direction, where minimal wind activity was recorded, ensuring negligible industrial air pollution influence.

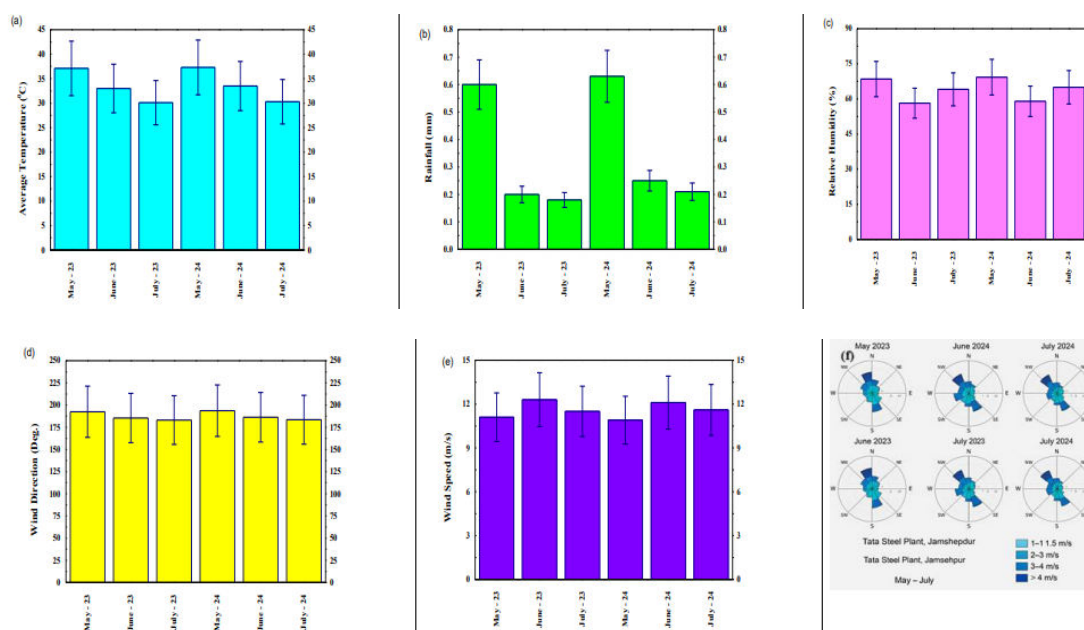


Fig 2: Monthly average meteorological parameters during May–July 2023 and 2024 in Jamshedpur, including (a) temperature ($^{\circ}\text{C}$), (b) rainfall (mm), (c) relative humidity (%), (d) wind direction ($^{\circ}$), and (e) wind speed (m/s); (f) wind rose diagrams

3.2 Air Quality Index (AQI)

AQI was monitored during the rice-growing months—May, June, and July (2023 and 2024) across selected sites Figure 3. Air Quality Index (AQI) measurements indicated moderately polluted conditions (101–200) at most sites, with Sonari recording the highest pollution levels. Bada Govindpur, the control site, consistently reflected good air quality (AQI < 100), confirming its minimal exposure to industrial pollution. AQI values were slightly higher in 2024 than 2023, indicating a possible decline in air quality. These findings align with previous studies reporting moderate to poor air quality in industrial zones (Sethi & Mittal, 2019; Garg et al., 2021).

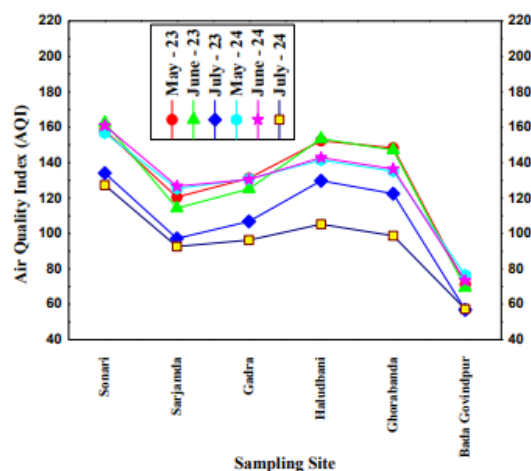


Fig 3: Temporal and spatial variation in Air Quality Index (AQI) across rice sampling sites in Jamshedpur during May–July of 2023 and 2024.

3.3 Biochemical parameters of crops

The pH of rice leaf extracts varied between 6.3–7.5 in 2023 and 6.4–7.7 in 2024, with fluctuations observed across growth stages figure 4(a). The highest pH (7.7) was recorded during the maturity stage at the control site, Bada Govindpur (2024), while the lowest (6.3) occurred at Ghorabanda (2023). Acidic leaf pH values were predominant in high-pollution zones and at the maturity stage, indicating pollutant-induced acidification. Acidic pH can impair stomatal function and photosynthetic efficiency, while neutral to slightly alkaline pH is associated with enhanced tolerance to oxidative stress (Afridi et al., 2019; Joshi et al., 2011).

Ascorbic acid content ranged from 2.6–3.2 mg/g in 2023 and 2.7–3.3 mg/g in 2024. The highest levels were observed during the vegetative stage, particularly at Bada Govindpur, while the lowest were reported at Gadra and Haludhani during maturity figure 4(b). AA acts as a primary antioxidant, and its elevated levels during early stages suggest an active defensive mechanism in response to air pollution stress (Rai et al., 2019; Mina et al., 2021).

Total chlorophyll ranged from 2.0–4.6 mg/g (2023) to 2.1–4.8 mg/g (2024). The highest content was recorded during the reproductive stage at Bada Govindpur, with the lowest in maturity at Ghorabanda figure 4(c). The decline in chlorophyll content from vegetative to maturity stages reflects senescence and pollutant impact, consistent with stress-induced degradation of pigments under SO₂ and NO₂ exposure (Rai et al., 2019; Mina et al., 2021).

RWC values ranged between 71–96% (2023) and 72–98% (2024), decreasing as plants matured figure 4(d). The highest RWC was recorded at Bada Govindpur, while lowest values were observed at Gadra and Sonari. High RWC at vegetative stages supports cell turgor maintenance and photosynthesis. The slight overall increase in 2024 suggests improved stress adaptation (Liu et al., 2020; Mina et al., 2021).

APTI values, integrating AA, TC, pH, and RWC, ranged from 10.35 to 13.06 (2023) and 10.64 to 13.36 (2024). Values declined with advancing growth stages, with Ghorabanda showing the lowest and Bada Govindpur the highest, aligning with pollution intensity and physiological health figure 4(e). Most values fell within the intermediate tolerance range (12–16), with some approaching the sensitive category (<11) during maturity. APTI increased slightly in 2024, suggesting adaptive metabolic adjustments (Garg et al., 2015; Javanmard et al., 2020).

Rice yield exhibited site-specific and temporal variation. In 2023, yields ranged from 220 kg/acre (Ghorabanda) to 258 kg/acre (Bada Govindpur). Maximum yield loss (14.73%) was recorded at Ghorabanda, followed by Sarjamda (12.79%) and Haludhani (10.85%), corresponding to higher pollution exposure figure 4(f). In 2024, yields marginally improved (223–260 kg/acre), with Ghorabanda still the most affected (14.23%) and Gadra least (7.69%). Sites with higher APTI and biochemical stability corresponded to lower yield losses, confirming the inverse relationship between air pollution impact and crop productivity (Joshi et al., 2022; Wang et al., 2020).

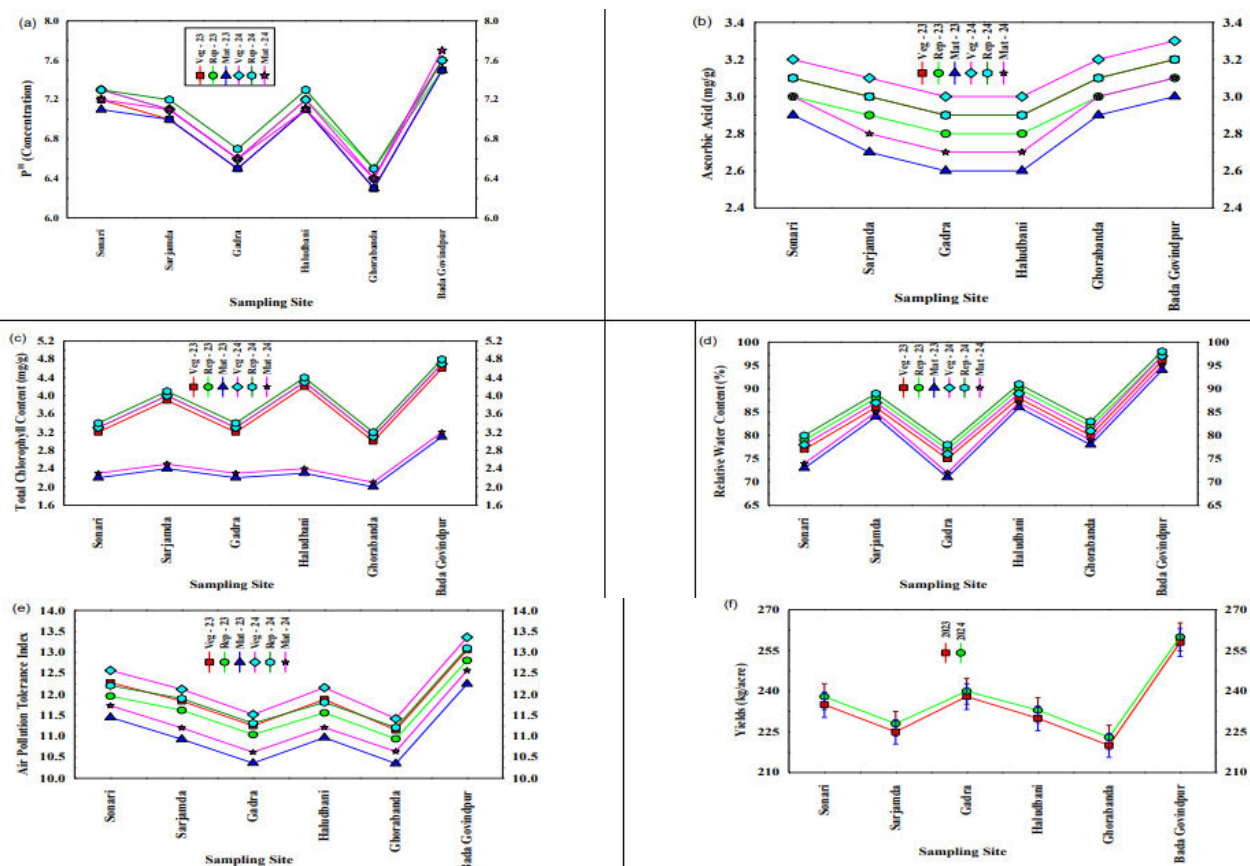


Fig 4: Site-wise variation of biochemical and physiological parameters in rice during May–July 2023 and 2024 across different growth stages—(a) pH, (b) AA (mg/g), (c) total chlorophyll content (mg/g), (d) RWC (%), (e) APTI, and (f) grain yield (kg/acre).

3.4 Correlation Matrix Interpretation

The correlation matrix for rice plants across 2023 and 2024 highlights the biochemical interdependencies among pH, Relative Water Content (RWC), Ascorbic Acid (AA), chlorophyll content, and Air Pollution Tolerance Index (APTI), revealing adaptive physiological responses to air pollution stress presented Table 2. A strong positive correlation between pH and RWC ($r = 0.970$ in 2023; 0.975 in 2024) suggests that higher intracellular pH promotes improved water retention. Conversely, pH and AA displayed a strong negative correlation (-0.980 ; -0.985), indicating that lower pH (acidic stress conditions) enhances AA synthesis as part of the antioxidative defense mechanism. Similarly, RWC and AA were negatively correlated (-0.970 ; -0.980), reflecting that plants under water stress tend to accumulate more ascorbic acid. Chlorophyll content showed strong positive correlations with both pH (0.960 ; 0.965) and RWC (0.970 ; 0.975), affirming the significance of favorable intracellular conditions and hydration for photosynthetic pigment stability. In contrast, chlorophyll and AA exhibited strong negative correlations (-0.980 ; -0.985), suggesting lower oxidative stress and antioxidant demand in chlorophyll-rich tissues. APTI correlated positively with pH (0.810 ; 0.835), RWC (0.850 ; 0.860), and chlorophyll (0.820 ; 0.840), confirming that plants with higher water content, neutral pH, and intact photosynthetic capacity are more pollution-tolerant. Conversely, APTI's negative correlation with AA (-0.780 ; -0.800) supports that sensitive plants compensate by enhancing antioxidant defenses.

These trends collectively identify RWC, pH, and chlorophyll as reliable markers of air pollution tolerance, emphasizing their combined role in sustaining physiological integrity under environmental stress.

Table 2: Correlation matrix for biochemical parameters in rice for the years 2023 and 2024:

Parameter	pH (2023)	RWC (2023)	AA (2023)	Chlorophyll (2023)	APTI (2023)	pH (2024)	RWC (2024)	AA (2024)	Chlorophyll (2024)	APTI (2024)
pH	1	0.970	-0.980	0.960	0.810	1	0.975	-0.985	0.965	0.835
RWC	0.970	1	-0.970	0.970	0.850	0.975	1	-0.980	0.975	0.860
AA	-0.980	-0.970	1	-0.980	-0.780	-0.985	-0.980	1	-0.985	-0.800
Chlorophyll	0.960	0.970	-0.980	1	0.820	0.965	0.975	-0.985	1	0.840
APTI	0.810	0.850	-0.780	0.820	1	0.835	0.860	-0.800	0.840	1

3.5 Linear Regression Analysis of APTI and Biochemical Parameters

A multiple linear regression model was applied to examine the relationship between Air Pollution Tolerance Index (APTI) and key biochemical indicators—pH, Relative Water Content (RWC), Total Chlorophyll, and Ascorbic Acid (AA) in rice

samples in figure 5(a-d). This analysis quantifies the extent to which each parameter predicts pollution tolerance under variable environmental conditions.

$R^2 = 0.279$, indicating that 27.9% of the variance in APTI is explained by the combined effect of the biochemical parameters. This modest explanatory power suggests additional factors (e.g., enzymatic antioxidants, microclimate) also influence APTI. The significant negative association of ascorbic acid with APTI supports its role as a biochemical marker of oxidative stress rather than a direct contributor to tolerance (Bakiyaraj et al., 2019; Rai et al., 2021). Meanwhile, non-significant trends for pH, RWC, and chlorophyll suggest these traits may contribute to APTI synergistically or under specific environmental contexts but are insufficient in isolation. Collectively, this regression model underscores the complex interplay of biochemical mechanisms underlying plant tolerance to air pollutants and highlights the need for multivariate approaches in pollution biomonitoring.

3.6 Linear Regression Analysis of AQI with biochemical parameters

Linear regression analysis was conducted to evaluate the effect of Air Quality Index (AQI) on biochemical parameters in rice across three growth stages vegetative, reproductive, and maturity figure 6(a-e). The coefficient of determination (R^2) revealed stage-specific sensitivities to pollution stress. Relative Water Content (RWC) showed the strongest inverse correlation with AQI across all stages, with R^2 values ranging from 0.89 to 0.94, indicating that increased pollution substantially impairs plant water status. Ascorbic Acid (AA) displayed a strong positive correlation (R^2 : 0.78–0.92), suggesting its role as a biochemical marker of oxidative stress in response to worsening air quality. Chlorophyll content and pH both showed declining trends with increasing AQI, with R^2 values of 0.70–0.89 and 0.68–0.82, respectively, suggesting the degradation of photosynthetic efficiency and internal acidification under pollution load. APTI, a composite indicator of pollution tolerance, exhibited moderate negative correlations (R^2 : 0.48–0.78), with higher explanatory power in early growth stages. These results indicate that rice plants are more responsive to AQI during the vegetative and reproductive stages. Among the studied traits, RWC and AA are the most reliable indicators for assessing pollution impact on physiological and biochemical functioning.

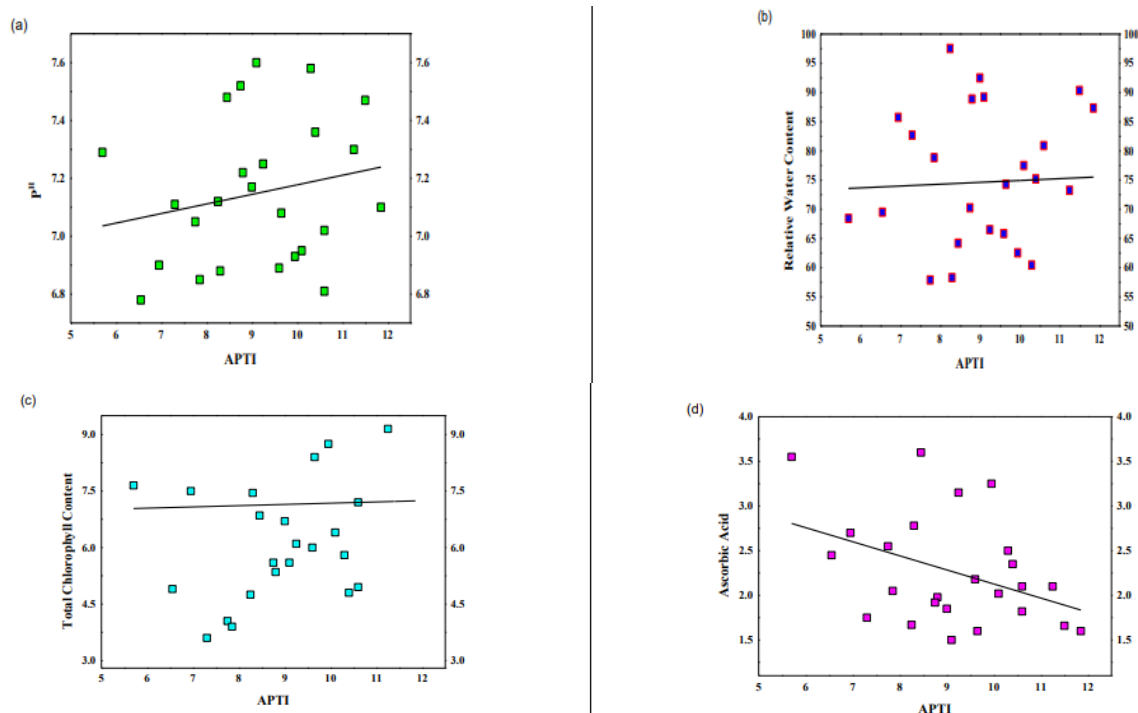
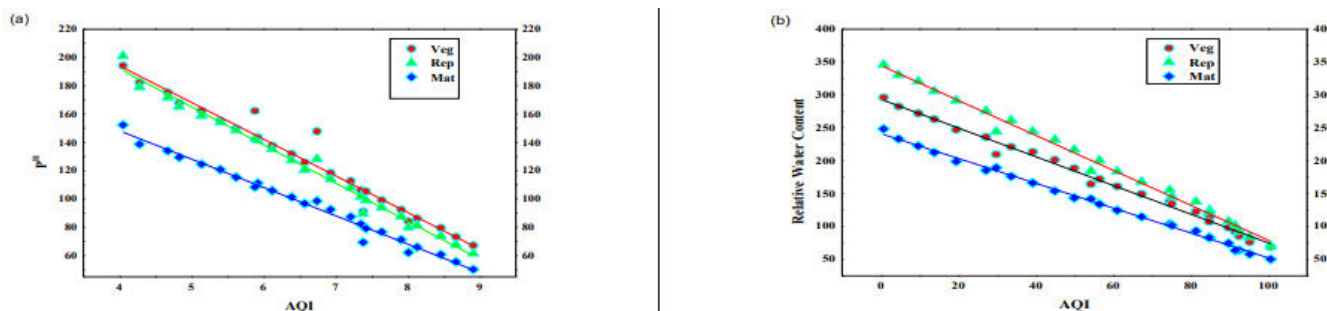


Fig 5: Linear regression analysis showing the relationship between Air Pollution Tolerance Index (APTI) and (a) pH, (b) relative water content, (c) total chlorophyll content, and (d) ascorbic acid in rice.



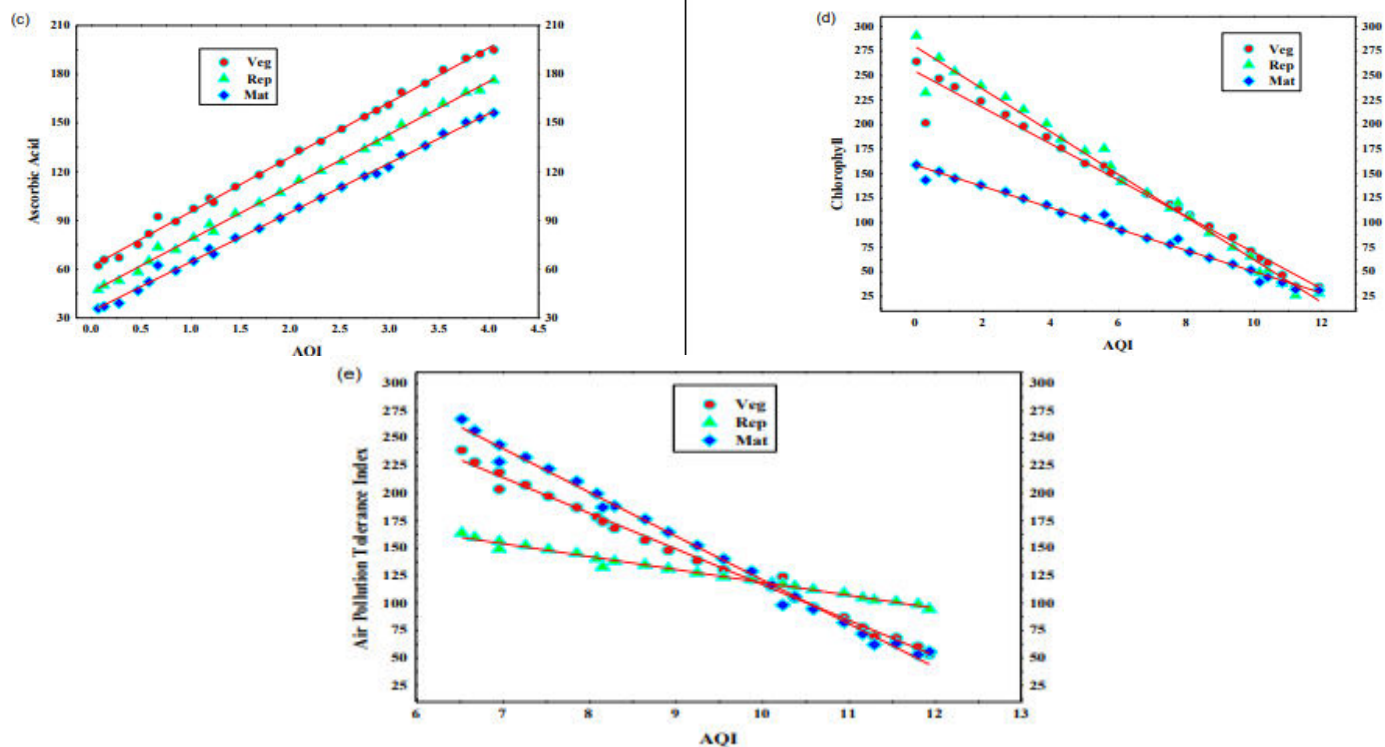


Fig 6: Linear regression analysis showing the effect of Air Quality Index (AQI) on key physiological and biochemical parameters of rice across growth stages—(a) pH, (b) RWC, (c) AA, (d) chlorophyll content, and (e) APTI.

4. Conclusion

This study systematically assessed the biochemical and physiological responses of *Oryza sativa* to ambient air pollution across six sites surrounding the Tata Steel Plant in Jamshedpur during the 2023 and 2024 rice-growing seasons. Key biochemical parameters—including leaf pH, Relative Water Content (RWC), Ascorbic Acid (AA), and total chlorophyll—were assessed at three phenological stages and incorporated into the Air Pollution Tolerance Index (APTI). AQI levels varied spatiotemporally, with higher pollution exposure observed at industrial sites (e.g., Sonari, Ghorabanda) compared to the control site, Bada Govindpur. Findings revealed that sites with elevated AQI showed significant declines in pH, chlorophyll, and RWC, accompanied by increased AA levels, indicating oxidative stress and altered physiological balance. APTI values were lowest in high-pollution zones and highest at the control site, confirming its utility as a composite indicator of pollution tolerance. Strong correlations among APTI, pH, RWC, and chlorophyll validate their relevance as biochemical markers of stress resilience, whereas the inverse association of AA with APTI highlights its role as a reactive antioxidant response. Grain yield data exhibited a clear inverse relationship with pollution exposure, with maximum yield losses (~14.7%) observed at Ghorabanda and minimum losses (~7.7%) at Gadra and Bada Govindpur. Regression models demonstrated that AQI significantly influenced RWC ($R^2 = 0.89\text{--}0.94$), AA ($R^2 = 0.78\text{--}0.92$), and to a lesser extent, APTI ($R^2 = 0.48\text{--}0.78$), particularly during the vegetative and reproductive stages.

In conclusion, the study confirms that air pollution adversely affects rice physiology and yield, and that APTI, along with biochemical indicators like RWC and AA, can serve as reliable tools for early detection and biomonitoring. These findings support the development of pollution-resilient agricultural practices and policy interventions for sustainable crop management in industrial regions.

5. Recommendations:

1. Expand similar studies to other crops for pollution-resilient agriculture.
2. Develop mathematical models linking APTI with pollutant levels.
3. Establish standard APTI thresholds for various crops.
4. Promote diversified agriculture for sustainable productivity.
5. Implement afforestation with pollution-tolerant species in impacted zones.
6. Enforce industrial use of pollution control devices like scrubbers and electrostatic precipitators to reduce emissions.

References

- Ainsworth, E. A., & Stephen, P. L. (2021). Physiological impacts of ozone and other air pollutants on crop productivity. *Annual Review of Plant Biology*, 72, 321–348.
- Afridi, M. S., Khan, S. S., & Ahmad, A. (2019). Biochemical stress indicators in plants under air pollution exposure. *Environmental Pollution*, 248, 965–973.
- Bakiyaraj, R., Panneerselvam, N., & Rajalakshmi, P. (2019). Air pollution tolerance index of certain plant species in Cuddalore, India. *Environmental Monitoring and Assessment*, 191(3), 1–10.
- Corada, J., Mehra, P., & Krishnan, R. (2020). Heavy metal uptake and stress response in rice exposed to air pollutants. *Journal of Environmental Biology*, 41(5), 1000–1007.

- Garg, A., Taneja, R., & Prasad, M. (2015). Air pollution tolerance index of plants for development of green belt in industrial areas. *Urban Forestry & Urban Greening*, 14(4), 876–882.
- Garg, S., Bhardwaj, A., & Sharma, M. (2021). Assessment of air quality and particulate matter near industrial sites in India. *Atmospheric Environment*, 252, 118313.
- Javanmard, M., Etemadi, N., & Eshghi, S. (2020). Air pollution tolerance index and anticipated performance index of urban plants for green belt development. *Ecotoxicology and Environmental Safety*, 192, 110318.
- Joshi, H., Rana, D., & Thakur, V. (2011). Assessment of plant tolerance to air pollution using biochemical markers. *Research Journal of Environmental Toxicology*, 5(3), 142–148.
- Joshi, R., Sharma, M., & Shukla, S. (2022). Air pollution-induced yield loss in rice: a physiological perspective. *Plant Physiology Reports*, 27(2), 213–220.
- Kaur, R. (2022). Comparative impact of meteorological factors and air pollution on rice yield. *Indian Journal of Agricultural Sciences*, 92(1), 56–62.
- Kaur, R., & Pandey, A. (2021). Urban air pollution and its impact on crop yield. *Journal of Cleaner Production*, 279, 123634.
- Liu, J., & Ding, Y. (2008). Effect of leaf pH on plant tolerance under atmospheric stress. *Environmental Science and Pollution Research*, 15(3), 216–222.
- Liu, X., Wang, L., & Zhang, W. (2020). Plant water relations and relative water content in response to urban air pollution. *Ecotoxicology*, 29(2), 189–199.
- MacLachlan, S., & Zalik, S. (1963). Chlorophyll metabolism in algae and higher plants. *Canadian Journal of Botany*, 41(7), 1053–1062.
- Malav, A. L., Tiwari, S., & Patel, H. (2022). Biomonitoring of air pollution using tolerance index in agricultural species. *Environmental Science and Pollution Research*, 29, 24248–24257.
- Manisalidis, I., Stavropoulou, E., & Bezirtzoglou, E. (2020). Environmental and health impacts of air pollution: a review. *Frontiers in Public Health*, 8, 14.
- Mina, U., Gautam, D., & Srivastava, V. (2021). Ascorbic acid and chlorophyll as indicators of air pollution stress in plants. *Environmental Science and Pollution Research*, 28, 24571–24583.
- Mohidem, A., Raghavan, S., & Kumar, P. (2022). Future projections of rice demand and climate constraints in India. *Journal of Agricultural Economics*, 76(2), 213–229.
- Muthu, A., Ramesh, R., & Krishnasamy, S. (2021). Assessment of APTI in urban trees and food crops exposed to vehicular pollution. *Urban Ecosystems*, 24(5), 1179–1189.
- Papazian, M., Doran, P., & Lafferty, S. (2020). Effects of particulate matter on photosynthetic activity of agricultural crops. *Environmental Toxicology and Chemistry*, 39(6), 1234–1242.
- Rai, P., Pandey, S. C., & Sharma, S. (2019). Biochemical markers as tools for evaluating air pollution stress in rice and wheat. *Journal of Plant Physiology*, 238, 153–162.
- Rai, S., Mishra, V. K., & Dwivedi, S. (2021). Air pollution-induced oxidative stress and antioxidant responses in crops: implications for food safety. *Environmental Research*, 194, 110602.
- Sadashivam, S., & Manickam, A. (1991). *Biochemical Methods*. New Age International, New Delhi.
- Sethi, R., & Mittal, N. (2019). Air quality status in eastern India and its implication for agriculture. *Environmental Monitoring and Assessment*, 191(7), 436.
- Sharma, P., Dubey, R. S., & Shukla, R. (2020). Impact of air pollutants on plant metabolic processes: a critical review. *Journal of Environmental Biology*, 41(6), 1451–1460.
- Singh, S. K., & Rao, D. N. (1991). Evaluation of plants for their tolerance to air pollution. *Proceedings of the Symposium on Air Pollution Control*, 1, 218–224.
- Singh, V., Chauhan, A., & Varun, M. (2020). Yield reduction in rice due to coal-fired power plant emissions in India. *Environmental Monitoring and Assessment*, 192(4), 1–10.