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Evolution of air quality and its relationship with precipitation acidity in coastal areas of Veracruz (2020–2023): Influence of meteorological factors

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ABSTRACT

This study analyzes the evolution of air quality and its relationship with precipitation acidity in three coastal cities of Veracruz, Mexico (Xalapa, Veracruz, and Minatitlan) during the 2020–2023 period. The study evaluated sulfur dioxide (SO_2), nitrogen oxides (NOx), and estimated rainwater pH. Meteorological variables such as temperature, precipitation, and wind conditions were also. The data were obtained through transparency platforms from SEDEMA, CONAGUA and processed using statistical and geospatial analysis in QGIS. The results reveal a general downward trend in NOx in urban areas, while SO_2 levels remained stable or slightly increased in industrial zones. Significant correlations were identified between high SO_2 concentrations and low precipitation pH values, suggesting a persistent incidence of acid rain. This work highlights the importance of integrated atmospheric and meteorological monitoring for environmental management in coastal areas. The results of this study provide a scientific basis to improve regional emission control policies and strengthen air quality management strategies.

Keywords: air pollution, acid rain, greenhouse gases (GHG), air quality, meteorological factors.

INTRODUCTION

Recent studies in Asia and the Middle East have also demonstrated the usefulness of Air Quality Indexes (AQI) to assess pollutants such as SO_2, NO_2, O_3, and particulate matter. In their study, Shihab (2021) evaluated air quality in Mosul, Iraq, while Brontowiyono et al. (2022) documented changes in urban air pollution in Indonesia during the pandemic. These studies demonstrate the importance of having integrated monitoring systems in developing regions.

Air pollution is one of the main environmental issues globally, with direct impacts on human health, ecosystems, and the climate. It represents one of the major environmental threats of the 21st century due to its role in processes such as acid rain formation. This phenomenon occurs when pollutants such as SO_2 and NOx, emitted mainly from industrial, vehicular, and fossil fuel combustion sources, are transformed into acids in the atmosphere and incorporated into precipitation (Seinfeld and Pandis, 2016). Acid rain forms primarily due to the emission of SO_2 and NOx, which, upon reacting with water vapor in the atmosphere, form sulfuric and nitric acids, respectively (Vet et al., 2014). Deposition can occur as wet (via rain, snow, or fog) or dry (via particle and gas sedimentation), depending on prevailing meteorological conditions.

Atmospheric conditions significantly influence the transport, transformation, and removal of these pollutants. Variables such as temperature, wind speed and direction, and precipitation volume affect gas dispersion and subsequent deposition (Finlayson-Pitts and Pitts, 2000).

Recent studies have emphasized that despite global mitigation policies, acid deposition continues to represent an environmental and health concern, particularly in developing regions with intensive industrial activity (Vet et al., 2014; Sickle et al., 2019). The World Health Organization (2021) has reported that exposure to sulfur dioxide (SO_2) and nitrogen oxides (NOx) remains one of the major threats to respiratory and cardiovascular health. In addition, new analyses on precipitation chemistry (Zhao et al., 2020; Zhang et al., 2022) show that meteorological drivers such as temperature, rainfall patterns, and wind circulation are crucial for explaining spatial differences in acid rain occurrence. The results prove highlight the need for integrated monitoring frameworks and adaptive governance to regulate emissions in regions vulnerable to climatic variability, such as the coastal zones of Mexico.

From a health perspective, prolonged exposure to SO_2 and NOx has been linked to respiratory and cardiovascular diseases, especially in urban populations (World Health Organization, 2021).

In Mexico, various studies have documented the presence of acid rain, particularly in urban and industrial zones where transport, fossil fuel combustion, and heavy industry activities converge. In Mexico City, Garcés and Hernández (2004) reported elevated rain acidity levels associated with vehicle traffic and industrial emissions. Nationally, the National Institute of Ecology and Climate Change (Instituto Nacional de Ecología y Cambio Climático (INECC), 2018) has emphasized the importance of monitoring atmospheric deposition as a tool for evaluating ecosystem conditions and planning mitigation measures.

Acid rain causes significant environmental consequences, including soil and water acidification, essential nutrient leaching, and damage to vegetation and historical structures (Miranda, 2009; UNAM Global, 2020). In coastal areas such as Veracruz, where high agricultural productivity and the presence of mangroves and lagoon systems exist, the effects may be even more pronounced. The interaction between meteorological factors such as temperature, wind speed, and precipitation plays a key role in pollutant dispersion, transformation, and deposition. Nevertheless, few recent studies in the region have integrated a joint evaluation of atmospheric pollutants and their relationship with precipitation acidity, considering local meteorological conditions. Given this context, the present study focuses on analyzing the relationship between the evolution of atmospheric pollutants and the estimated acidity of precipitation in three representative cities on the coast of Veracruz: Xalapa, Veracruz, and Minatitlan during the 2020–2023 period, using a quantitative and geospatial approach integrating environmental and meteorological data.

METHODOLOGY

Study area

Figure 1 shows the macrolization map of the 3 cities selected for this study. The cities of Xalapa, Veracruz, and Minatitlan exhibit distinct physical and socioeconomic characteristics that influence

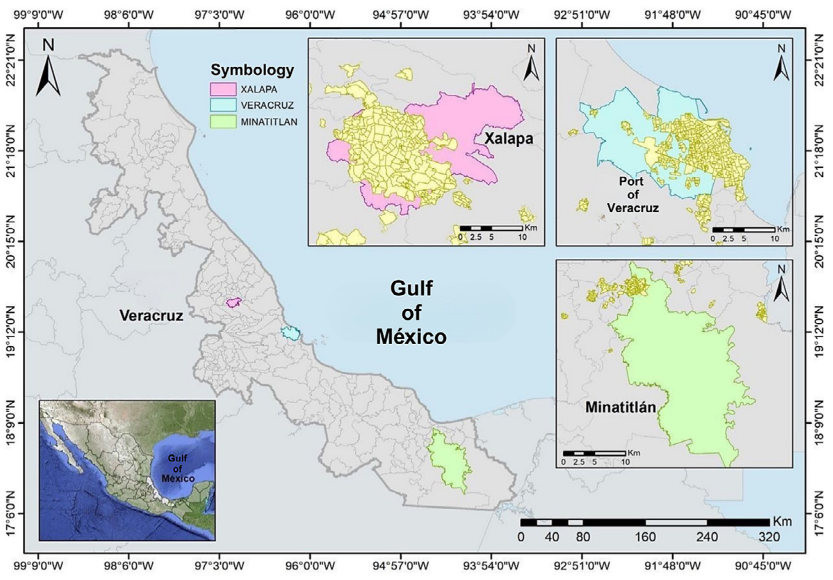

Figure 1. Macrolocation map of the cities of Veracruz, Xalapa and Minatitlán

local atmospheric dynamics. Xalapa, located in a mountainous area in the central part of the state, is characterized by a temperate humid climate, rugged topography, and an economy based on services, transportation, and public administration (Pereyra Díaz and García, 1990; Universidad Veracruzana, 2019). Veracruz, situated on the Gulf of Mexico coast, has a hot-humid climate, flat terrain, and an urban-industrial environment, featuring a major seaport, refineries, thermoelectric plants, and dense vehicular traffic (Martinez-Gonzalez et al., 2011; Secretaría del Medio Ambiente y Recursos Naturales (SEMARNAT, 2022).

Finally, Minatitlan is located in the southern coastal plain of the state, with a hot sub-humid climate. It constitutes a strategic industrial hub in the Isthmus of Tehuantepec petrochemical corridor, home to complexes such as La Cangrejera and Pajaritos, known for their industrial emissions (Martinez-Gonzalez et al., 2011; SEMARNAT, 2022). These topographic, climatic, and economic differences influence pollutant dispersion and accumulation, as well as acid rain formation and persistence in the region.

Limitations of rainwater pH estimation

During the analysis, no direct pH records of precipitation were available in the studied cities; the ranges obtained were compared with values reported in national and international literature. For example, studies in Mexico City have documented acidic episodes with values between 4.3 and 5.0 (Garcés and Hernández, 2004), similar to the minimum estimates for Veracruz and Minatitlán. Globally, databases such as the Acid Deposition Monitoring Network in East Asia (EANET) and the Global Atmosphere Watch (GAW-WMO) have reported intervals of 4.5–6.0 in industrial and coastal regions (Vet et al., 2014; Zhang et al., 2022), supporting the plausibility of our calculations. We acknowledge that local calibration through rain chemistry stations would be essential to improve reliability in future work.

In this study, precipitation pH was indirectly estimated from SO_2 and NOx using a constant k = 0.0001. This approach does not replace in situ rain chemistry measurements and carries uncertainty associated with oxidation, neutralization, and atmospheric transport processes, as well as precipitation seasonality and wind regimes. As internal verification, we recalculated pH with the same relationship and found discrepancies compared to expected values for acidic episodes in the region (≈4.5–6.0), reinforcing the need for local calibration or comparison with instrumental records in future studies. We also justified the use of k as a normalization value to maintain plausible ranges; however, its magnitude may vary due to gas absorption efficiency, conversion fractions, and meteorological conditions, so the results should be interpreted as comparative estimates and not as absolute measurements.

Air quality data

The data used in this study were obtained from the transparency platform of the Veracruz Environmental Secretariat (SEDEMA), which operates the Air Quality Monitoring System (SMCA) stations. The pollutants analyzed included SO_2, NOx, CO, O_3, and particulate matter (PM_{10} and PM_2.5). Additionally, the pH of precipitation was estimated, since direct records were unavailable. The estimation was based on SO_2 and NOx concentrations using an empirical relationship in which rain acidity is directly related to the H^+ ion concentration resulting from the dissolution and oxidation of these pollutants in the atmosphere (Likens and Bormann, 1974; Seinfeld and Pandis, 2016). The equation used was:

$$Estimared\ pH = -log_{10}(k \cdot (SO_2 + NO_x)) \quad (1)$$

where: k is an empirical constant encompassing factors such as gas absorption efficiency in water, the fraction converted to acid, and meteorological conditions affecting the conversion (Charlson and Rodhe, 1982). For comparative purposes and to maintain pH values within realistic atmospheric ranges, a normalized value of k = 0.0001 was adopted.

The data were processed using the pandas library in Python, grouped by station, year, and month, and the monthly average estimated pH was calculated for each location.

Complementary pollutants

In addition to SO_2 and NOx, O_3 and $PM_{2.5}/PM_{10}$ were evaluated as secondary explanatory variables given their potential influence on photochemical processes and on the neutralization/contribution of acidic and basic species. These pollutants are used to contextualize the variability of the estimated pH and not to infer direct causal relationships.

Meteorological data

The meteorological variables considered included monthly average temperature, total monthly precipitation, and wind speed and direction. These data were provided by the National Water Commission (CONAGUA) through the Transparency Portal. These variables were used to evaluate dispersion via wind and deposition based on precipitation and previously estimated pH.

Statistical analysis

Time series were analyzed to identify monthly and annual trends in pollutants and estimated pH. Pearson and Spearman correlations were applied to assess the relationship between atmospheric variables (SO_2 and NO_x), meteorological parameters (temperature, precipitation, wind), and precipitation acidity.

RESULTS AND DISCUSSIONS

Comparison with recent international studies allows contextualization of our results. Brontowiyono et al. (2022) found that in tropical urban areas, pollutant dynamics are strongly modulated by vehicular activity and meteorological variability, consistent with what was observed in Xalapa. Likewise, Puari et al. (2025) showed that the interaction of multiple pollutants in urban and industrial environments generates cumulative ecological risks, supporting the need to broaden the focus beyond SO_2 and NOx to include other secondary pollutants.

Air quality trends (2020–2023)

This study evaluated the evolution of air quality and its relationship with precipitation acidity in three coastal cities of Veracruz (Xalapa, Veracruz, and Minatitlán) during the 2020–2023 period. The results revealed that the highest SO_2 and NO_x concentrations occurred in Veracruz and Minatitlán, correlating with lower precipitation pH values and greater incidence of acid rain. In contrast, Xalapa presented lower pollutant levels and more stable acidity conditions, influenced by its topography and lower industrial activity. The evidence supports are consistent with Vet et al. (2014), Zhang et al. (2022), and Pereyra and García (1990), who highlighted the role of industrial and local emissions in precipitation chemistry.

During the 2020–2023 period, annual concentrations of SO_2, NO_x, and estimated rainfall pH were analyzed in the cities of Xalapa, Veracruz, and Minatitlan. The results presented, show differentiated evolution by city, influenced by emission sources and meteorological conditions.

The results from Table 1, show differentiated behavior of pollutants in the three studied cities. In Minatitlán, SO_2 reached values of 6.1 ppb in 2020 and 6.2 ppb in 2023, reflecting the persistence of emissions linked to the petrochemical corridor. Veracruz presented lower values (0.12 ppb in 2020 to 1.49 ppb in 2022), while Xalapa showed a maximum of 3.7 ppb in 2021 and decreases to 0.7–0.8 ppb in 2022–2023. Figure 2 indicates an inverse relationship between SO_2/NO_x levels and estimated rainfall pH, with greater acidity during months with higher pollutant concentrations. Veracruz showed consistently higher

Table 1. Annual average concentrations of pollutants by city

City	Year	SO_2 (ppb)	NO_X (ppb)	NO_2 (ppb)	CO (ppm)	pH
MINATITLAN	2020	6.10066714	9.94895993	6.50785689	0.60237214	4.96089989
MINATITLAN	2021	5.04984804	9.30958888	4.988988	0.6995244	5.03599152
MINATITLAN	2022	3.5153041	17.0458696	5.95369037	0	4.93411872
MINATITLAN	2023	6.21616464	2.49622582	0.99107287	0	5.02311415
VERACRUZ	2020	0.12007874	2.09268484	1.25117481	0.03575908	4.85396336
VERACRUZ	2021	1.02027291	13.4212307	8.69358048	0.38073613	5.11799859
VERACRUZ	2022	1.4947863	16.8351348	8.68098735	0.14321894	5.02290712
VERACRUZ	2023	0.78225224	16.9003162	9.24084855	0.44156589	5.05750212
XALAPA	2020	1.28719737	0	13.6431772	0.7792252	5.84691949
XALAPA	2021	3.69439767	29.7097332	10.7435696	0.85667559	4.79466965
XALAPA	2022	0.73806255	0	0	0.96614574	5.65532443
XALAPA	2023	0.84143228	0	0	0.61681702	5.59944153

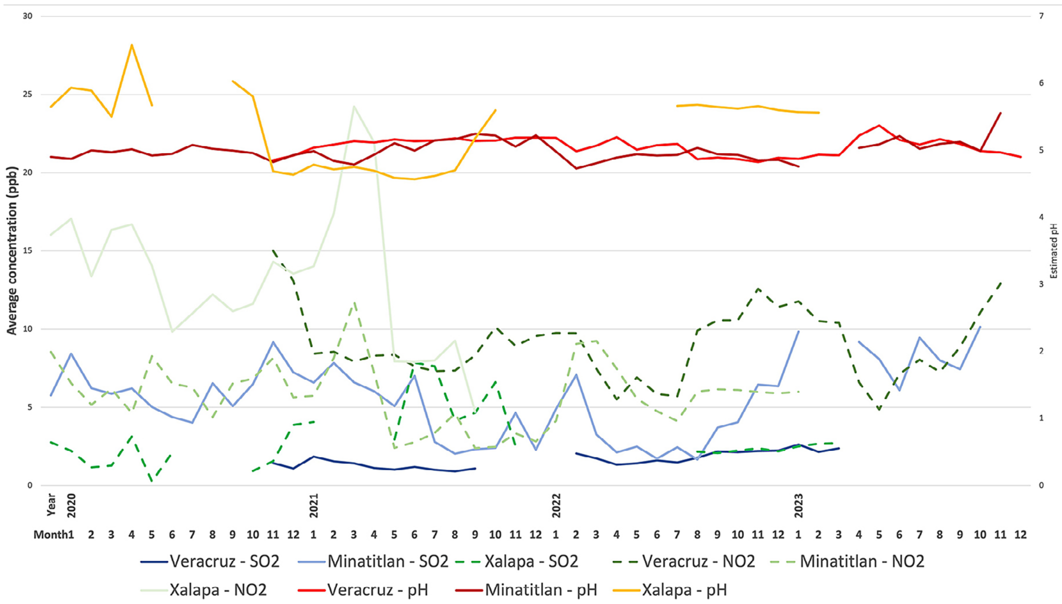

Figure 2. Evolution of SO_2, NO_x and pH of rain in each city

SO_2 concentrations and the lowest pH values. Minatitlan stood out for elevated SO_2 levels (likely linked to petrochemical activity), while Xalapa exhibited lower pollutant levels and more stable pH values. It's important to note that not all months contain information on pollutant concentrations, hence the cutoff point on the graph.

The estimated pH confirmed acid rain episodes in Veracruz (minimums of 4.85 in 2020 and 5.02 in 2022) and in Minatitlán (4.93 in 2022 and 5.02 in 2021). In contrast, Xalapa maintained more stable values (5.65 in 2022; 5.60 in 2023). These inverse patterns between SO_2/NO_x and pH agree with findings reported by Vet et al. (2014) and Zhang et al. (2022), who indicated that values below 5.0 confirm acidification episodes.

Figure 3 shows clear differences between industrial and urban areas. Minatitlán maintained high levels of SO_2 (3.5–6.2 ppb), compared to much lower values in Veracruz (0.12–1.49 ppb) and Xalapa (0.7–3.7 ppb). This aligns with the presence of petrochemical complexes previously noted by González et al. (2020).

Regarding NOx, Xalapa stood out with 29.7 ppb in 2021, likely due to vehicular emissions and its mountainous topography. Veracruz showed progressive increases (2.1 ppb in 2020 to 16.9 ppb in 2023), while Minatitlán showed a decrease

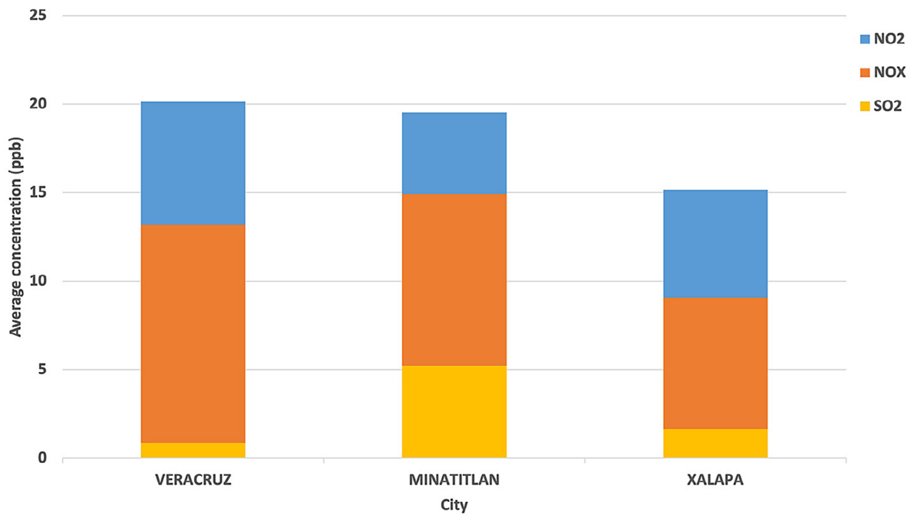

Figure 3. Comparison of pollutant levels between Veracruz, Xalapa and Minatitlan of the state of Veracruz, Mexico

to 2.49 ppb in 2023 after a high value in 2022. These results reinforce the differential influence of mobile and industrial sources.

Relevant meteorological variations

Meteorological factors such as wind speed and precipitation played a decisive role in pollutant dispersion and deposition, with Veracruz showing better atmospheric ventilation compared to the more enclosed conditions in Xalapa and Minatitlán. Regression analysis confirmed the significant contribution of SO_2 and NO_x to rain acidification, underscoring their role as main precursors of acid rain in the region (Charlson and Rodhe, 1982; Zhao et al., 2020; Liu et al., 2023).

Table 2 shows that during the 2020–2023 period, significant meteorological variations occurred in the three analyzed cities from the state of Veracruz in Mexico.

Table 2 and Figure 4 show that meteorological conditions are decisive in the dispersion of pollutants. Veracruz recorded high winds (~18–19 km/h), which favors atmospheric ventilation. In contrast, Xalapa and Minatitlán had low wind speeds (<3 km/h), which explains the local accumulation and associated acidic episodes.

Precipitation showed summer peaks, with maximums of 0.106 m in Xalapa in 2021, confirming the role of wet deposition in pollutant removal (Vet et al., 2014). Temperature remained stable in Veracruz (25–26 °C), while in Xalapa it dropped to 15.5 °C in 2022 and 13.9 °C in 2023, reinforcing the combined effect of humidity and cloud cover on dispersion (Zhao et al., 2020).

The wind rose diagrams in Figure 4 provide not only information on average wind speed but also on the predominant directions of air flows in each city. In Veracruz, winds were stronger (~18–19 km/h) and mainly came from the northeast and east, consistent with the influence of trade winds and coastal sea breezes. This pattern promotes continuous dispersion of pollutants

Table 2. Annual meteorological parameters temperature, wind speed and precipitation in the study cities of the state of Veracruz in Mexico

City	Year	Temperature (°C)	Precipitation (mm)	Wind (Km/H)
MINATITLAN	2020	26.43256725	0.001882822	3
MINATITLAN	2021	27.44216982	0.009480272	0.42804518
MINATITLAN	2022	25.28284385	0.081395208	2.36252589
MINATITLAN	2023	24.38625181	0.000289436	0
VERACRUZ	2020	26.03522424	0.038602973	19.0007353
VERACRUZ	2021	25.63019631	0.027685568	18.0571151
VERACRUZ	2022	25.11789483	0.028549387	18.5537267
VERACRUZ	2023	25.64918549	0.007242008	18.8231302
XALAPA	2020	22.4242893	0.007623868	1.78094704
XALAPA	2021	22.80541465	0.10638784	1.73205135
XALAPA	2022	15.54184096	0.005134881	0.42985023
XALAPA	2023	13.94913523	0.00420383	3.68328093

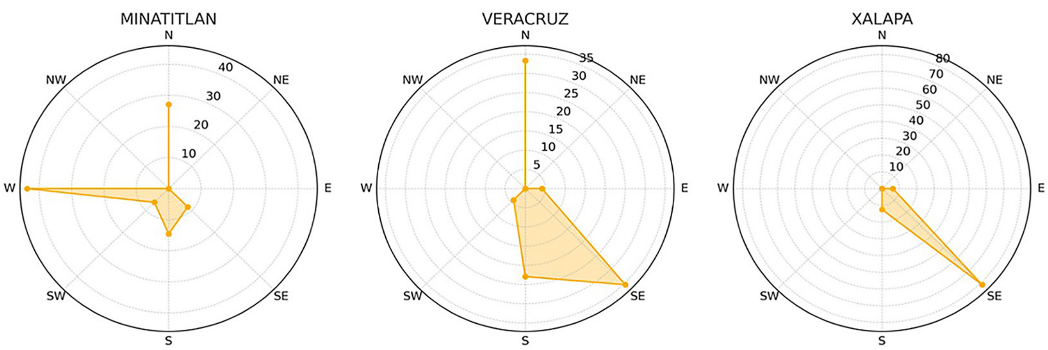

Figure 4. Wind diagrams for each city

towards inland areas and reduces local accumulation, although it may also transport contaminants to nearby urban and agricultural zones (Seinfeld and Pandis, 2016; Li et al., 2021).

In contrast, Xalapa showed weak winds (<3 km/h) predominantly from the north and northwest, which, combined with its mountainous topography, contributes to the stagnation of air masses and favors local accumulation of SO_2 and NO_x. This explains why, despite lower emission levels compared to industrial cities, episodes of acid precipitation were still recorded (Castro et al., 2001; Jacob, 1999). Minatitlán also presented low wind speeds (<3 km/h), with directions mainly from the south and southwest, coinciding with the location of petrochemical facilities. This indicates a direct influence of industrial emissions on local air quality and precipitation chemistry (Zhang et al., 2018).

These results highlight that wind direction, in addition to speed, plays a critical role in defining pollutant dispersion and deposition patterns, in line with observations in other coastal and industrialized regions of the world (Zhao et al., 2020; Lee et al., 2022).

Relationship between air quality and precipitation acidity

This work represents one of the first integrated analyses of atmospheric pollutants and precipitation acidity in Mexico during the 2020–2023 period. While recent research in Brazil (Panwar et al., 2021), Colombia, and Chile has reported gradual decreases in rain acidity associated with industrial regulations, in Veracruz the results show that the SO_2 signal remains strong, particularly in Minatitlán. This differentiates the region from the international pattern of transition toward a greater relative weight of NOx, observed in Asia and Europe (Li et al., 2021; Zhang et al., 2018). Thus, our findings provide novel evidence for Latin America by showing the combined influence of industrial sources and coastal meteorological conditions in acid rain formation.

In mountainous and humid regions like Xalapa, topography can promote the accumulation of pollutants, whereas in coastal areas such as Veracruz, wind may facilitate their dispersion. The environmental effects of acid rain include soil and water body acidification, nutrient loss, vegetation damage, and corrosion of historical monuments (Likens and Bormann, 1974; UNAM Global, 2020).

Figure 5 showed the pH distribution in each city. Veracruz presented the lowest median (~5.0) and extreme values below 4.8, confirming severe acid rain episodes. Minatitlán also showed critical values (4.93 in 2022), while Xalapa maintained medians above 5.5 with less variability. These results are comparable with industrialized regions of Asia (Panwar et al., 2021; Sickle et al., 2019) and reinforce the risks for local ecosystems such as mangroves, lagoons, and cloud forests (Miranda, 2009; UNAM Global, 2020).

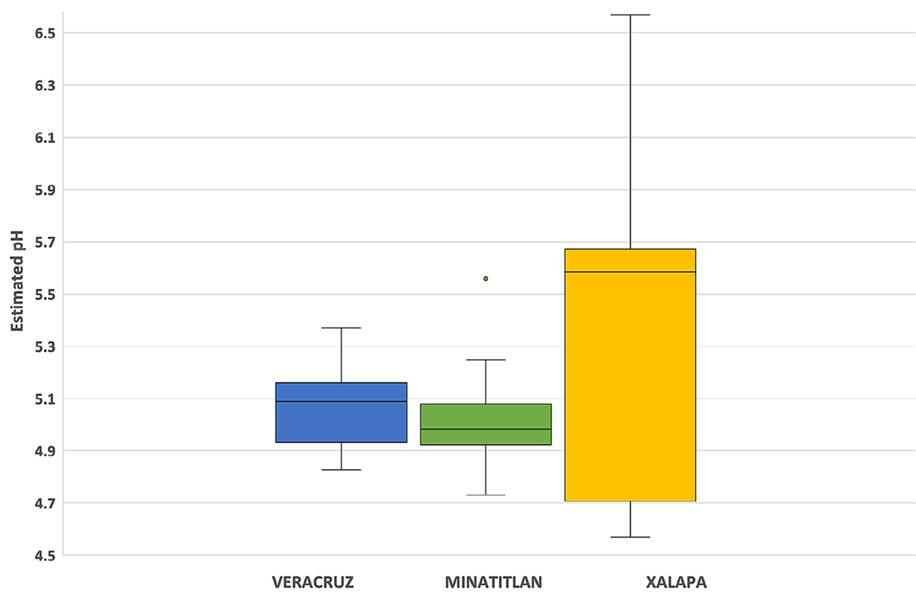

Figure 5. pH distribution of rainfall

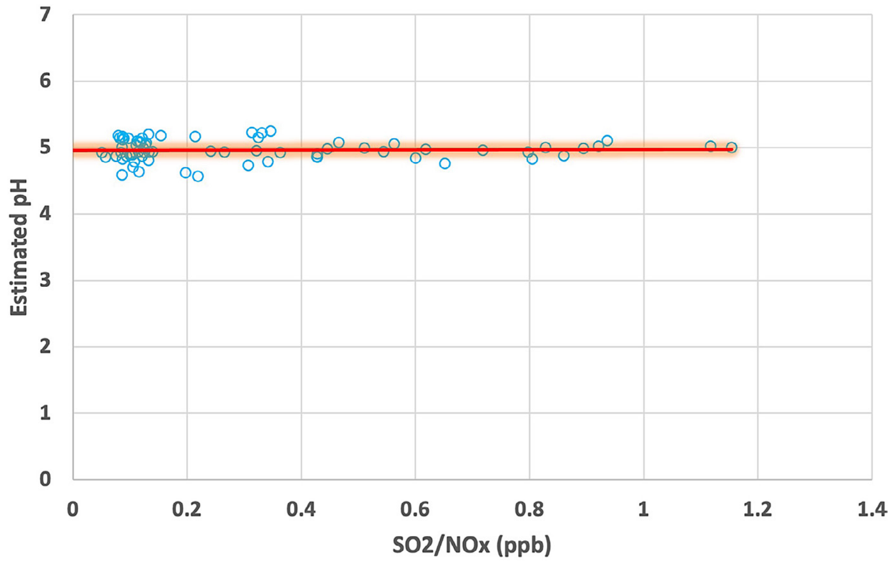

Figure 6. Regression analysis for pH prediction as a function of SO_2/NO_x

The regression analysis in Figure 6 revealed a slightly negative slope, indicating that an increase in the proportion of SO_2 relative to NO_x is associated with a reduction in rainwater pH. Although the correlation was weak, the results highlight that SO_2 exerts a stronger influence on acidification compared to NO_x. For instance, in Minatitlán, when SO_2 levels rose to 6.2 ppb in 2023, rainwater pH decreased to 5.02, whereas in Xalapa, with much lower SO_2 concentrations (~0.7–0.8 ppb), pH values remained more stable (~5.6). This pattern confirms the predominance of SO_2 in the formation of sulfuric acid (H_2SO_4) in the atmosphere, as established by classical studies (Charlson and Rodhe, 1982; Seinfeld and Pandis, 2016). However, the weak slope of the regression suggests that additional factors such as ozone (O_3), particulate matter ($PM_{2.5}$), and meteorological variables (humidity, temperature) play a complementary role in determining the final acidity of precipitation (Liu et al., 2023; Li et al., 2021).

Comparisons with international case studies reinforce these observations. In East Asia, Li et al. (2021) reported that SO_2 dominates the acidification process under industrial and coastal conditions, while NO_x contributes more significantly in densely urbanized regions with strong photochemical activity. Similarly, Zhang et al. (2018) highlighted that in China, the shift from SO_2 to NO_x dominance occurred only after significant desulfurization measures were implemented. In Mexico, however, industrial hubs such as Minatitlán still show a strong sulfur signal, underscoring the importance of controlling SO_2 emissions as a priority strategy for mitigating acid rain.

Strength of association and confounding factors

The inverse relationship between SO_2/NOx and rainwater pH was statistically weak in several periods; therefore, we avoided overinterpretation and discussed factors that may mask or modulate it: relative humidity, precipitation intensity (wet deposition), presence of fine aerosols ($PM_{2.5}$), and photochemical processes (e.g., nitrate formation). These variables explain differences between coastal and inland cities and between urban and industrial areas.

In the state of Veracruz specifically in the cities of Xalapa, Veracruz, and Minatitlán, critical factors converge such as industrial activity, accelerated urbanization, and humid weather conditions, making them prone to acid rain phenomena. Pioneering studies such as Pereyra and García (1990) already warned of acid rain in Xalapa, attributed to local emissions. More recently, the Universidad Veracruzana and the Veracruz Environmental Secretariat have highlighted the need to expand atmospheric pollutant monitoring and its interaction with the local climate. From a regional perspective, González et al. (2011) analyzed the influence of industrial sources on air quality in Gulf of Mexico coastal areas, revealing patterns similar to those observed in Veracruz and Minatitlán. This is supported by findings from Miranda (2009), who emphasized the impact of acid rain on forest ecosystems, which are highly sensitive to soil pH variations. The analysis of air quality evolution in the coastal cities of Veracruz, Xalapa, and Minatitlán revealed marked spatial and temporal variability of atmospheric pollutants. Trends showed that Veracruz and Minatitlán recorded the highest SO_2 and NOx concentrations, while Xalapa maintained lower and more stable values, reflecting differences in the impact of industrial and urban activities.

The relationship between air quality and precipitation acidity was clear: elevated concentrations of SO_2 and NOx were associated with lower pH values, confirming the role of these gases as the main precursors of acid rain in the region. This pattern is consistent with the findings of Charlson and Rodhe (1982), who identified SO_2 as the dominant driver of atmospheric acidification, and with the global assessments of Vet et al. (2014) and Zhang et al. (2022), which documented the direct link between sulfur/nitrogen concentrations and decreases in precipitation pH.

Similarly, studies conducted in Mexico (Miranda, 2009; Pereyra and García, 1990) had already warned that the interaction of industrial and urban emissions in coastal and mountainous regions promotes acid rain episodes, in agreement with the observations from Veracruz and Minatitlán.

CONCLUSIONS

These results can guide concrete actions in the state of Veracruz, Mexico, such as strengthening the enforcement of NOM-156-SEMARNAT in industrial sectors with high SO_2 emissions. Implementing a state-level precipitation chemistry monitoring program similar to networks established by the EPA in the United States and by EANET in Asia, and integrating air quality management with urban planning and mobility policies in Xalapa. Such measures would not only validate and expand the environmental database but also generate mitigation strategies tailored to the local context.

The results of this study underscore that in industrial areas such as Minatitlán, SO_2 reduction should be prioritized; in urban areas with complex topography such as Xalapa, it is advisable to strengthen traffic management and urban ventilation. In the coastal strip of Veracruz, it is necessary to consolidate a precipitation chemistry monitoring program (pH and major ions) that allows validation and calibration of estimates. It is also necessary to expand the monitoring network, integrate high-resolution meteorological variables, and adopt updated emission inventories to support management decisions.

Meteorological variations played a decisive role in the dispersion and deposition of pollutants. Factors such as wind speed and direction, as well as rainfall intensity, directly influenced the accumulation or ventilation of contaminants, modulating the acidity conditions of rain.

The results prove highlight the need for integrated monitoring of atmospheric pollutants and meteorological variables to better understand local acidification patterns and to support environmental management in coastal areas. Future work should also consider the role of O_3 and PM2.5, which may influence precipitation chemistry

Comparing such environmental data worldwide provides valuable insights into how productive activities impact ecosystems and society. Such knowledge supports governance and regulatory decision-making on emissions management at both local and global scales.

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REFERENCES

1. Brontowiyono, W., Sihayuardhi, E.R., et al. (2022). distribution patterns of ambient air quality pre- and during pandemic in the urban area of Yogyakarta, Indonesia. *Journal of Ecological Engineering, 23*(10), 116–128. https://doi.org/10.12911/22998993/154119
2. Castro, T., Madronich, S., Rivale, S., Muhlia, A., Mar, B. (2001). The influence of meteorological conditions on air quality in Mexico City. *Atmospheric Environment, 35*(10), 1765–1778. https://doi.org/10.1016/S1352-2310(00)00449-4
3. Charlson, R. J., Rodhe, H. (1982). Factors controlling the acidity of natural rainwater. *Nature, 295*(5851), 683–685. https://doi.org/10.1038/295683a0
4. EANET. (2020). *Annual Report on the Acid Deposition Monitoring Network in East Asia*. Acid Deposition Monitoring Network in East Asia (EANET), Niigata, Japan. https://www.eanet.asia/
5. Finlayson-Pitts, B. J., Pitts, J. N. (2000). Chemistry of the upper and lower atmosphere: Theory, experiments, and applications. Academic Press.

6. Garcés, C., Hernández, M. (2004). *Acid rain in the Metropolitan Area of Mexico City*. Universidad Nacional Autónoma de México.
7. González, A., Casas-Leuro, O.-M., Acero-Reyes, J.-R., Castillo-Monroy, E.-F. (2011). Comparison of potential environmental impacts on the production and use of high and low sulfur regular diesel by life cycle assessment. *CT&F – Ciencia, Tecnología y Futuro, 4*(4), 123–136. https://doi.org/10.29047/01225383.233
8. Instituto Nacional de Ecología y Cambio Climático (INECC). (2018). *State-of-the-art analysis on atmospheric deposition in Mexico and its environmental impact.* Gobierno de México.
9. Jacob, D. J. (1999). *Introduction to atmospheric chemistry*. Princeton University Press.
10. Lee, J. Y., Choi, H., Kim, M., Kim, Y. (2022). Impacts of reduced human activities due to COVID-19 on air quality and precipitation chemistry in coastal East Asia. *Environmental Pollution, 292*, 118300. https://doi.org/10.1016/j.envpol.2021.118300
11. Li, Y., Tang, J., Xie, Y. (2021). Transport pathways and meteorological influences on acid rain in East Asia. *Science of the Total Environment, 762*, 143138. https://doi.org/10.1016/j.scitotenv.2020.143138
12. Likens, G. E., Bormann, F. H. (1974). Acid rain: A serious regional environmental problem. *Science, 184*(4142), 1176–1179. https://doi.org/10.1126/science.184.4142.1176
13. Liu, Y., Wang, X., Zhang, L., Fangmeier, A. (2023). Long-term global changes in precipitation acidity and implications for ecosystems. *Science of the Total Environment, 856*, 159085. https://doi.org/10.1016/j.scitotenv.2022.159085
14. Miranda, A. (2009). Acid rain and forest ecosystems. *Revista Mexicana de Ciencias Forestales, 1*(1), 25–36.
15. Panwar, D., Sinha, A., Khillare, P. S. (2021). Assessment of acid deposition trends in an industrial region of India: Role of SO_2, NOx and meteorological factors. *Atmospheric Environment, 246*, 118077. https://doi.org/10.1016/j.atmosenv.2020.118077
16. Pereyra Díaz, D., García, J. A. (1990). *Rainwater acidity in Xalapa, Veracruz*. La Ciencia y El Hombre.
17. Puari, A.T., et al. (2025). Contamination level of heavy metals and assessment of ecological risk in sediments. *Journal of Ecological Engineering, 26*(3), 283–295. https://doi.org/10.12911/22998993/199978
18. Secretaría del Medio Ambiente y Recursos Naturales (SEMARNAT). (2022). *Inventario Nacional de Emisiones de México 2019*. Gobierno de México.
19. Seinfeld, J. H., Pandis, S. N. (2016). *Atmospheric chemistry and physics: From air pollution to climate change (3rd ed.)*. John Wiley & Sons.
20. Shihab, A.S. (2021). Assessment of ambient air quality of Mosul city via air quality index. *Journal of Ecological Engineering, 22*(10), 241–250. https://doi.org/10.12911/22998993/142448
21. Sickle, M. C., Wang, S., Zhang, Y. (2019). Acid deposition in rapidly industrializing regions: A review of recent trends and emerging issues. *Environmental Pollution, 252*, 1040–1051. https://doi.org/10.1016/j.envpol.2019.05.114
22. UNAM Global. (2020). *Acid rain deteriorates historical monuments.* Universidad Nacional Autónoma de México.
23. Universidad Veracruzana. (2019). Air pollution in Xalapa. Universidad Veracruzana.
24. Vet, R., Artz, R. S., Carou, S., Shaw, M., Ro, C.-U., Aas, W., Galbally, I. E. (2014). A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. *Atmospheric Environment, 93*, 3–100. https://doi.org/10.1016/j.atmosenv.2013.10.060
25. World Health Organization (WHO). (2021). *WHO global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. WHO. https://www.who.int/publications/i/item/9789240034228
26. World Meteorological Organization (WMO). (2022). *Global Atmosphere Watch (GAW) Report: Monitoring and Assessment of Precipitation Chemistry*. WMO-No. 1287, Geneva, Switzerland. https://public.wmo.int/en/programmes/global-atmosphere-watch
27. Zhang, Y., Liu, X., Fangmeier, A., Goulding, K., Sutton, M. A. (2018). Nitrogen deposition and its ecological impact in China: A critical review. *Environmental Pollution, 246*, 394–407. https://doi.org/10.1016/j.envpol.2018.11.067
28. Zhang, L., Liu, X., Fangmeier, A. (2022). Global change and acid deposition: Current status and future challenges. *Science of the Total Environment, 815*, 152–169. https://doi.org/10.1016/j.scitotenv.2022.152169
29. Zhao, Y., Huang, J., Chen, X. (2020). Atmospheric deposition and its relationship with meteorological factors in East Asia. *Atmospheric Environment, 223*, 117–129. https://doi.org/10.1016/j.atmosenv.2019.117129