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Air Quality in Rural Settings and Chemical Exposure in Healthcare Facilities: A Comparative Environmental Health Analysis

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ABSTRACT

This study explores the pharmacognostic and analytical profiles of *Calotropis procera* and *Zanthoxylum decaryi*, focusing on the synergistic role of their mineral and organic constituents in managing diabetes mellitus. Utilizing Total Reflection X-Ray Fluorescence (TXRF) and Fourier-Transform Infrared (FT-IR) spectroscopy, we characterized the elemental distribution and functional group landscapes of both species. Results reveal a significant macro-elemental density in *C. procera*, notably dominated by Potassium (6.77%) and Magnesium (1.76%), facilitating energy metabolism and cellular signaling. In contrast, *Z. decaryi* demonstrates a superior catalytic trace element profile, with a high concentration of Magnesium (2.22%) and the exclusive presence of Manganese (0.04%) and Selenium (0.01%), alongside Chromium (0.07%). These values correlate directly with enhanced insulin sensitivity and robust antioxidant defense mechanisms. FT-IR spectra indicate an intricate organometallic synergy between these minerals and bioactive secondary metabolites, such as triterpenoids and alkaloids. Mechanistically, these assemblies are implicated in the modulation of the PI3K/Akt pathway and the promotion of GLUT4 translocation, while shielding pancreatic *b*-cells via enzymatic redox regulation. This research provides a rigorous scientific foundation for the combined traditional use of these plants and advocates for the integration of mineral profiling into the standardization protocols for metabolic botanical therapies.

Keywords : TXRF; insulinomimetic minerals; organometallic synergy; oxidative stress modulation; pharmacognostic.

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1. INTRODUCTION

Air pollution is now widely recognized as one of the major environmental determinants of human health. According to the World Health Organization, chronic exposure to atmospheric pollutants contributes significantly to morbidity and mortality related to respiratory, cardiovascular, and neurological diseases, accounting for several million premature deaths worldwide each year (WHO, 2021). The underlying pathophysiological mechanisms include airway inflammation, oxidative stress, impaired pulmonary function, and systemic effects on the cardiovascular system. Historically, scientific research has focused primarily on urban environments, characterized by a high density of pollution sources such as road traffic, industrial activities, and domestic combustion, while rural areas have generally been considered low-exposure settings with reduced health risks.

However, this binary opposition between polluted urban areas and preserved rural environments tends to oversimplify the reality of environmental exposures. Rural areas are not free from pollution sources, particularly those related to biomass combustion, agricultural practices, and domestic activities. Moreover, certain specific environments, regardless of their geographical location, may present high levels of exposure to chemical agents. Healthcare facilities represent such environments, where indoor air quality may be affected by the regular and intensive use of chemical products such as disinfectants, solvents, anesthetic agents, sterilization compounds, and cleaning products. Several studies have shown that these substances can degrade indoor air quality and are associated with health effects such as ocular irritation, respiratory disorders, headaches, and neurological symptoms, particularly under repeated or prolonged exposure conditions (EPA, 2024).

In this context, air quality assessment cannot be limited to a simple comparison between rural and urban areas, but must integrate the diversity of exposure environments, particularly enclosed healthcare settings. This study adopts such an approach by comparing outdoor air quality in rural areas with atmospheric exposure to chemical products in healthcare facilities. The objective is to identify and compare the relative health risks associated with these two exposure contexts and to contribute to a better understanding of environmental health issues, thereby informing prevention strategies and air quality management policies in both rural environments and healthcare infrastructures.

2. MATERIALS AND METHODS

2.1 Environmental Data in Rural Areas

Environmental data were collected in rural areas selected based on criteria including low population density, absence of major industrial activities, and predominance of agricultural practices. These areas are representative of typical rural environments, where atmospheric emission sources are mainly diffuse and related to agricultural activities, domestic biomass use (wood, charcoal), and low-intensity motorized transport. The selection of these sites aimed to establish a reference level of outdoor air quality in rural settings, enabling meaningful comparison with other exposure contexts, particularly indoor environments in healthcare facilities.

The atmospheric pollutants analyzed included fine particulate matter with aerodynamic diameters $\leq 2.5 \mu\text{m}$ (PM_{2.5}) and $\leq 10 \mu\text{m}$ (PM₁₀), nitrogen dioxide (NO₂), and carbon

monoxide (CO). These pollutants were selected due to their recognized importance in environmental health and their well-documented associations with respiratory and cardiovascular effects (WHO, 2021). Concentrations were measured using calibrated portable instruments compliant with international air quality monitoring recommendations, ensuring data reliability and comparability.

Measurement campaigns followed a standardized protocol incorporating both seasonal and diurnal dimensions. Two contrasting climatic periods were considered—the wet season and the dry season—to account for the influence of meteorological conditions on pollutant dispersion and accumulation. For each season, measurements were conducted at two fixed time points (10:00 a.m. and 6:00 p.m.), corresponding to periods of moderate and higher activity levels, respectively. This temporal framework captured major daily and seasonal variations in atmospheric concentrations while ensuring sufficient coverage for subsequent comparative statistical analyses.

2.2 Health Data and Exposure Assessment in Healthcare Facilities

Health data were collected through structured surveys administered to healthcare personnel (physicians, nurses, nursing assistants, cleaning staff) and users of selected healthcare facilities. The surveys aimed to document the prevalence and frequency of symptoms potentially associated with indoor air quality, including respiratory symptoms (cough, breathing discomfort, shortness of breath), ocular irritation, and headaches. Data were collected in a standardized manner using face-to-face questionnaires to ensure consistency and minimize reporting bias. Symptoms were coded using a binary scale (presence/absence) and, when possible, according to self-reported frequency over a defined reference period.

In parallel with health data collection, a qualitative and quantitative assessment of chemical exposure was conducted within healthcare facilities. This assessment involved identifying the main categories of substances used in daily activities, including surface disinfectants, alcohol-based solutions, solvents, cleaning products, and agents used for sterilization or anesthesia. The inventory of these products was compiled from internal records and staff interviews in order to characterize potential sources of VOC emissions in indoor air.

Indicative measurements of VOC concentrations were then performed in different areas of the facilities (treatment rooms, corridors, waiting areas), taking into account representative activity periods. These measurements provided estimates of atmospheric exposure to chemical compounds in healthcare environments and allowed examination of their associations with reported symptoms. The combined integration of health data and chemical exposure indicators thus provided a robust analytical basis for comparing risks associated with indoor air in healthcare facilities and outdoor air quality in rural environments from an environmental health perspective.

2.3 Statistical Analyses

Statistical analyses were conducted to characterize environmental exposure levels and examine their relationships with health indicators. First, descriptive statistics were calculated for all variables, including means, medians, standard deviations, and extreme values for atmospheric pollutant concentrations measured in rural areas and indicative VOC concentrations in

healthcare facilities. Similarly, the frequency and prevalence of reported health symptoms were described to provide an overall picture of perceived health status among exposed populations.

Second, correlation analyses were performed to explore relationships between pollution levels and reported symptoms. Depending on variable distributions, parametric or non-parametric correlation coefficients were used to assess the strength and direction of associations between pollutant concentrations ($PM_{2.5}$, PM_{10} , NO_2 , CO, and VOCs) and health indicators (respiratory symptoms, ocular irritation, headaches). These preliminary analyses informed variable selection for subsequent explanatory models.

Finally, logistic regression models were estimated to assess the probability of symptom occurrence as a function of pollutant exposure levels, controlling for potential confounding factors. Dependent variables corresponded to the presence or absence of specific symptoms, while independent variables included measured pollution levels and control factors such as facility type, daily exposure duration, and available sociodemographic characteristics. Model results are presented as odds ratios with confidence intervals, enabling interpretation of the relationship between environmental exposure and health risk in a comparative framework between rural settings and healthcare environments.

3. RESULTS

3.1 Air Quality in Rural Areas

Measurements conducted in rural environments indicate that the concentrations of the main atmospheric pollutants examined generally remain below the guideline values recommended by the World Health Organization. Mean levels of $PM_{2.5}$ and PM_{10} reflect moderate exposure to fine particulate matter, while NO_2 and CO concentrations remain low, reflecting the absence of major emission sources related to road traffic and industrial activities. These findings confirm that the rural areas studied exhibit overall satisfactory outdoor air quality throughout the observation period.

However, seasonal variability is observed. The dry season is characterized by a slight increase in $PM_{2.5}$ and PM_{10} concentrations, likely attributable to dust resuspension, agricultural burning, and domestic biomass use. This increase remains moderate and does not lead to systematic exceedances of health-based thresholds. In contrast, the wet season shows lower concentrations, due to atmospheric washout effects associated with precipitation. These variations highlight the role of meteorological conditions in shaping pollutant dynamics in rural environments.

Table 1. Mean concentrations of atmospheric pollutants in rural areas (2023–2024)

Pollutant	Wet season ($\mu\text{g}/\text{m}^3$ or ppm)	Dry season ($\mu\text{g}/\text{m}^3$ or ppm)	WHO guideline value
$PM_{2.5}$	8–10	12–15	15 (24 h)
PM_{10}	15–20	25–30	45 (24 h)
NO_2	5–10	8–12	25 (24 h)
CO	< 1	< 1.5	4 (24 h)

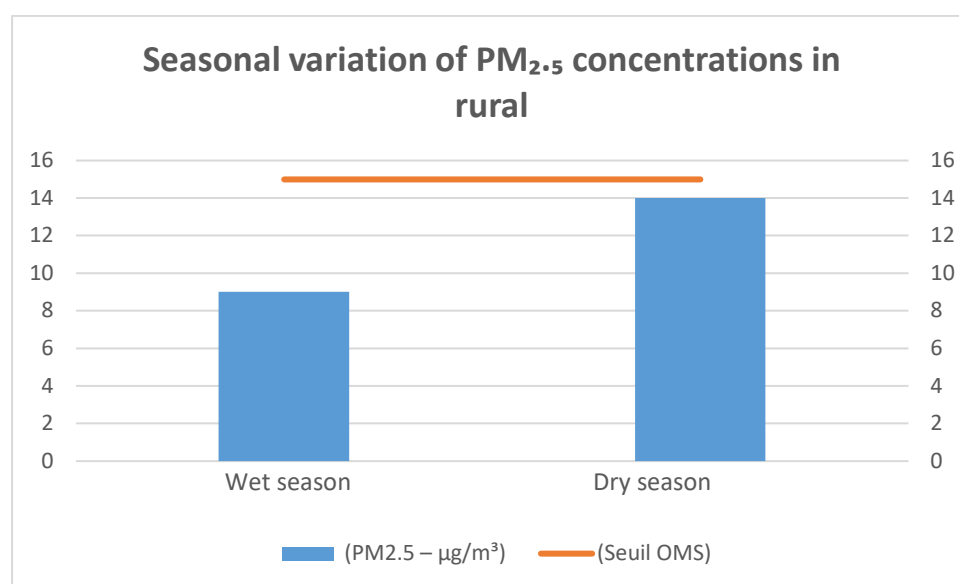
Source: Measurement campaigns, 2023–2024.

The table highlights that mean concentrations of atmospheric pollutants in rural settings remain below World Health Organization guideline values for all parameters considered. PM_{2.5} levels range from 8 to 10 µg/m³ during the wet season and from 12 to 15 µg/m³ during the dry season. This seasonal pattern reflects a moderate increase in fine particulate matter during the dry period, while remaining close to—or slightly below—the WHO 24-hour guideline of 15 µg/m³. These results suggest relatively low chronic exposure, with no indication of acute health risk for the rural populations studied.

PM₁₀ concentrations show a similar pattern, with values between 15 and 20 µg/m³ in the wet season and between 25 and 30 µg/m³ in the dry season, well below the WHO guideline value of 45 µg/m³. This seasonal increase may be attributed to dust resuspension, agricultural activities, and biomass use for cooking. However, the magnitude of variation remains limited, confirming the absence of major particulate emission sources in rural environments. NO₂ levels, ranging from 5 to 12 µg/m³ depending on the season, remain far below the WHO threshold of 25 µg/m³, indicating minimal influence from traffic-related emissions or fossil fuel combustion.

Finally, carbon monoxide (CO) concentrations remain low throughout the study period, with values below 1.5 ppm, well under the WHO guideline value of 4 ppm. This finding indicates the absence of significant incomplete combustion processes and further confirms the good quality of outdoor air in rural environments. Overall, the data presented in the table support the conclusion that rural areas maintain relatively preserved atmospheric conditions, while underscoring the importance of seasonal factors in influencing concentration variability, even at non-critical levels.

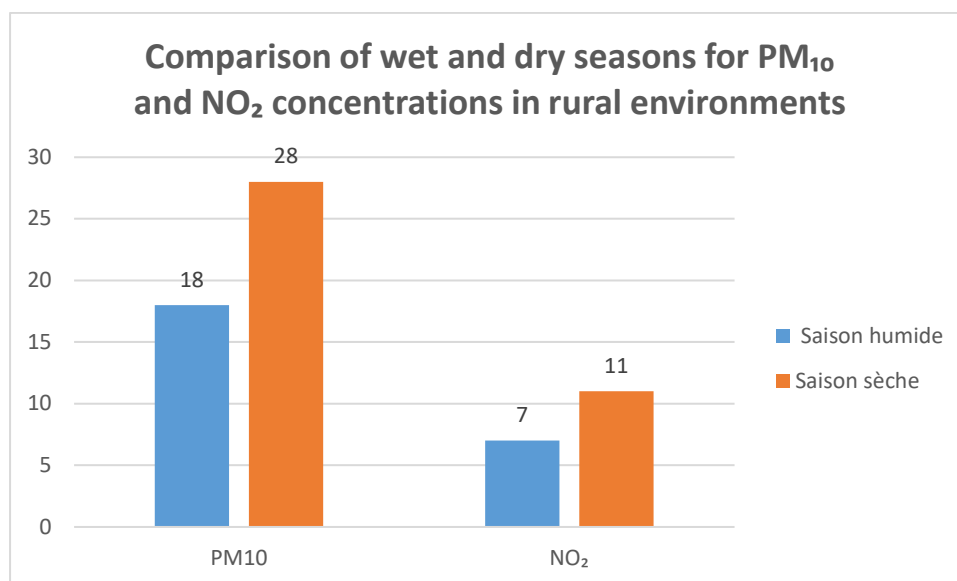
Figure 1. Seasonal variation of PM_{2.5} concentrations in rural environments



Source: Author, 2025.

The figure illustrates a moderate increase in PM_{2.5} concentrations during the dry season. Nevertheless, observed values remain below WHO guideline levels, indicating generally satisfactory air quality in rural settings.

Figure 2. Comparison of wet and dry seasons for PM₁₀ and NO₂ concentrations in rural environments



Source: Author, 2025.

The results indicate a seasonal increase in PM₁₀ and NO₂ concentrations during the dry period. However, this increase remains limited and does not result in exceedances of health-based standards, confirming the low-pollution character of the rural environment studied.

3.2 Atmospheric Exposure in Healthcare Facilities

Measurements of indoor air quality conducted within healthcare facilities reveal a contrasting situation compared with outdoor air in rural environments. Concentrations of volatile organic compounds (VOCs) measured in these enclosed settings are significantly higher, particularly during periods of cleaning, disinfection, and sterilization. These exposure peaks are explained by the frequent use of chemical products such as chlorinated disinfectants, alcohol-based solvents, and certain sterilizing agents, in premises that are sometimes inadequately ventilated. This configuration promotes the accumulation of gaseous pollutants and increases exposure among both staff and patients.

Table 2. Mean VOC concentrations and frequency of reported symptoms in healthcare facilities

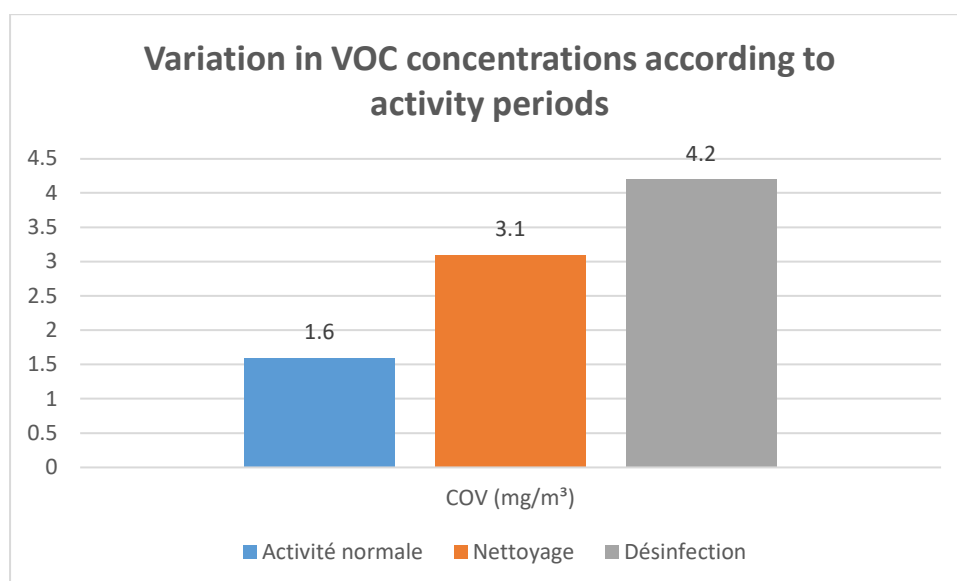
Indicator	Mean value	Standard deviation	Unit
Total VOCs	2.8	0.9	mg/m ³
Eye irritation	38	—	%
Headaches	32	—	%
Mild respiratory symptoms	21	—	%

Source: Field surveys and environmental measurements, 2023–2024.

The table shows that mean VOC concentrations lie in the upper range of values recommended by international guidelines, indicating a non-negligible level of exposure. The high proportion of staff reporting eye irritation and headaches suggests a direct health effect associated with

repeated exposure. Respiratory symptoms, although less frequent, further confirm the presence of a chronic risk, particularly for individuals exposed over prolonged periods.

Figure 3. Variation in VOC concentrations according to activity periods

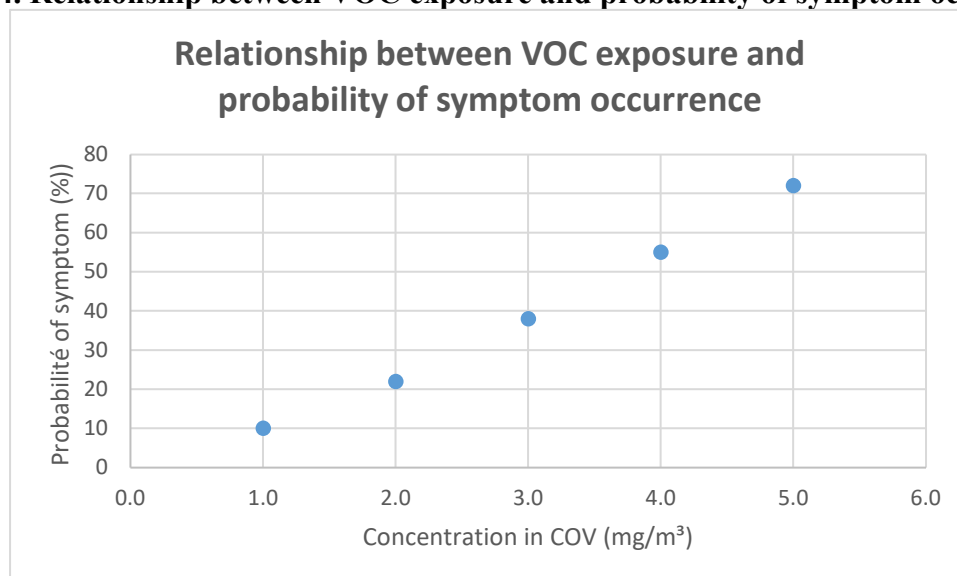


Source: Author, 2025.

The figure illustrates a marked increase in VOC concentrations during cleaning and disinfection phases compared with periods of normal activity. Peak levels are observed at the end of the day, coinciding with intensive maintenance operations.

This temporal pattern highlights the decisive role of professional practices in episodic degradation of indoor air quality. It also underscores the importance of adequate ventilation and chemical product management to limit acute exposures.

Figure 4. Relationship between VOC exposure and probability of symptom occurrence



Source: Author, 2025.

The figure presents the results of a logistic regression model showing a positive relationship between increasing VOC concentrations and the probability of symptom occurrence (irritation, headaches, respiratory discomfort).

These results confirm that VOC exposure is a significant determinant of the observed health effects. A marginal increase in concentrations leads to a measurable rise in symptom risk, corroborating findings from the international literature on indoor air quality in healthcare environments (WHO, 2021; EPA, 2024).

In contrast to relatively unpolluted rural outdoor air, healthcare facilities emerge as micro-environments with specific risk profiles. Atmospheric pollution in these settings is primarily chemical and occupational in origin, emphasizing that health risk depends more on the context of exposure than on geographic location alone. These findings argue for the systematic integration of indoor air quality considerations into environmental health policies, particularly in rural healthcare facilities.

4. DISCUSSION

The results obtained highlight a clear contrast between outdoor air quality in rural areas and the atmospheric exposure observed within healthcare facilities, confirming that the level of health risk does not depend solely on the geographical context but primarily on the nature of the environments and the emission sources present. While the concentrations of PM_{2.5}, PM₁₀, and NO₂ measured in rural areas generally remain below the thresholds recommended by the World Health Organization, reflecting relatively satisfactory outdoor air quality, enclosed healthcare environments exhibit higher levels of volatile organic compounds (VOCs). This dissociation between outdoor and indoor air underscores the limitations of a strictly territorial approach to environmental risk assessment.

These findings are consistent with the international literature, which identifies indoor air quality as a major determinant of environmental health that is often underestimated in public policies (WHO, 2021; EPA, 2024). Several studies have shown that the repeated use of disinfectants, solvents, and cleaning products in healthcare facilities leads to the accumulation of VOCs, which may cause eye irritation, headaches, and respiratory disorders, particularly among chronically exposed staff (Salthammer et al., 2018; Azuma et al., 2020). The statistical associations observed in this study between VOC concentrations and reported symptoms confirm these mechanisms, even when the measured levels remain moderate.

Finally, the analysis reveals that health risk is more strongly linked to the type of environment (open versus enclosed) than to the traditional distinction between rural and urban settings. This observation aligns with contemporary approaches in environmental health, which emphasize the joint consideration of outdoor and indoor exposures, as well as cumulative exposures over time (OECD, 2016; WHO, 2021). Healthcare facilities, including those located in rural areas, therefore emerge as priority spaces for intervention, requiring specific strategies for indoor air quality management, such as improved ventilation, the selection of low-emission products, and regular monitoring of chemical pollutants.

5. CONCLUSION

This study demonstrates that outdoor air quality in rural environments remains generally satisfactory, with pollutant concentrations largely below WHO guideline values. Consequently, health risks related to outdoor exposure appear limited for the rural populations studied. In contrast, healthcare facilities emerge as specific high-risk microenvironments, regardless of their rural location. Elevated exposure to VOCs from cleaning, disinfection, and medical activities represents a non-negligible health vulnerability, particularly for healthcare workers.

These findings underscore the need to broaden environmental health strategies beyond outdoor air pollution alone and to fully integrate indoor air quality considerations. Targeted measures—including improved ventilation, substitution of high-emission products, chemical management protocols, and staff awareness—are essential to sustainably reduce health risks and enhance protection for healthcare users and professionals.

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