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Synergistic Characteristics of $PM_{2.5}$ and O_3 on the Development of Behavioral Guidance

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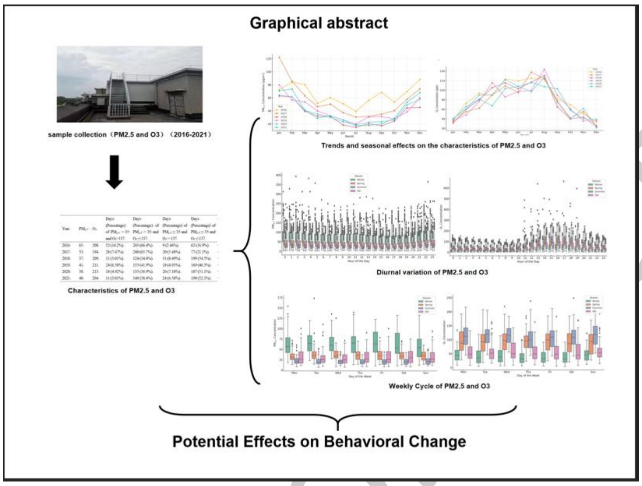
Graphical abstract



Abstract

Objective: This study aims to establish time- and scenario-specific behavioral recommendations for vulnerable populations, based on the pollution characteristics and meteorological drivers of $PM_{2.5}$ and O_3 in Luzhou (2016–2021), with the objective of mitigating health risks associated with air pollution. **Methods:** Hourly data on pollutants and meteorological factors were acquired from Luzhou Environmental Monitoring Station of Sichuan Province. After going through strict quality assurance and control procedures, an effective data collection rate of 96.6% was achieved, temporal distribution and influencing factors were analyzed. **Results:** A significant decreasing trend in $PM_{2.5}$ concentrations was observed, whereas O_3 levels remained persistently elevated (194–213 μg/m³) during the observation period. $PM_{2.5}$ levels peaked during winter nights (21:00–2:00), while O_3 concentrations were highest in the summer afternoons (14:00–15:00). which was closely related to the meteorological conditions (temperature and humidity) in this area. **Conclusions:** Although a reduction in $PM_{2.5}$ levels, O_3 pollution continues to pose a significant challenge. It is recommended that outdoor activities be avoided during winter nights and outdoor exercise be minimized during summer afternoons. Vulnerable populations should limit prolonged exposure when O_3 concentrations exceed 160 μg/m³. These targeted behavioral interventions can effectively reduce acute exposure risks and contribute to public health management.

Keyword: Activity guidance; Behavioral modification; O_3; $PM_{2.5}$; Temporal variation

1. Introduction

With the implementation of the Action Plan for Air Pollution Prevention and Control and the Three-Year Action Plan for Winning the Blue Sky Defense, significant improvements in China's air quality have been observed annually, with a marked reduction in the concentrations of $PM_{2.5}$ and O_3 in ambient air. Despite these reductions, air pollution remained severe in each city, with $PM_{2.5}$ and O_3 identified as the primary pollutants. (Li *et al.* 2025). However, $PM_{2.5}$ and O_3 pollution continued to pose significant challenges in various cities, particularly with frequent occurrences of O_3 pollution. O_3 pollution exhibited an upward trend in key cities and regions. The nature of air pollution has progressively shifted toward a composite form characterized by both $PM_{2.5}$ and O_3, drawing increasing attention to health effect and behavioral changes for the public (Shao *et al.* 2025).

Long-term exposure to environments where pollutant concentrations exceed safety thresholds has been linked to significantly elevated prevalence rates of respiratory and cardiovascular diseases among residents, as well as substantial impairments in physiological function and cognitive performance (Xue *et al.* 2021; Yang *et al.* 2019; Meo *et al.* 2024). Moreover, such exposure has been shown to negatively affect subjective well-being and mental health (Yuan *et al.* 2018). These adverse effects are particularly pronounced in vulnerable groups, including the elderly (Zheng *et al.* 2024), children (Cui *et al.* 2023), and other sensitive populations (Ma *et al.* 2023).

In terms of environmental pollution control and Response, in developed countries, the mechanism for public participation was quite mature. However, many developing countries were only gradually realizing the importance of emphasizing public participation and community development strategies. (Ahmed N. Budur *et al.* 2008). Air pollution exerts a direct influence on environmental health behaviors, including defensive actions (e.g., purchasing masks and air purifiers, reducing outdoor exposure, and opting for private vehicles to minimize pollutant exposure) (Zhang *et al.* 2018; An *et al.* 2018), health-related exercise behaviors (An *et al.* 2015), migration patterns (Qin *et al.* 2017), tourism behaviors (Cheung *et al.* 2001), and eco-friendly product choices (Zhao *et al.* 2019). However, research suggests that adaptive individual health behaviors during severe pollution episodes are not universally adopted. For example, surveys indicated that 85-90% of residents in Poland and Houston did not reduce driving on days with poor air quality (Semenza *et al.* 2008), suggesting that individuals may not decrease car usage during smog alerts (Noonan *et al.* 2014) and may even increase reliance on private vehicles, perceiving them as barriers against pollution (Ban *et al.* 2017; Neidell *et al.* 2009). Domestic studies in China indicate that residents adjust travel and residential location choices in response to $PM_{2.5}$ pollution, with younger populations prioritizing active "protection" strategies, while older groups tend to avoid exposure risks through "avoidance" measures. Nevertheless, the consistent adoption of individual adaptive health behaviors during high pollution periods remains infrequent (Na *et al.* 2016).

Although extensive research have indicated that The proposed IoT-CAPM-DL model, the hybrid RNN-PBO model, a transfer learning-based lightweight recurrent network with skip connection (TL2RN-SC) modelIt can accurately predict air quality, enhance the understanding of air pollution dynamics, provide real-time information to avoid damage to the environment and public health. ((Mohandas P, *et al. 2025 ;* Periasamy S*, et al. 2024;* Prajul Mohandas, *et al.* 2025). Meanwhile extensive research has focused on the health impacts of air pollution (Yi *et al.* 2024; Zhuang *et al.* 2024; Tan, *et al.* 2025), only a limited number of surveys have addressed the effects of haze and smog on residents' health, with few examining the current status of adaptive behaviors employed to cope with air pollution (Karina *et al.* 2024; Susa *et al.* 2025). These studies generally lack specific investigations into behavioral changes or actionable travel recommendations for the public. Research explicitly exploring behavioral modifications and providing practical guidance for reducing exposure during atmospheric pollution events remains scarce.

This study aims to address this gap. By analyzing the daily, weekly, monthly, and seasonal pollution characteristics of $PM_{2.5}$ and O_3 in Luzhou, China, from 2016 to 2021, evidence-based recommendations for resident travel and behavioral change strategies will be developed. The objective is to reduce direct exposure and mitigate high-concentration environmental exposure, thereby lowering disease incidence and minimizing health risks, particularly among vulnerable groups such as the elderly, infants, children, and other sensitive populations. This study is intended to contribute to reducing the disease burden in Luzhou and to provide actionable insights for similar studies in other regions.

Figure 1. Distribution Map of Monitoring Stations in the Study Area.

2. Data and methods

2.1. Study area

Luzhou City is situated in the southeast of Sichuan Province, China, at the transition zone between the southern margin of the Sichuan Basin and the Yunnan-Guizhou Plateau. The average annual wind speed in Luzhou is relatively low (1.0–2.5 m/s), with a high frequency of calm wind conditions (6.1%), which tends to facilitate the accumulation rather than dispersion of air pollutants, resulting in elevated pollution concentrations. The city's topography, which is lower in the north and higher in the south, creates a natural barrier that further traps pollutants. In addition, Luzhou, with a built-up area of 101 km² and a population of 1.64 million, is a densely populated urban area. The subtropical humid climate, characterized by high humidity and moderate temperatures, also influences the dispersion of air pollutants. These factors collectively contribute to the persistent accumulation of pollutants, rendering air pollution a significant and ongoing challenge. Luzhou was identified as one of the cities in the region most severely affected by air pollution, with consistently high concentrations of key air pollutants, particularly $PM_{2.5}$ and O_3, when compared to other cities in Sichuan Province. Therefore, it has been designated as a key city for air pollution prevention and control. This highlights the importance of characterizing the primary air pollutants, particularly $PM_{2.5}$ and O_3, in Luzhou to inform the development of targeted strategies aimed at improving air quality and safeguarding public health. There are a total of 4 national air quality monitoring stations in the urban area, namely the Jiushishan, Environmental Monitoring Station, Lan Tian Xianqiao, Xiaoshi Dock, As shown in **Figure 1**.

2.2. Data sources and monitoring methods

2.2.1. Data sources

The $PM_{2.5}$ and O_3 concentration data were obtained from the Sichuan Luzhou Ecological Environment Monitoring Center Station, encompassing hourly measurements from 00:00 on January 1, 2016, to 24:00 on December 31, 2021. Data cleaning and handling of missing values and outliers were carried out in accordance with the "Technical Specifications for the Operation and Quality Control of Continuous Automatic Monitoring Systems for Gaseous Pollutants in Ambient Air (SO_2, NO_2, O_3, CO)" (HJ 818-2018) and the "Technical Specifications for the Operation and Quality Control of Continuous Automatic Monitoring Systems for Particulate Matter (PM_{10} and $PM_{2.5}$)" (HJ 817-2018). After excluding records with missing values, a total of 210,432 data entries were gathered, of which 203,277 were valid, yielding an effective data completeness rate of 96.6%. For $PM_{2.5}$, the hourly concentration of the four monitoring stations was averaged to obtain the hourly average concentration the daily average concentrations were calculated as the 24-hour mean values, with monthly and annual averages derived from these daily means. For O_3, the hourly concentration of the four monitoring stations was averaged to obtain the hourly average concentration, the daily maximum 8-hour moving average (MDA8) concentration was used as the daily value, with monthly averages computed from these daily MDA8 values and annual averages represented by the annual 4th highest daily maximum 8-hour average concentration. Additionally, meteorological parameters, including air temperature (T) and relative humidity (RH), were collected from the Luzhou Environmental Protection Online Monitoring Data Sharing Platform for the period from January 1, 2018, to December 31, 2021. All 1,462 daily records were valid, ensuring 100% data completeness.

2.2.2. Monitoring instruments and monitoring methods

Ambient $PM_{2.5}$ concentrations were measured using an XHPM2000E particulate monitor (Xianhe Co., Ltd., Hebei, China), which operates based on the beta attenuation method. Ozone (O_3) concentrations were measured using an EC9810 ozone analyzer (EC Pty Ltd, Australia), which employs the ultraviolet absorption method.

2.3. Analytical methods

2.3.1. Classification of pollution levels and compliance assessment

The assessment of air quality was performed in accordance with the secondary limit of the Ambient Air Quality Standard (GB 3095-2012), the National Ambient Air Quality Standards (NAAQS), and the World Health Organization (WHO) Air Quality Guidelines (AQG 2021). The classification of pollution levels was performed in accordance with National Ambient Air Quality Standards (NAAQS). Utilizing National Ambient Air Quality Standards (NAAQS)'s annual $PM_{2.5}$ standard (35.0 μg/m³) annual O_3 guideline (137 μg/m³), the pollution conditions during the study period were classified into four distinct levels. This classification system enabled a comprehensive evaluation of air quality by considering both particulate matter and photochemical pollution indicators.

2.3.2. Statistical and graphical tools

Data preprocessing, time-series analysis, and box-plot visualization were conducted using Origin 9.0 (OriginLab Corporation, Northampton, MA, USA). Heatmap generation and nonparametric statistical analyses, including the Mann-Kendall trend test, Mann-Whitney-Wilcoxon rank-sum test, and Kruskal-Wallis one-way ANOVA by ranks, were performed using R software (version 4.5.1; R Foundation for Statistical Computing, Vienna, Austria). A significance level of $\alpha = 0.05$ was applied to all statistical tests.

3. Results and discussion

3.1. Characteristics of $PM_{2.5}$ and O_3

The annual average concentrations of $PM_{2.5}$ and O_3 in Luzhou City from 2016 to 2021 are summarized in Table 1. The concentrations of $PM_{2.5}$ demonstrated a pronounced declining trend (Mann-Kendall, $\tau = -0.93$, $P < 0.01$) from 2016 to 2021, decreasing from 65 μg/m³ in 2016 to 40 μg/m³ in 2021. These concentrations were 1.1, 3.3, and 8.0 times above the secondary limit of the Ambient Air Quality Standard (GB 3095-2012; 35 μg/m³), the National Ambient Air Quality Standards (NAAQS; 12 μg/m³), and the World Health Organization (WHO) Air Quality Guidelines (AQG 2021; 5 μg/m³), respectively. A significant reduction in $PM_{2.5}$ concentrations was observed from 2018 onward ($P < 0.01$), aligning with the implementation of the Action Plan for Air Pollution Prevention and Control (2017) and the Three-Year Action Plan for Winning the Blue Sky Defense Battle (2020), both of which had a substantial influence on the reduction of $PM_{2.5}$ levels.

In contrast, O_3 concentrations remained elevated, fluctuating between 194 and 213 μg/m³, with no discernible trend (Mann-Kendall, $\tau = 0.07$, $P = 0.69$). These concentrations consistently exceeded the limits of GB 3095-2012 (100 μg/m³), NAAQS (137 μg/m³), and WHO AQG 2021 (60 μg/m³), with exceedance factors of 2.0–2.1, 1.4–1.6, and 3.2–3.6, respectively, thereby indicating severe O_3 pollution in the region.

Table 1 presents the proportion of days with simultaneous exceedances of $PM_{2.5}$ and O_3 ($PM_{2.5}$ > 35 μg/m³ & O_3 > 137 μg/m³), which decreased from 14.2% in 2016 to 3.0% in 2021, reflecting a cumulative reduction of 78.8%. This decline signifies a substantial improvement in the control of both $PM_{2.5}$ and O_3 pollution. The proportion of days with $PM_{2.5}$ exceedance and O_3 compliance ($PM_{2.5}$ > 35 μg/m³ & O_3 ≤ 137 μg/m³) also declined from 66.4% in 2016 to 38.4% in 2021, representing a decrease of 42.2%, further substantiating the significant reduction in $PM_{2.5}$

levels. The proportion of days with $PM_{2.5}$ compliance and O_3 exceedance ($PM_{2.5} \leq 35$ μg/m³ & $O_3 > 137$ μg/m³) remained relatively stable, fluctuating between 5% and 8%, except for a value of 2.5% in 2016. Simultaneously, the proportion of days with compliance for both pollutants ($PM_{2.5} \leq 35$ μg/m³ & $O_3 \leq 137$ μg/m³) increased from 16.9% in 2016 to 52.1% in 2021, further demonstrating the overall improvement in air quality management. However, notable discrepancies persist when compared to the annual standard limits established by the WHO (5 μg/m³ for $PM_{2.5}$, 100 μg/m³ for peak season O_3) and the United States Environmental Protection Agency (USEPA, 9 μg/m³ for $PM_{2.5}$, 137 μg/m³ for O_3).

Table 1. Characteristics of annual average $PM_{2.5}$ and O_3 from 2016 to 2021 in Luzhou, ($\mu g/m^3$)

Year	$PM_{2.5}$	O_3	Days (Percentage) of $PM_{2.5} > 35$ and $O_3 > 137$	Days (Percentage) of $PM_{2.5} > 35$ and $O_3 \leq 137$	Days (Percentage) of $PM_{2.5} \leq 35$ and $O_3 > 137$	Days (Percentage) of $PM_{2.5} \leq 35$ and $O_3 \leq 137$
2016	65	208	52 (14.2%)	243 (66.4%)	9 (2.46%)	62 (16.9%)
2017	53	194	28 (7.67%)	240 (65.7%)	20 (5.48%)	77 (21.1%)
2018	37	209	11 (3.01%)	124 (34.0%)	31 (8.49%)	199 (54.5%)
2019	41	211	24 (6.58%)	153 (41.9%)	18 (4.93%)	169 (46.3%)
2020	38	213	18 (4.92%)	135 (36.9%)	26 (7.10%)	187 (51.1%)
2021	40	204	11 (3.01%)	140 (38.4%)	24 (6.58%)	190 (52.1%)

Note: In 2019, data were collected for 364 days, with December 31 missing. Data for other years were complete. $PM_{2.5}$ refers to annual average concentrations, while O3 represents the annual 4th highest daily maximum 8-hour average concentration.

3.2. Trends and seasonal effects on the characteristics of $PM_{2.5}$ and O_3

The monthly average $PM_{2.5}$ concentrations in the urban area of Luzhou from 2016 to 2021 exhibited a distinct U-shaped seasonal pattern, with the lowest levels observed in July and August, and peak concentrations recorded in December, January, and February (**Figure 2**). Winter consistently presented the highest $PM_{2.5}$ levels across all months, with median concentrations remaining elevated and exhibiting greater variability. This suggests more frequent pollution episodes, likely influenced by meteorological factors such as temperature inversions and stagnant air, alongside increased emissions, particularly from heating activities. Spring and fall exhibited moderate $PM_{2.5}$ levels, with reduced variability compared to winter. Summer was characterized by the lowest $PM_{2.5}$ concentrations, indicative of cleaner air, likely resulting from enhanced atmospheric mixing and dispersion.

The monthly average O_3 concentrations in Luzhou's urban area from 2016 to 2021 demonstrated a stable distribution (Mann-Kendall, $\tau = 0.03$, $P > 0.1$), following a distinct "n"-shaped seasonal pattern (**Figure 2**). Summer and spring recorded the highest O_3 concentrations, with medians exceeding 100 ppb on numerous occasions. This trend aligns with the intensified sunlight and higher temperatures, which facilitate photochemical ozone formation. In contrast, winter exhibited the lowest O_3 concentrations, frequently falling below 50 ppb, consistent with diminished photochemical activity. Fall, exhibiting intermediate O_3 levels, was lower than summer and spring but higher than winter.

During ozone pollution episodes ($O_3 > 137$ μg/m³), temperatures ranged from 18.5 to 34.0 °C, while RH varied between 57.1% and 75.0%. In contrast, non-pollution periods ($O_3 \leq 137$ μg/m³) were characterized by temperatures between 2.9 and 20.9 °C and RH ranging from 66.1% to 99.8%. During non-ozone-polluted periods, lower temperatures were associated with higher $PM_{2.5}$ concentrations (**Figure 3**). Elevated temperatures facilitate chemical reactions and enhance fluxes within the atmospheric boundary layer, thus influencing the distribution of gases and particulate matter. This promotes the conversion of pollutants into gaseous forms, accelerates photochemical reaction rates, and facilitates NO_2 photolysis and volatile organic compounds (VOCs) oxidation, thereby creating favorable conditions for O_3 formation. In contrast, lower temperatures inhibit photochemical fluxes, resulting in reduced O_3 concentrations. High-humidity environments increase ultraviolet scattering by aerosols, diminishing photolysis efficiency. Furthermore, elevated humidity fosters the wet deposition of HNO_3, curtailing the recycling of NO_x and weakening O_3 production (Zou *et al.* 2024).

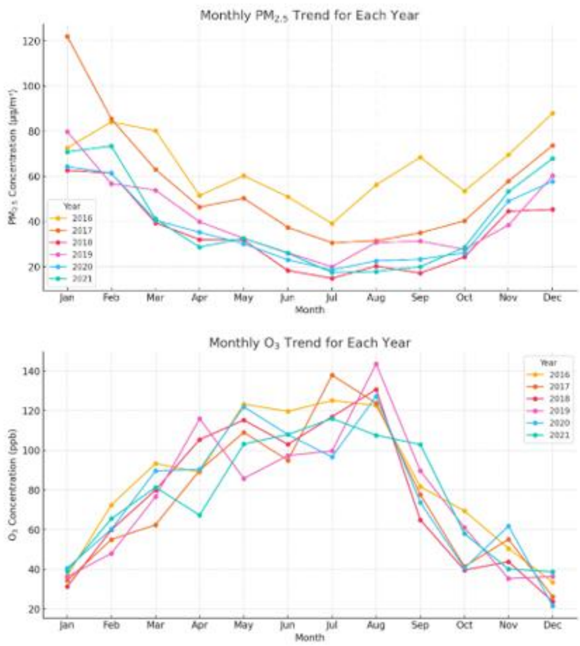


Figure 2. Monthly $PM_{2.5}$ and O_3 concentration trends for each year

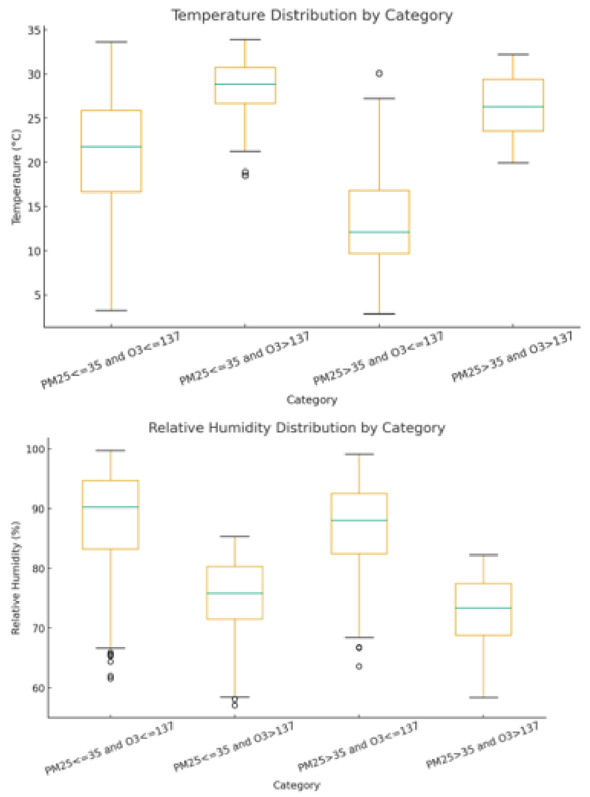


Figure 3. Distribution of temperature and relative humidity at the different $PM_{2.5}$ and O_3

3.3. Diurnal and weekly cycle of $PM_{2.5}$ and O_3

3.3.1. Diurnal variation of $PM_{2.5}$ and O_3

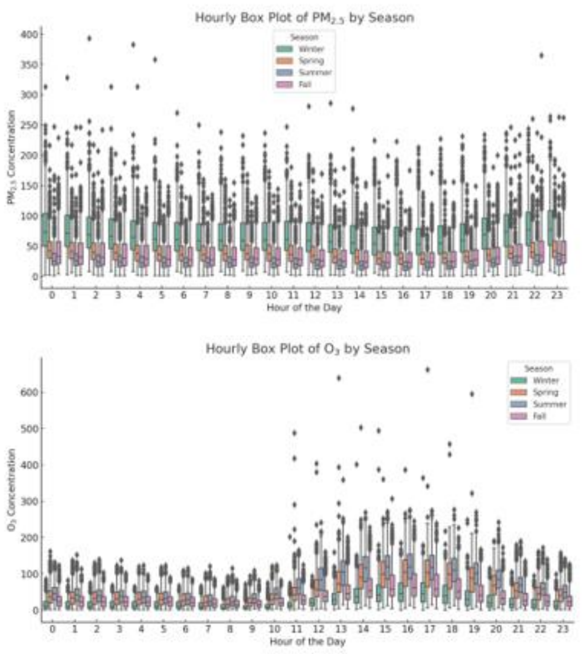


Figure 4. Hourly boxplot of $PM_{2.5}$ and O_3 by different seasons from 2016 to 2021

Figure 4 presents the boxplots of hourly concentrations of $PM_{2.5}$ and O_3 from 2016 to 2021. $PM_{2.5}$ concentrations during winter were significantly higher than those observed in the other three seasons throughout all 24 hours (Mann-Whitney-Wilcoxon, $P < 0.01$), with the peak occurring between 23:00 and 24:00. A distinct diurnal pattern was evident, characterized by elevated levels from 21:00 to 02:00 and lower concentrations between 13:00 and 17:00. A notable inflection point, marked by a rapid increase in $PM_{2.5}$, occurred between 17:00 and 19:00. The periods from 11:00 to 13:00 and from 18:00 to 20:00 correspond to morning and evening traffic rush hours, respectively, suggesting a significant contribution from traffic-related dust and vehicle emissions to fine particulate matter concentrations. In contrast, the diurnal variation of O_3 followed a consistent "single-valley, single-peak" pattern across all seasons. This pattern can likely be attributed to suppressed photochemical activity during nighttime, due to lower temperatures, reduced sunlight, and weaker solar radiation. Additionally, nitric oxide (NO) actively consumes O_3, and this titration effect is intensified during traffic peak hours by increased emissions of nitrogen oxides (NO_x) from vehicles, further reducing O_3 levels. Therefore, O_3 concentrations reached their daily minimum between 07:00 and 08:00. From 09:00 onward, strengthening sunlight, rising solar radiation, and increasing temperatures promote photochemical production, leading to the gradual accumulation of O_3. Peak concentrations typically occurred around 14:00–15:00, followed by a decline as solar radiation diminished and temperatures decreased. Furthermore, O_3 concentrations were highest from June to August, consistent with enhanced photochemical formation driven by more intense solar radiation and higher temperatures during the summer.

3.3.2. Weekly cycle of $PM_{2.5}$ and O_3

Figure 5 illustrates that $PM_{2.5}$ concentrations were significantly higher on all days during winter compared to other seasons (Mann-Whitney-Wilcoxon, $P < 0.01$). The day-of-week effect was found to be minimal. While $PM_{2.5}$ levels remained relatively consistent from Monday to Sunday within each season, a statistically significant difference was observed between weekdays and weekends (Kruskal-Wallis, H = 10.76, P = 0.001, ε^2 = 0.0002). Outliers, characterized by extremely high $PM_{2.5}$ events, were most prevalent in winter. Similarly, O_3 concentrations were significantly elevated across all days in summer compared to winter (Mann-Whitney-Wilcoxon, $P < 0.01$). Additionally, although concentrations remained relatively stable across days, a clear weekday-weekend trend was detected (Kruskal-Wallis, H = 45.70, P < 0.001, ε^2 = 0.0009). Outliers, defined by very high ozone events, occurred predominantly in summer, consistent with episodic high-ozone days. The very small effect sizes ($\varepsilon^2 < 0.01$) indicate that these differences stem from the large sample size rather than representing practically significant factors. From a public health perspective, PM2.5 and O_3 levels show no substantial variation between weekdays and weekends, suggesting a negligible "weekend effect.

3.4. Potential effects on behavioral change

During periods of high temperature and low humidity (T > 30 °C, RH < 50%), intense solar radiation accelerates the photolysis of NO_2 and the oxidation of VOCs, resulting in peak ground-level O_3 concentrations typically occurring between 14:00 and 15:00. To minimize exposure, it is recommended to avoid outdoor activities from 12:00 to 17:00, as this can reduce the inhaled O_3 dose by 40–60%. If outdoor exposure is necessary, it is advised to wear a mask with an activated carbon layer (compliant with GB/T 32610 Class A standards-Class A masks are regarded as the most effective in terms of protection, with a protection level of no less than 90%, and are suitable for use in extremely polluted environments.), replacing it every 4 hours. Vehicle occupants should activate the air conditioning recirculation mode and clean the filters biweekly. It should be noted that vigorous exercise can increase the inhaled O_3 dose by 2–3 times (USEPA 2022). For commuting by cycling or walking, trips should ideally be scheduled during early morning (06:00–08:00) or evening (19:00–21:00) hours, avoiding major roads to minimize exposure to traffic-related emissions. In the cold and humid season (T < 10 °C & RH > 70%), emissions from coal combustion for heating, combined with a thickened inversion layer and stable atmospheric conditions, contribute to a reduction in boundary layer height. High humidity fosters the aqueous-phase formation of SPM, resulting in a bimodal $PM_{2.5}$ concentration pattern, with peaks between 11:00–13:00 (associated with morning traffic and cooking emissions) and 21:00–02:00 (due to nocturnal boundary layer compression). During hazy days, outdoor activities should be minimized, particularly during the morning hours of 07:00–10:00, when the inversion layer is most pronounced. Indoors, the use of air purifiers equipped with a HEPA filter (with a Clean Air Delivery Rate ≥ 200 m³/h) is effective. If outdoor activity is unavoidable, the period between 10:00 and 14:00 is relatively safer. Enclosed modes of transportation can significantly reduce personal exposure (Li *et al.* 2015), and wearing a KN95/N95 respirator (with a filtration efficiency ≥ 95%) is strongly recommended. Precipitation events have a scavenging effect on $PM_{2.5}$, making post-rain ventilation by opening windows beneficial.

Under compound pollution conditions (T 15–25 °C & RH 50–70%), synergistic increases in $PM_{2.5}$ and O_3 concentrations are frequently observed. Monitoring real-time Air Quality Index (AQI) and O_3 levels is essential. Outdoor activities should be minimized when the AQI exceeds 100 or when O_3 concentrations surpass 137 μg/m³. Vulnerable populations, such as children and individuals with chronic obstructive pulmonary disease (COPD), should adopt an "indoor micro-environment strategy", establishing a clean air space by utilizing air purifiers, air conditioning, and keeping windows closed.

The implementation of a real-time alert system for special populations is recommended. A push notification advising "Reduce Outdoor Activities" should be activated on mobile devices when the AQI exceeds 100 (indicating an exceedance in either $PM_{2.5}$ or O_3). For vulnerable groups (e.g., children, COPD patients), a "Red Alert" protocol should be initiated. Automated notifications recommending medical consultation should be dispatched when the AQI exceeds 150 or when O_3 concentrations exceed 180 μg/m³.

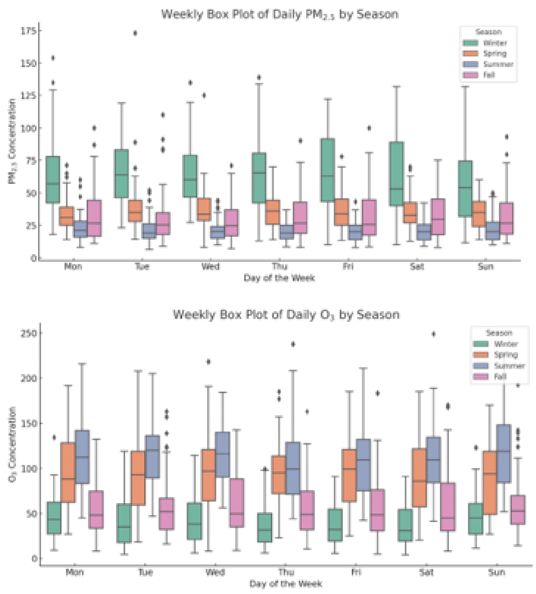


Figure 5. Weekly boxplot of $PM_{2.5}$ and O_3 by different seasons from 2016 to 2021

4. Conclusion

From 2016 to 2021, the annual average $PM_{2.5}$ concentration in the urban area of Luzhou ranged from 38.0 to 65.0 μg/m³, exhibiting a consistent year-on-year decrease, while the O_3 concentration remained between 194 and 213 μg/m³, without displaying a significant temporal trend. Throughout the study period, the number of days with concurrent exceedances of both $PM_{2.5}$ (>35 μg/m³) and O_3 (>137 μg/m³) decreased annually, while the proportion of days meeting both standards ($PM_{2.5}$ ≤ 35 μg/m³ and O_3 ≤ 137 μg/m³) increased correspondingly, indicating effective control of $PM_{2.5}$ and O_3 pollution. $PM_{2.5}$ concentrations were higher in winter and lower in summer, while O_3 concentrations peaked in summer and were at their lowest in winter. $PM_{2.5}$ levels were elevated from 21:00 to 02:00 the following day and lower between 13:00 and 17:00. O_3 concentrations reached their daily minimum between 07:00 and 08:00, with peaks occurring between 14:00 and 15:00.

Based on these patterns, several recommendations for exposure mitigation are proposed: avoiding outdoor activities from 21:00 to 02:00 during winter and wearing KN95 or higher-grade masks if outdoor exposure is unavoidable; reducing outdoor exercise between 13:00 and 17:00 in summer, with a preference for well-ventilated indoor spaces; encouraging children and the elderly to use public transportation and minimize waiting time during cold and humid conditions; and consulting real-time O_3 forecasts before outdoor activities in hot and dry weather, postponing prolonged exercise when O_3 concentrations exceed 160 μg/m³. The implementation of precise, time- and meteorology-specific behavioral interventions is recommended to significantly reduce acute exposure risks for sensitive populations. These findings provide a data-driven foundation for individual health protection and public health management.

5. Research Prospects

This research provides a preliminary analysis of $PM_{2.5}$ and O_3 pollution characteristics and proposes mitigation strategies based on the findings. However, the temporal incongruity between pollution exposure metrics and population health data, alongside privacy constraints, precluded any analysis of individual health effects or exposure-disease relationships. Consequently, epidemiological studies and the evaluation of public health interventions are necessary next steps to corroborate the behavioral suggestions put forth herein.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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