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Association between ambient air pollution and dry eye symptoms among Chinese individuals during the COVID-19 pandemic: A national-based study

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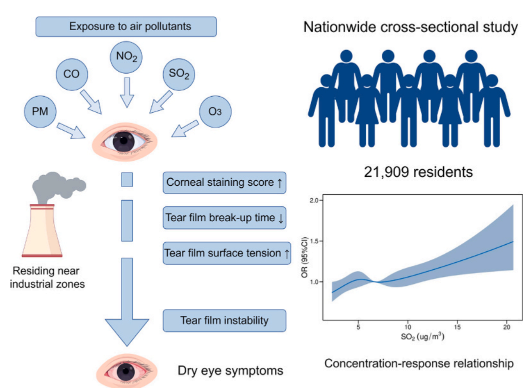
HIGHLIGHTS

- Residing near industrial zones was associated with increased risk of DES.
- There is a linear concentration-response relationship between SO_2 and DES.
- Our study used a large-scale nationally representative sample.
- The impact of air pollution on dry eye may have been mitigated during the pandemic.

GRAPHICAL ABSTRACT



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ABSTRACT

Purpose: To examine the association between ambient air pollution and dry eye symptoms (DES) during the COVID-19 pandemic and explore whether air pollution had increased the risk of DES to a greater extent than other risk factors.

Methods: A nationwide cross-sectional survey was conducted from June 20, 2022 to August 31, 2022. The Ocular Surface Disease Index-6 (OSDI-6) questionnaire was used to assess the presence of DES. Logistic regression models were employed to analyze the associations between DES and air pollution variables, including air quality index (AQI), fine particulate matter ($PM_{2.5}$), PM_{10}, sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3) and residing near industrial zones. We explored the interactions of air pollutants and other risk factors in the additive models by calculating the synergy index (SI). Standardized regression coefficients were calculated to compare the relative importance of risk factors for DES.

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Results: A total of 21,909 participants were included in the analysis. Residing near industrial zones was significantly correlated with a higher risk of DES (Odds ratio (OR): 1.57, 95 % confidence interval (CI): 1.38–1.79). No significant associations were found between DES and air pollutants except SO_2 (OR: 1.05, 95 % CI: 1.02–1.09, per standard deviation increment in SO_2 concentration). The restricted cubic spline analyses revealed a linear concentration-response relationship between SO_2 and DES. The interaction analyses suggested synergetic interactions of SO_2 with depression and problematic internet use. Among the risk factors, depression, anxiety and problematic Internet use contributed more to the increased risk of DES.
Conclusion: The association between ambient air pollutants and DES may have been mitigated during the pandemic due to increased time spent indoors. Despite this, our findings support the deleterious health impact of air pollutants. Future urban planning should plan industrial zones further away from residential areas.

1. Introduction

Dry eye disease has been rising as a major public health concern in recent years. It is characterized by tear film instability and debilitating symptoms such as pain, blurred vision and burning sensation (Wolffsohn et al., 2017). Dry eye symptoms (DES) have been a fundamental component of dry eye diagnosis (Wolffsohn et al., 2017), and can interfere with usual activities, leading to impaired quality of life (Barabino et al., 2016). The latest systematic review in 2023 revealed that the prevalence of dry eye has increased significantly during the COVID-19 pandemic (Ji et al., 2023). However, the included studies were limited to specific populations such as high school students (Lin et al., 2022), doctors and nurses (Long et al., 2020). The prevalence of dry eye among the general population during the pandemic is still unclear.

The etiology of dry eye is multifactorial and several possible risk factors have been examined (Ferrero et al., 2018; Wang et al., 2023; Vehof et al., 2021). Among them, air pollution is an important factor which is linked with several ocular disorders (Grzybowski and Mimier, 2019; Markeviciute et al., 2023). Accumulating evidence has supported the association between air pollution and dry eye (Kim et al., 2020; Chung et al., 2021; Mu et al., 2021; Hao et al., 2022; Jung et al., 2018; Alves et al., 2023). For example, Hwang et al. reported that higher ozone (O_3) levels were associated with an increased risk of dry eye disease (Hwang et al., 2016). Another prospective study suggested that increased particulate matter ($PM_{2.5}$ & PM_{10}) exposure was associated with worse DES (Kim et al., 2020). However, considering the remarkable changes in people's life during the pandemic (e.g. reduced time spent outdoors), it is unclear whether the relationship between ambient air pollution and DES had changed over this special period. Furthermore, although numerous risk factors for dry eye have been previously discovered (e.g. cataract surgery, diabetes) (Ferrero et al., 2018; Wang et al., 2023; Vehof et al., 2021), what remains less elucidated is which of them are the most important factors contributing to high prevalence of DES.

Therefore, the aims of the present study were to (1) estimate the prevalence of DES in China using a nationally representative sample (2) investigate the relationship between air pollution and DES during the COVID-19 pandemic and (3) explore whether air pollution increased the risk of DES to a greater extent than other risk factors.

2. Methods

2.1. Study population and data collection

Data for this study were derived from the psychology and behavior investigation of Chinese residents (PBICR), which is a multicenter, nationwide cross-sectional survey conducted from June 20, 2022 to August 31, 2022. To obtain a nationally representative sample, the survey covered all the 23 provinces, 5 autonomous regions, and 4 municipalities in Chinese mainland (excluding Hong Kong, Macao, and Taiwan) and a multistage sampling method was adopted. Specifically, stratified equal probability sampling was used to select samples at the provincial, municipal, district, county, township/town, street, and community/village levels, and then individuals were selected using the quota sampling methods based on the demographics from the 2021 National Census. An electronic questionnaire was used to collect information, which was administered by trained investigators through face-to-face interviews or online video investigation. The inclusion criteria were Chinese residents aged 12 or older capable of understanding each item of the questionnaire. Individuals who were involved in other similar studies or failed to complete the questionnaire were excluded. Finally, a total of 21,916 subjects were recruited in the PBICR study. The response rate was 71.8 %. The detailed study protocol has been published elsewhere (Wang et al., 2022).

2.2. Ethical approval

The survey was approved by the Medical Ethics Committee (No. JKWH-2022-02) and the Clinical Research Ethics Committee of the Second Xiangya Hospital of Central South University (No.2022-K050). The study compiled with the Declaration of Helsinki. All subjects provided written informed consent.

2.3. Measurement of dry eye symptoms

The Ocular Surface Disease Index-6 (OSDI-6) was utilized to evaluate the DES of the participants. It is the simplified version of the OSDI, which may be the most frequently used questionnaire for assessing DES and was recommended by the International Dry Eye Workshop (DEWS) as a useful tool to screen for dry eye (Wolffsohn et al., 2017). The OSDI consists of three subscales: ocular symptoms, vision-related function, and environmental factors. The OSDI-6 selects the six most discriminative questions from the original OSDI (two from each subscale) to form a shorter version which is highly predictive of the original OSDI score ($r = 0.893$) (Pult and Wolffsohn, 2019). The OSDI-6 has a better repeatability than the full OSDI as the shortened version is more likely to be completed by the participants (Pult and Wolffsohn, 2019). Each item of the questionnaire is scored on a scale of 0 (never) – 4 (constantly), with the summated total score ranging from 0 to 24. The OSDI-6 score ≥ 4 denotes having DES, and < 4 denotes DES-free status.

2.4. Measurement of exposure data

The air pollution data included air quality index (AQI), $PM_{2.5}$, PM_{10}, sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), O_3 and whether the participants live near industrial zones. The monthly averaged AQI and concentrations of the six air pollutants from June to August 2022 were collected from Chinese atmospheric monitoring stations according to the home address of the participants. Three-month averaged levels of these air pollutants were calculated to estimate participants' exposure to air pollution during the survey. Additionally, we asked participants to report whether there were high-polluting factories within a 5-km radius of their home. Possible responses included “Yes”, “No” or “Unclear”. We hypothesize that residents living near industrial zones were exposed to higher concentrations of air pollutants than those who didn't.

2.5. Measurement of covariates

Based on previous studies, covariates were adjusted including sociodemographic factors, body mass index, smoking status, secondhand smoke exposure, alcohol drinking, problematic internet use, subjective health awareness, depression, anxiety symptoms, self-reported conditions of diseases and meteorological factors. Sociodemographic factors included age, sex, residence (urban/rural), education level (high school or below/college or above) and household income. The Problematic Internet Use Questionnaire Short-Form-6 (PIUQ-SF-6) was used to assess problematic internet use, with higher scores indicating worse problems. The subjective health awareness was evaluated using the EQ-5D visual analogue scale (EQ-VAS). The Patient Health Questionnaire-9 (PHQ-9) and the Generalized Anxiety Disorder-7 (GAD-7) questionnaire were used to assess depression and anxiety symptoms, respectively. Self-reported conditions of disorders including hypertension, diabetes, dyslipidemia, myopia, cataract, glaucoma and other retinal diseases were also controlled. The data of meteorological factors including temperature and relative humidity were collected from the same period as air pollutants.

2.6. Statistical analysis

We conducted descriptive analyses to examine the prevalence of DES and the participants' characteristics. Differences between groups were compared using the chi-square test for categorical variables and *t*-tests for continuous variables. Pearson correlation analysis was adopted to assess the correlations between the six major air pollutants. To explore the concentration-response relationships between air pollutants and DES, we employed restricted cubic spline (RCS) analysis and identified thresholds for all air pollutants, excluding SO_2. Above the threshold concentration, air pollutants were linearly correlated with risk of DES. Therefore, we reported the odds ratio (OR) and 95 % confidence interval (95 % CI) for DES above the threshold using logistic regression models adjusted for the aforementioned covariates. Given the presence of multicollinearity among air pollutants, each pollutant was entered into the models individually. We performed stratified analyses of air pollutants and further explored the additive interactions between air pollutants and other risk factors for dry eye by calculating the synergy index (SI) (Xing et al., 2023). The air pollutant concentrations were classified into two levels according to quartiles (quartile 1: low; quartile 4: high). A categorical variable with four groups was then created to combine the original two variables (e.g. SO_2 and depression): (1) SO_2 level was low and the participant was without depression; (2) SO_2 level was high and participant without depression; (3) SO_2 level was low but participant with depression; (4) SO_2 level was high and participant with depression. Using the low SO_2-no depression group as reference, the adjusted ORs for DES in the other three groups (OR_{11}: high-yes, OR_{01}: low-yes, OR_{10}: high-no) were estimated for the calculation of the SI: $SI = (OR_{11}-1)/[(OR_{01}-1) + (OR_{10}-1)]$. $SI > 1$ indicates a synergetic interaction of the two variables on DES (Andersson et al., 2005). In addition, we assessed the risk associated with residing near industrial zones using logistic regression analysis, calculating standardized regression coefficients (SRC) to compare the relative significance of different risk factors.

A subgroup analysis based on age was conducted. To test the robustness of the results, sensitivity analyses were performed by conducting the logistic regression models after excluding participants who had ever been diagnosed with ocular diseases including myopia, cataract, glaucoma and other retinal diseases. A figure displaying the possible pathogenic mechanism of air pollution-induced DES was drawn by Figdraw (www.figdraw.com). All the statistical analyses were conducted using Stata 16.0 and R 4.2.2. A two-tailed *P* value less than.05 was considered statistically significant.

3. Results

Overall, 21,909 participants were included in the analysis (50.0 % women, mean age 39.4 ± 18.8) after excluding 7 individuals who did not provide their home address. The total prevalence of DES during the pandemic was 43.6 % (95 % CI, 43.0 %–44.3 %). DES were more prevalent among women, adolescents and the elderly (Supplemental Table S1). Table 1 displays the characteristics of both DES and non-DES subjects. The proportion of participants residing near industrial zones was significantly higher among subjects with DES compared to those without DES ($P < .001$).

Fig. 1 depicts the correlations between the six major air pollutants. $PM_{2.5}$ was highly correlated with PM_{10} ($r = 0.85$) and both of them were highly correlated with O_3 ($PM_{2.5}$: $r = 0.73$ and PM_{10}: $r = 0.63$). Fig. 2 shows the results of RCS analyses. The concentration-response relationships between air pollutants and DES were either J-shaped or U-shaped, except that SO_2 was linearly associated with the risk of DES. Logistic regression analyses showed that only SO_2 was significantly associated with increased risk of DES (OR: 1.05, 95 % CI: 1.02–1.09, per standard deviation increment in SO_2 concentration) (Table 2), whereas no significant associations were found for other air pollutants. The possible underlying mechanisms of air pollution-induced DES are

Table 1
Characteristics of participants by dry eye symptoms (DES).

Characteristics	DES (n = 9559)	Non-DES (n = 12,350)	P value
AQI	68.0 (19.9)	68.2 (19.8)	.52
$PM_{2.5}$ (μg/m^3)	17.4 (5.5)	17.4 (5.1)	.84
PM_{10} (μg/m^3)	35.6 (14.1)	35.6 (12.5)	.95
SO_2 (μg/m^3)	6.9 (2.8)	6.7 (2.6)	<.001
CO (mg/m^3)	0.55 (0.13)	0.55 (0.13)	.29
NO_2 (μg/m^3)	15.9 (4.9)	16.1 (4.8)	.01
O_3 (μg/m^3)	116.0 (26.8)	116.3 (27.0)	.39
Residing near industrial zones (%)	767 (8.0)	526 (4.3)	<.001
RH (%)	69.2 (10.1)	69.2 (9.7)	.75
Temperature (°C)	25.9 (3.6)	26.2 (3.3)	<.001
Age (years)	40.2 (19.4)	38.8 (18.4)	<.001
Women (%)	4862 (50.9)	6091 (49.3)	.02
Urban (%)	6469 (67.7)	8712 (70.5)	<.001
Education level (%)			
High school or below	4627 (48.4)	6326 (51.2)	<.001
College or above	4932 (51.6)	6024 (48.8)	
Household income (%)			
Low	4096 (42.8)	4773 (38.6)	<.001
High	5463 (57.2)	7577 (61.4)	
BMI	21.6 (3.9)	21.8 (3.7)	<.001
Ever smoking (%)	1979 (20.7)	2034 (16.5)	<.001
Secondhand smoke exposure (%)	4913 (51.4)	5841 (47.3)	<.001
Alcohol drinking (%)	2193 (22.9)	2359 (19.1)	<.001
Hypertension (%)	1026 (10.7)	885 (7.2)	<.001
Diabetes (%)	343 (3.6)	309 (2.5)	<.001
Dyslipidemia (%)	419 (4.4)	300 (2.4)	<.001
Myopia (%)	4025 (42.1)	4251 (34.4)	<.001
Cataract (%)	309 (3.2)	86 (0.7)	<.001
Glaucoma (%)	210 (2.2)	85 (0.7)	<.001
Retinal diseases (%)	153 (1.6)	46 (0.4)	<.001
Problematic Internet use	13.6 (5.8)	10.3 (4.8)	<.001
Depression (%)	3562 (37.3)	1424 (11.5)	<.001
Anxiety (%)	2345 (24.5)	760 (6.2)	<.001
Subjective health awareness (VAS)	67.2 (23.0)	78.2 (19.1)	<.001

Mean (SD) for continuous and No. (%) for categorical variables are presented. The differences in characteristics between groups were analyzed using the chi-square test for categorical variables and t-tests for continuous variables. *P* values indicated the overall significance of each comparison.

DES: dry eye symptoms; SD: standard deviation; AQI: air quality index; PM: particulate matter; SO_2: sulfur dioxide; CO: carbon monoxide; NO_2: nitrogen dioxide; O_3: ozone; RH: relative humidity; BMI: body mass index; VAS: visual analog scale.

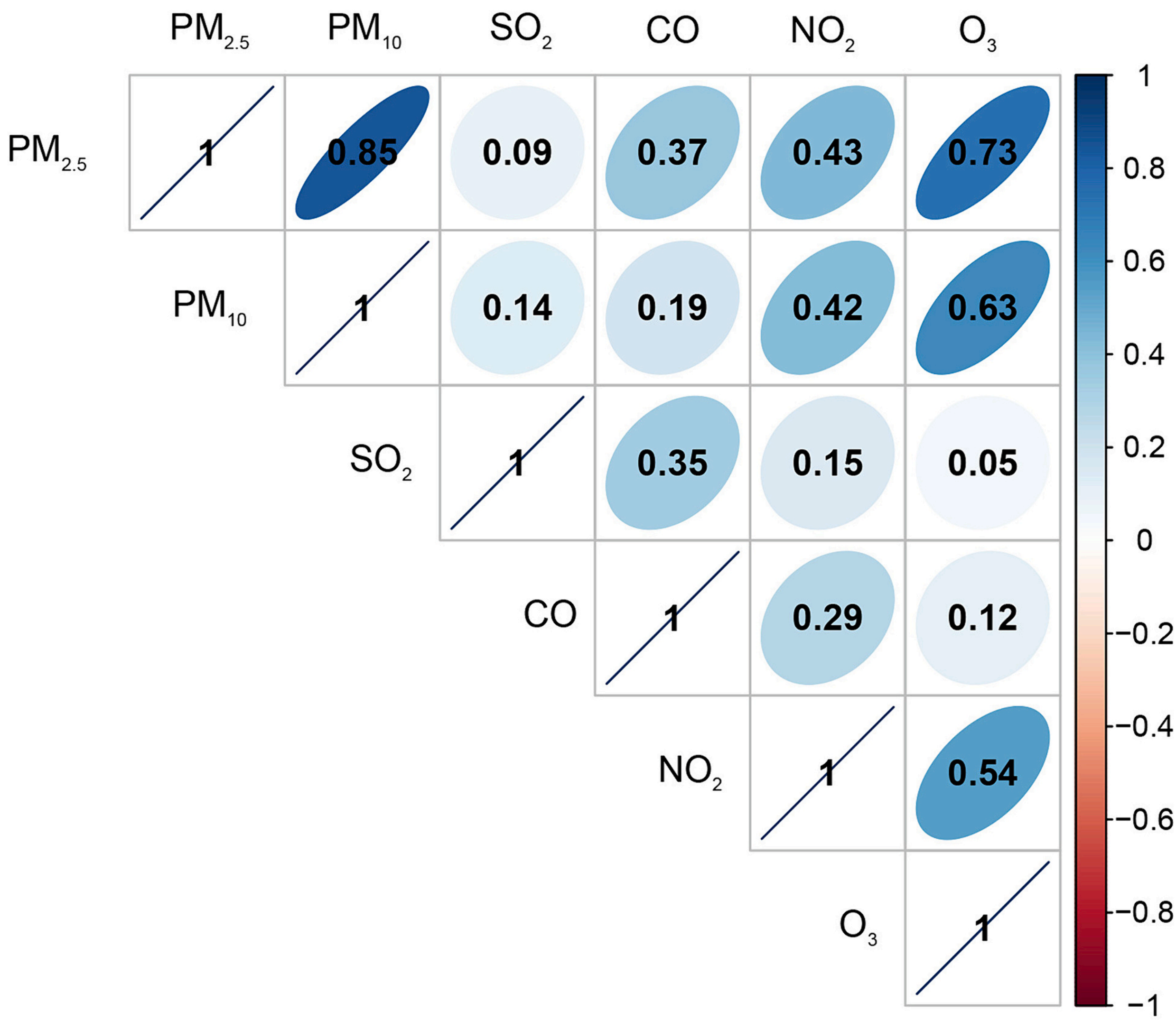

Fig. 1. Correlation plots showing Pearson correlation values of air pollutants.
Dark blue ellipses represent strong positive correlations and light blue ellipses represent weak positive correlations.
PM: particulate matter; SO_2: sulfur dioxide; CO: carbon monoxide; NO_2: nitrogen dioxide; O_3: ozone.

presented in Fig. 3.

The joint effect of SO_2 and depression (OR: 2.50, 95 % CI: 2.10–2.97) was larger than their separate effects (SO_2 OR: 1.14, 95 % CI: 1.02–1.26; depression OR: 2.15, 95 % CI: 1.82–2.54), denoting a synergetic interaction with a SI of 1.17 (95 % CI: 0.84–1.62) (Table 3). We also found a synergetic interaction of SO_2 and problematic internet use on DES with a SI of 1.31 (95 % CI: 1.04–1.65). Residing near industrial zones was significantly correlated with higher risk of DES (OR: 1.57, 95 % CI: 1.38–1.79) (Table 4). The variable with higher relative importance as indicated by SRC was cataract (SRC: 1.27), followed by retinal diseases (SRC: 0.75), depression (SRC: 0.74), anxiety (SRC: 0.60), problematic internet use (SRC: 0.59) and residing near industrial zones (SRC: 0.45).

The results of sensitivity analyses are presented in Supplemental Table S2. The associations of DES with SO_2 and residing near industrial zones remained significant ($P < .05$ for both) after excluding participants with ocular diseases including myopia, cataract, glaucoma and other retinal diseases. In the subgroup analysis divided by age (Supplemental Table S3), SO_2 maintained a significant association with DES (OR: 1.14, 95 % CI: 1.08–1.21) only among participants aged over 50 years. Similarly, significant associations between residing near an industrial zone and DES were observed among participants aged 20–50 years (OR: 1.64, 95 % CI: 1.38–1.96) and those aged over 50 years (OR: 1.84, 95 % CI: 1.42–2.38).

4. Discussion

In the present study, we estimated the prevalence of DES among the general population during the pandemic and investigated the associations between air pollution variables and DES. We found that residing near industrial zones had a robust association with increased risk of DES. However, no significant association was observed between DES and air pollutants except SO_2. Among the risk factors included in the logistic regression analyses, depression, anxiety and problematic internet use had larger relative importance.

SO_2 concentrations were linearly correlated with the risk of DES without any meaningful threshold, indicating that even low concentrations of SO_2 can trigger adverse effects on the ocular surface. A study conducted in South Korea found similar results (Um et al., 2014). The authors investigated the associations of dry eye with SO_2, NO_2, O_3, CO and PM_{10} and reported that only SO_2 was significantly associated with dry eye. Another case-crossover study conducted in China have also found that a 10 μg/m^3 increase in SO_2 concentrations was significantly associated with outpatient visits for dry eye (Mo et al., 2019). The mechanism underlying air pollution-induced dry eye is still not well understood. It has been postulated that SO_2, a combustion product mainly from motor vehicles and industries, may act as a hapten after being solubilized and forming sulfates, which could lead to immune-

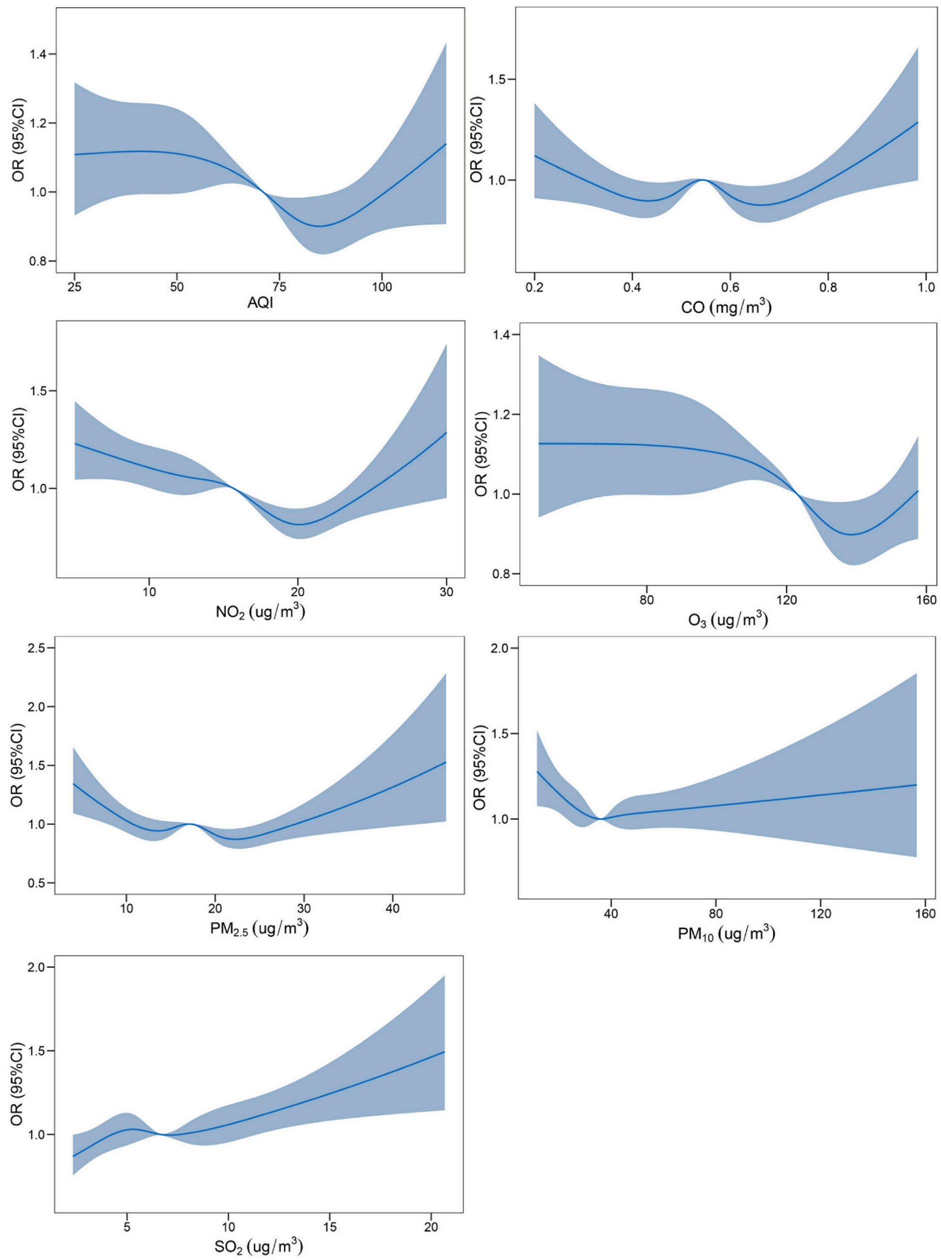

Fig. 2. The concentration-response relationships between air pollutants, air quality index and dry eye symptoms. Shaded areas show confidence intervals.
All the models adjusted for age, sex, residence, education level, household income, body mass index, ever smoking, secondhand smoke exposure, alcohol drinking, hypertension, diabetes, dyslipidemia, myopia, cataract, glaucoma, retinal diseases, problematic internet use, depression, anxiety, subjective health awareness, temperature, and relative humidity.
OR: odds ratio; CI: confidence interval; AQI: air quality index; PM: particulate matter; SO_2: sulfur dioxide; CO: carbon monoxide; NO_2: nitrogen dioxide; O_3: ozone.

mediated damage in the ocular surface epithelium (Jung et al., 2018). Another possible explanation is that the tear pH is decreased after the solubilization of SO_2, which triggers eye irritation (Andrés et al., 1988). In addition, a prospective cohort study found that exposure to SO_2 was correlated with increasing corneal staining score and decreasing tear film break-up time (Hao et al., 2022). However, some studies have reported contradictory results. The findings from another crossover study conducted in northeast China indicated that the relation between SO_2 and the risk of dry eye was insignificant (Lu et al., 2023). The authors additionally considered the effect of climate change and meteorological factors including air pressure and wind speed, which may partly contribute to the differences in our findings. Further research is needed to examine the relationship between SO_2 and DES.

Although no significant associations were found for $PM_{2.5}$, PM_{10}, CO, NO_2 and O_3, we should not rule out the possibility that the five air pollutants may also be risk factors for DES. Several epidemiologic studies have supported the role of these pollutants in increasing the risk of dry eye (Kim et al., 2020; Hwang et al., 2016; Mandell et al., 2020). Animal experiments also found that exposure to particulate matter can lead to decreased tear volume in rats and may induce dry eye (Song et al., 2020). The difference between our findings and prior research results may be attributed to the special period during which our study was conducted. During the pandemic, to prevent the spread of COVID-19, people reduced time spent outdoors and increased indoor activities, which in turn reduced their exposure to ambient air pollutants (Recchioni et al., 2022). As indicated by the RCS plots, unlike SO_2, there may exist thresholds for the other five pollutants. Therefore, the actual decreased exposure to air pollutants may have biased the results.

Table 2
Logistic regression analyses of the associations between air pollution variables and dry eye symptoms.

Variable	OR (95 % CI)[a]	P value
$PM_{2.5}$	1.03 (0.92, 1.16)	.62
PM_{10}	1.03 (0.98, 1.08)	.29
SO_2	**1.05 (1.02, 1.09)**	**<.001**
CO	0.95 (0.80, 1.12)	.53
NO_2	1.02 (0.83, 1.25)	.84
O_3	0.74 (0.53, 1.05)	.09
AQI	0.82 (0.65, 1.04)	.10

Bold indicates significant associations (P < .05).
Multivariate models adjusted for age, sex, residence, education level, household income, body mass index, ever smoking, secondhand smoke exposure, alcohol drinking, hypertension, diabetes, dyslipidemia, myopia, cataract, glaucoma, retinal diseases, problematic internet use, depression, anxiety, subjective health awareness, temperature, and relative humidity.
OR: odds ratio; CI: confidence interval; SD: standard deviation; AQI: air quality index; PM: particulate matter; SO_2: sulfur dioxide; CO: carbon monoxide; NO_2: nitrogen dioxide; O_3: ozone.
[a] Adjusted ORs (95 % CI) of dry eye symptoms per SD increment of AQI/air pollutant concentrations above their threshold (AQI > 85, $PM_{2.5}$ > 22 μg/m^3, PM_{10} > 36 μg/m^3, CO > 0.66 mg/m^3, NO_2 > 20 μg/m^3, O_3 > 139 μg/m^3). There was no threshold for SO_2.

Residing near industrial zones showed a robust association with a higher risk of DES. A study from Argentina have reported similar findings (Gutierrez et al., 2019), in which subjects residing in industrial zones had a higher incidence of dry eye. Our results reflect that although the associations between air pollutants and DES may have been weakened during the pandemic among general population, the adverse health effect of long-term exposure to high concentrations of air pollutants may not change. Therefore, future urban planning should plan industrial zones further away from residential areas.

The standardized regression coefficients indicated that cataract attained the highest relative importance among all the risk factors, followed by retinal diseases. Several studies have previously identified cataract surgery as a risk factor for DES (Vehof et al., 2021, 2014). Dry eye might be a complication of these ocular disorders. In addition, depression, anxiety and problematic internet use had larger relative importance than the air pollution in the present study. This observation might shed light on why the prevalence of DES remained elevated during the pandemic, even in the presence of reduced exposure to outdoor air pollution. Previous studies have reported increased prevalence of problematic internet use, depression and anxiety during the pandemic (Gjoneska et al., 2022; Hawes et al., 2022), which may have contributed to the high prevalence of DES. A study on shielding patients during the COVID-19 lockdown has obtained similar results (Recchioni et al., 2022). They found no significant correlation between DES and air pollutants during the pandemic. The air pollutant concentrations were reduced during the lockdown whereas the dry eye symptoms persisted, which may be attributed to increased time spent on digital devices. In

Table 3
The additive interactions of air pollutants and other risk factors on the risk of dry eye symptoms.

Subgroups	OR (95 % CI)[a]
SO_2-Depression	
Low-No	Reference
High-No	1.14 (1.02, 1.26)
Low-Yes	2.15 (1.82, 2.54)
High-Yes	2.50 (2.10, 2.97)
SI	1.17 (0.84, 1.62)
SO_2-Problematic internet use	
Low-Low	Reference
High-Low	1.06 (0.94, 1.21)
Low-High	2.19 (1.93, 2.48)
High-High	2.65 (2.32, 3.02)
SI	1.31 (1.04, 1.65)

OR: odds ratio; CI: confidence interval; SO_2: sulfur dioxide; SI: synergy index.
[a] Adjusted for age, sex, residence, education level, household income, body mass index, ever smoking, secondhand smoke exposure, alcohol drinking, hypertension, diabetes, dyslipidemia, myopia, cataract, glaucoma, retinal diseases, problematic internet use, depression, anxiety, subjective health awareness, temperature, and relative humidity.

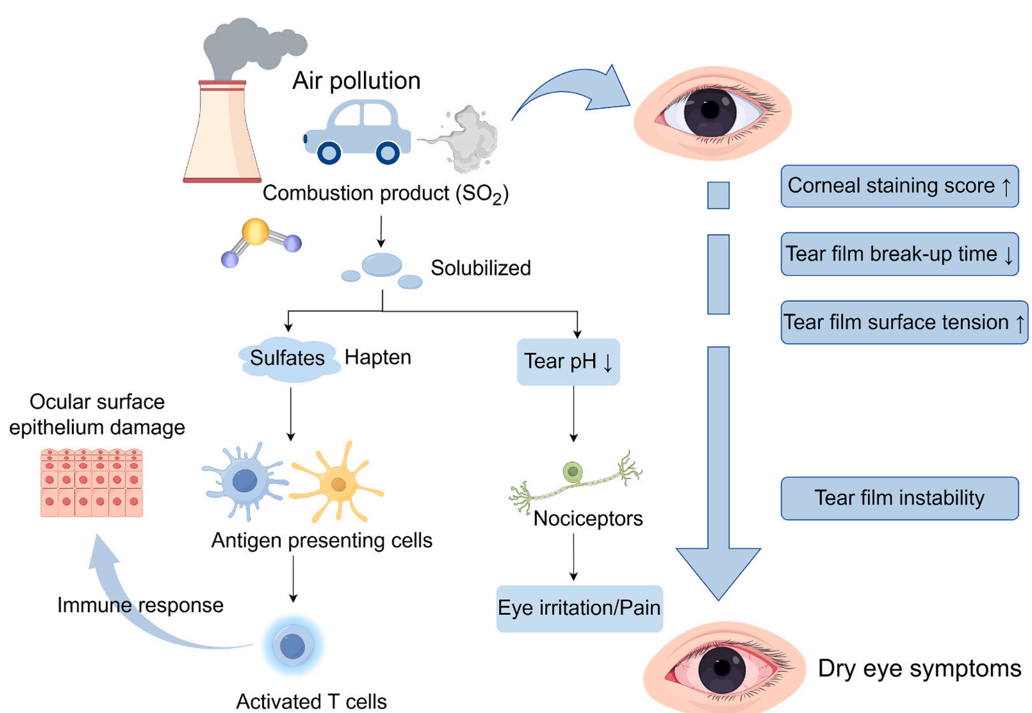

Fig. 3. Possible underlying mechanisms of air pollution-induced dry eye symptoms.

Table 4
Odds ratios and standardized regression coefficients (in decreasing order) of possible risk factors for dry eye symptoms.

Variable	OR (95 % CI)	P value	Standardized regression coefficient
Cataract	3.57 (2.66, 4.78)	<.001	1.27
Retinal diseases	2.12 (1.42, 3.17)	<.001	0.75
Depression	2.09 (1.88, 2.32)	<.001	0.74
Anxiety	1.82 (1.59, 2.09)	<.001	0.60
Problematic Internet use	1.80 (1.72, 1.87)	<.001	0.59
Residing near industrial zones	1.57 (1.38, 1.79)	<.001	0.45
Glaucoma	1.55 (1.12, 2.14)	.009	0.44
Myopia	1.51 (1.39, 1.63)	<.001	0.41
Subjective health awareness	0.69 (0.67, 0.72)	<.001	−0.37
Hypertension	1.38 (1.21, 1.58)	<.001	0.32
Age	1.34 (1.28, 1.40)	<.001	0.29
Dyslipidemia	1.24 (1.01, 1.52)	.04	0.22
Sex	1.21 (1.12, 1.30)	<.001	0.19
Household income	0.86 (0.80, 0.93)	<.001	−0.15
Alcohol drinking	1.15 (1.05, 1.27)	.003	0.14
Secondhand smoke exposure	1.15 (1.07, 1.24)	<.001	0.14
Education level	0.89 (0.82, 0.96)	.002	−0.12
Ever smoking	1.08 (0.97, 1.19)	.16	0.07
Residence	0.93 (0.86, 1.01)	.09	−0.07
Temperature	0.94 (0.90, 0.97)	<.001	−0.07
Diabetes	1.06 (0.86, 1.31)	.56	0.06
RH	0.94 (0.91, 0.98)	.001	−0.06
BMI	0.96 (0.92, 0.99)	.02	−0.04

OR: odds ratio; CI: confidence interval; BMI: body mass index; RH: relative humidity.

addition, the subgroup analysis by age groups has shown that the association between air pollution and DES was more significant among the elderly. The interaction analyses indicate synergetic interactions of SO_2 with depression and problematic internet use on DES. Thus, the elderly and those with depression or problematic internet use may be more vulnerable to air pollution.

To our knowledge, this is the first study to examine the relationship between air pollution and DES during the pandemic. The large nationally representative sample is an advantage of our study. However, limitations should also be considered. Firstly, we failed to perform objective examinations such as the Schirmer tear test to detect clinical signs of dry eye. Therefore, DES could not be extrapolated to clinically diagnosed dry eye disease in this study. Secondly, we used the three-month averaged air pollution data collected from the air quality monitoring stations, which may not be accurate in exposure assessment. Thirdly, other possible confounding factors such as the use of eye drops and residential greenness were not controlled, which could have biased the results.

5. Conclusion

In conclusion, residing near industrial zones and exposure to SO_2 were significantly associated with increased risk of DES, while no significant correlations were observed for $PM_{2.5}$, PM_{10}, CO, NO_2, O_3. The effect of air pollution on DES may have been mitigated during the pandemic due to increased time spent indoors. Conversely, emerging issues such as depression, anxiety and problematic internet use may have played a more pronounced role in the development of DES. Further studies are warranted to validate our findings.

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Ethical approval

The survey was approved by the Medical Ethics Committee (No. JKWH-2022-02) and the Clinical Research Ethics Committee of the Second Xiangya Hospital of Central South University (No.2022-K050). The study compiled with the Declaration of Helsinki. All subjects provided written informed consent.

CRediT authorship contribution statement

Jia-Yan Kai: Writing – review & editing, Writing – original draft, Formal analysis. **Yi-Bo Wu:** Writing – review & editing, Data curation. **Xing-Xuan Dong:** Writing – review & editing, Formal analysis. **Yi-Fan Miao:** Writing – review & editing, Data curation. **Dan-Ning Hu:** Writing – review & editing, Formal analysis. **Carla Lanca:** Writing – review & editing, Formal analysis. **Andrzej Grzybowski:** Writing – review & editing, Formal analysis. **Chen-Wei Pan:** Writing – review & editing, Conceptualization.

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.

Data availability

The data that has been used is confidential.

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None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.173386.

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