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Children's Allergic Sensitization to Pets: The Role of Air Pollution

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Abstract

Allergic sensitization (AS) to pets is a notable health concern, with a 10–30% prevalence in developed countries, significantly higher than in developing nations; however, the critical exposure windows and reasons for this global disparity remain unclear. This study aimed to investigate associations between perinatal and current animal exposure and childhood AS among 2598 preschoolers (aged 3–6) in Changsha, China. Data on AS and pet exposure were gathered via questionnaires, while children's prenatal and current exposure to outdoor air pollutants (PM_{10}, NO_2) was estimated from monitoring stations. Multiple logistic regression models revealed an overall AS prevalence of 1.8%. Current animal or pet exposure was significantly associated with childhood AS (adjusted OR 2.40, 95% CI 1.12–4.29). Conversely, no significant association was found for perinatal exposure. Intriguingly, a stratified analysis showed that the association with current exposure was significant only in children exposed to low levels of outdoor PM_{10} (adj. OR 2.97, 95% CI 1.21–7.27) and NO_2 (adj. OR 3.01, 95% CI 1.23–7.37). The study concludes that current exposure to pets significantly increases childhood AS risk. This effect is unexpectedly magnified in environments with low outdoor air pollution. This novel finding not only may explain the higher prevalence of pet allergies in developed countries but also suggests that as air quality improves alongside rising pet ownership, developing nations like China could face a significant future increase in pet sensitization, highlighting a critical emerging public health challenge.

Keywords: allergic sensitization; pet allergy; hypersensitivity; furry animals; air pollution

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1. Introduction

With the advancement of social technologies, individuals are experiencing increasing isolation and loneliness. Dogs have the ability to socialize flexibly and be sensitive to human behavior [1], and positive interactions such as sustained eye contact and hugging between humans and dogs cause oxytocin to spike in both, which is linked to positive emotions [2,3]. Keeping pets has a positive impact on mental health [4,5] through a series of mechanisms, including reducing stress [6,7], promoting social interaction [8,9], and providing emotional support [10]. In addition, psychological well-being improved with an increase in the number of pets owned, while life satisfaction rose with higher levels of perceived support from pets [11]. Pets are helpful as friends to children's growth and development [12]. Therefore, the demand for the companionship of pets is constantly

increasing. The proportion of pet owners ranges from about 19% in Greece to about 22% in South Korea and 70% in America [13–16]. The number of pets in Japan exceeds the number of children [17]. The increase in pet ownership led to an increase in asthma and allergic diseases over the past five years [18]. The prevalence of allergic sensitization (AS) to pets is growing and accompanies the increase in pet [19–21] ownership. AS to pets is considered one of the most important causes of severe asthma [22].

Sensitization to cat dander and other inhaled allergens is more frequent in preschool and school-age children [23]. The results of a recent study on the effect of early exposure (for example, perinatal and infantile exposure) to animal allergens on AS in childhood are complex and unclear [24–26]. The results of another study are contradictory [27]. Some studies have shown that animal ownership in early life can help prevent the risk of subsequent AS and asthma [28–37], some have reported that it has no effect [23,24,38–40], while others have suggested that it increases the risk of developing asthma [41,42]. However, more and more studies have shown that pet exposure [43], endotoxin [44–47] and air pollution [48–50] are all related to increased reports of allergies and asthma at some stage of life [51]. Many studies have shown that exposure to animals, and particularly to cats, can lead to a higher risk of AS in children [23,24,52,53]. In addition, research indicates that pet ownership is associated with increased asthma severity in children with atopic asthma, regardless of their pet sensitization status [54]. The key exposure window impacting AS to pets needs further study.

An estimated 10-30 percent of people show AS to pets in developed countries [55]. In most developing countries, the prevalence of AS to pets is much less than in developed countries [56]. The key reason of the difference is still unknown. A study has shown that keeping pets can reduce respiratory diseases and asthma in Chinese children caused by outdoor air pollution [51]. However, there are very few studies that investigate the effect of air pollution on the association between exposure to animals or pets and children's AS.

The interplay between pet allergen exposure and air pollution is an area of growing interest. Epidemiologically, the varying air quality levels across regions with differing pet ownership rates might contribute to heterogeneous AS prevalences. Immunologically, air pollutants can act as adjuvants, potentially exacerbating immune responses to inhaled allergens like those from pets or increasing airway inflammation and permeability [57,58]. The odds ratios are crucial, especially in regions undergoing changes in both pet ownership and air quality.

The rising pet ownership, driven by socioeconomic shifts and changing lifestyles, has been paralleled by an increase in the global prevalence of allergic sensitization (AS) to pets [18,20,21,59]. A key paradox remains: the prevalence of pet-related AS is significantly higher in developed countries than in many developing nations, and the reasons for this disparity are poorly understood. One underexplored hypothesis is that ambient air pollution may modify the association between pet exposure and AS. Addressing this issue, this study draws on data from a large Chinese cohort and aims to answer two primary questions: (1) Is the critical window for pet-related AS development situated in the perinatal period or in the current period? (2) Could the effect of air pollution on pet–AS association help explain the observed global disparity in allergy prevalence?

2. Materials and Methods

2.1. Study Protocol and Questionnaire

This investigation drew upon data from a cross-sectional survey conducted in Changsha, China, between September 2011 and January 2012. This survey formed part of the national "China–Children–Homes–Health (CCHH)" study [60]. The study design received approval from the Ethics Committee of Central South University, and its methodology has

been comprehensively detailed in prior publications [48]. Information collection was primarily facilitated by a standardized questionnaire, adapted from the International Study of Asthma and Allergies in Childhood (ISAAC) [20] and a Swedish questionnaire focused on building dampness and health (DBH) [19,61]. In total, 4,988 questionnaires were distributed to children attending 36 kindergartens (Figure 1). Following the exclusion of incomplete responses, a final dataset of 2598 valid questionnaires from children aged 3–6 years was incorporated into the analysis.

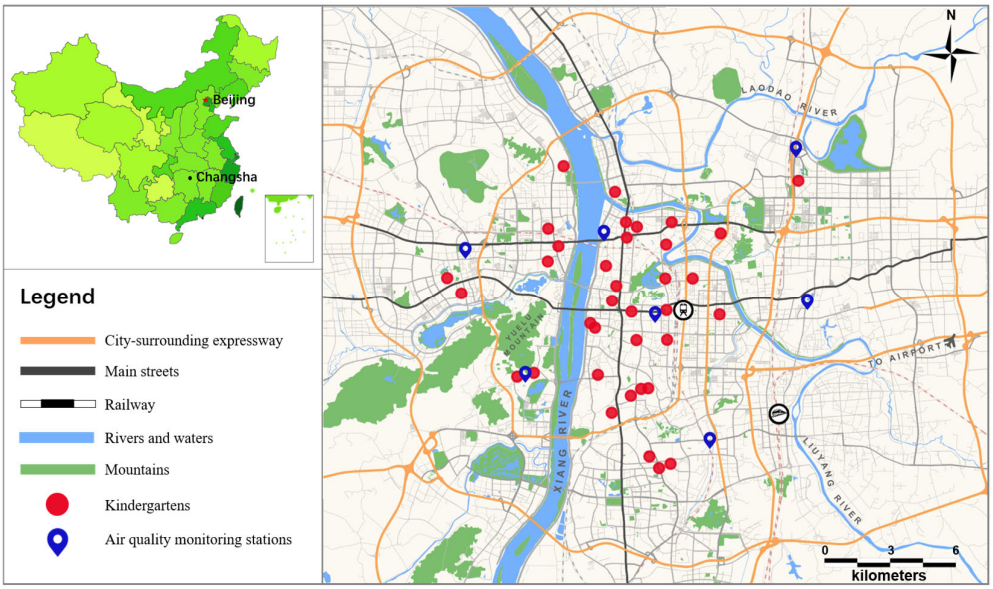

Figure 1. Distribution of 36 kindergartens and seven air pollution monitoring stations in Changsha.

2.2. Exposure Windows

For outdoor air pollution, two primary exposure windows were defined: prenatal and current. The prenatal period encompassed the duration from the first month through the final month of pregnancy. The current period referred to the preceding 12 months or recent year. Similarly, exposure to animals or pets was categorized into perinatal and current periods, with the perinatal period signifying the child's birth time.

2.3. Exposure to Animals or Pets

Perinatal and current exposure to animals or pets was ascertained through confirmed responses to two questionnaire items: "When the child was born, did you keep animals or pets in your residence?"; and "Currently, do you keep animals or pets in your residence?"

2.4. Exposure to Air Pollution

Three air pollutants were chosen for analysis: sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and particulate matter with a diameter of $\leq$10 μm (PM_{10}). SO_2 served as an indicator of industrial-related air pollution (IRAP) [59,62,63], NO_2 represented traffic-related air pollution (TRAP), and PM_{10} acted as a surrogate for complex pollutant mixtures [64]. The daily (24 h) average concentrations of these pollutants were procured from monitoring stations. Each child's exposure to air pollution was then estimated using the inverse distance weighted (IDW) method, as described elsewhere [64]. The monthly average concentrations of PM_{10}, SO_2, and NO_2 were utilized to compute prenatal exposure (spanning the entire pregnancy) and current exposure (covering the 12 months preceding questionnaire completion).

2.5. Health Outcome

The primary health outcome in this study was allergic sensitization (AS) to pets. This was identified by a positive response to the questionnaire item: "During the past 12 months, did your child have rhinitis-like and eye symptoms including sneezing, running nose, stuffy nose, eye pain, and tears after contact with pets?"

2.6. Confounding Covariates

Potential confounding variables, collected via the parent-administered questionnaire, included personal factors (child's sex, age, birth season, breastfeeding status, antibiotic use, parental atopy, and house size) and indoor environmental factors [65]. The indoor environment-related factors comprised environmental tobacco smoke (ETS) exposure at home, presence of new indoor furniture, recent house redecoration, visible mold/damp stains, and winter window condensation [66–71]. Comprehensive details regarding these covariates are provided in Table S1.

2.7. Statistical Analysis

The associations between childhood AS to pets and both perinatal and current exposure to animals/pets, alongside the outdoor levels of air pollutants (PM_{10}, SO_2, and NO_2), were assessed using multiple logistic regression models. The results are presented as odds ratios (ORs) with corresponding 95% confidence interval (95% CI). For childhood AS linked to pet exposure, ORs were derived from classification models, using non-exposure as the reference category. The relationship between childhood AS to pets and outdoor air pollutant exposure was investigated using continuous models. In these continuous models, OR (95% CI) values were calculated per interquartile range (IQR) increase for each pollutant. To explore the potential effect of air pollution, outdoor air pollutants (PM_{10}, SO_2, NO_2) were stratified into low (<median)- and high (≥median)-exposure subgroups. This stratification was adopted for the initial exploratory analysis due to the limited number of AS cases, which could challenge the stability of continuous interaction models. While acknowledging that dichotomizing exposure variables may reduce statistical power and potentially obscure true dose–response relationships for an interaction, this approach provided a feasible starting point. The risk of AS to pets associated with current pet exposure was then evaluated within these established strata. A p-value less than 0.05 ($p < 0.05$) was deemed statistically significant. All statistical computations were performed using SPSS software (version 16.0, SPSS Inc., Chicago, IL, USA).

3. Results

Of the 2598 children, 48 (1.8%) had AS to pets in the last 12 months. Table 1 shows the prevalence of AS to pets stratified by covariates. We found that children with parental atopy (3.2%) had significantly higher prevalence than those without parental atopy (1.7%) ($p < 0.05$). New furniture was found to have a significant effect on AS to pets. We further observed a higher prevalence of AS to pets in boys (2.3%), children without breastfeeding (3.2%), and those living in a dwelling with mold/damp stains (2.6%) compared to girls (1.3%), children with breastfeeding (1.7%), and those living in a dwelling without mold/damp stains, although the difference did not reach statistical significance. However, no difference in the prevalence was observed among children stratified by all the other covariates, including age, birth season, antibiotics use, house size, ETS at home, house redecoration, and window condensation in winter.

Table 1. Covariates, demographic information, and prevalence of allergic sensitization to pets among children 3–6 years old (n = 2598).

	n (Case)/N (Number)	Prevalence (%)	p-Value
Total	48/2598	1.8	—
Sex			
Boys	32/1399	2.3	0.071
Girls	16/1199	1.3	
Age (years)			
3	10/665	1.5	0.182
4	14/952	1.5	
5	22/815	2.7	
6	2/166	1.2	
Birth season			
Warm (May–September)	21/1152	1.8	0.928
Cold (October–April)	27/1446	1.9	
Breastfeeding			
No	7/222	3.2	0.124
Yes	41/2376	1.7	
Antibiotics use			
No	7/432	1.6	0.650
Yes	41/2115	1.9	
Parental atopy			
No	372214	1.7	**0.046**
Yes	11/340	3.2	
House size (m^2)			
≤75	19/836	2.3	0.306
>75	29/1732	1.7	
Environmental tobacco smoke (ETS) at home			
No	16/864	1.9	0.997
Yes	32/1734	1.8	
Indoor new furniture			
No	16/1248	1.3	**0.036**
Yes	28/1156	2.4	
House redecoration			
No	26/1689	1.5	0.356
Yes	13/620	2.1	
Visible mold/damp stains at home			
No	32/1985	1.6	0.101
Yes	16/606	2.6	
Window condensation in winter			
No	18/1175	1.5	0.217
Yes	30/1369	2.2	

The p-values < 0.05 are in bold.

Animal or pet ownership during the perinatal and current periods was reported by 9.2% and 14.2% of all families, respectively. Table 2 provides the association between exposure to animals or pets during the perinatal and current periods and childhood AS to pets. The ORs in the crude model was similar to that in the adjusted model. We found that only current exposure to animals or pets was significantly associated with childhood AS to pets, with adjusted OR (95% CI) = 2.40 (1.17–4.93). In contrast, no risk of AS to pets was observed due to perinatal exposure to animals or pets.

Table 2. Association between perinatal and current animal or pet ownership and allergic sensitization to pets in children (n = 2598).

	n with AS/total N	(%)	Crude OR (95% CI)	Adjusted OR (95% CI) #
Perinatal animal or pet ownership				
No (Ref = no pet exposure)	44/2341	(1.9)	1	1
Yes	4/238	(1.7)	0.89 (0.32–2.51)	1.09 (0.38–3.15)
Current animal or pet ownership				
No (Ref = no pet exposure)	36/2216	(1.6)	1	1
Yes	12/369	(3.3)	2.02 (1.04–3.93) *	2.40 (1.17–4.93) *

Models were adjusted for all the covariates in Table 1. * $p \leq 0.05$.

We did not find a significant risk of childhood AS to pets due to prenatal and current exposure to outdoor air pollutants including PM_{10}, SO_2, and NO_2 (Table 3, personal exposure levels of the three air pollutants shown in Table S2). However, all ORs for pet-related AS associated with current exposure to outdoor air pollution were below 1.

Table 3. Associations between prenatal and current exposure to outdoor air pollution and allergic sensitization to pets in children (n = 2598).

	Crude OR (95% CI)	Adjusted OR (95% CI) #
Outdoor air pollution		
Prenatal		
PM_{10}	1.09 (0.80–1.48)	0.84 (0.50–1.42)
SO_2	1.12 (0.77–1.65)	0.92 (0.55–1.53)
NO_2	0.74 (0.47–1.16)	0.62 (0.33–1.14)
Current		
PM_{10}	0.83 (0.46–1.48)	0.64 (0.32–1.28)
SO_2	0.99 (0.61–1.61)	0.90 (0.52–1.57)
NO_2	0.94 (0.50–1.75)	0.74 (0.36–1.55)

OR (95% CI) was estimated for an IQR increase in PM_{10}, SO_2, and NO_2. # Models were adjusted for all the covariates in Table 1.

A significant association between current exposure to animal or pets and AS to pets was detected in children with low exposure to outdoor air pollution (PM_{10} and NO_2), respectively, with ORs (95% CI) = 2.97 (1.21–7.27) and 3.01 (1.23–7.37), compared to children with high exposure (Table 4).

Table 4. Associations between current animal or pet ownership and allergic sensitization to pets in children stratified by low and high levels of current exposure to outdoor air pollution (n = 2598).

	Exposure Level	Number	OR (95% CI)
Outdoor air pollution			
PM_{10}	Low	1277	2.97 (1.21–7.27) *
	High	(1321	1.60 (0.43–5.91)
SO_2	Low	1288	2.22 (0.84–5.89)
	High	1310	2.80 (0.93–8.46)
NO_2	Low	1283	3.01 (1.23–7.37) *
	High	1315	1.59 (0.43–5.86)

Exposure levels were divided into low (<median) and high (≥median) categories. (For detailed exposure levels please refer to Table S2). OR (95% CI) was adjusted for all the covariates in Table 1. * $p \leq 0.05$.

4. Discussion

This study yields two principal findings. First, concerning the exposure window for pet-related allergic sensitization (AS) in preschool children, our data indicate that current exposure, rather than perinatal exposure, is the primary risk factor. Second, and most novel, this association appears to be significantly modified by ambient air pollution; the

risk conferred by current pet exposure was only statistically significant in environments with lower concentrations of outdoor air pollutants.

Our finding on the critical exposure window aligns with a growing body of evidence. While some studies have reported no strong association between pet exposure in infancy and later sensitization [23,38,39], our results are consistent with research identifying ongoing animal contact as a significant risk factor for AS and respiratory symptoms at various life stages [51,72–74]. This distinction reinforces the hypothesis that for this age group, the allergenic risk stems more from concurrent exposure than from immune programming effects in early life.

The most important contribution of this study is the evidence for effect modification. The association between current pet exposure and AS was statistically significant only among children exposed to lower levels of PM_{10} (OR = 2.97, 95% CI: 1.21–7.27) and NO_2 (OR = 3.01, 95% CI: 1.23–7.37). This observation is of considerable importance, as it offers a plausible explanation for a long-observed global paradox: the higher reported prevalence of pet allergies in developed countries, which generally have cleaner air, compared to many developing nations. To contextualize our setting, the air pollution level in Changsha (e.g., PM_{10}: 85 $\mu g/m^3$) is moderate on a national scale, making it a suitable environment to observe such modifying effects.

While our study was not designed to elucidate biological mechanisms, the observed interaction warrants speculation. Oxidative stress is a pathway implicated in many allergic disorders. Research has linked air pollutants like PAHs to allergic rhinitis via oxidative stress markers like 8-OHdG [75], and co-exposure to multiple pollutants has been shown to exacerbate symptoms by increasing markers such as malondialdehyde (MDA) [60]. It is conceivable that in low-pollution environments, the immune system's response is more specifically directed toward pet allergens, whereas in high-pollution settings, a generalized, pollution-driven oxidative stress response dominates. Further research is needed to clarify this interplay.

Our study reveals a seemingly paradoxical finding: the allergenic risk associated with pet exposure is amplified in cleaner air environments. This observation is supported by multiple lines of immunological evidence. Early-life exposure to farm environments and pet animals protects against allergy/asthma primarily through microbiota-driven immunomodulation, involving innate immune activation (e.g., TLR pathways), microbial metabolites (e.g., butyrate-induced Tregs), and Th1/Treg bias, with the prenatal-infant period as the critical window for durable immune programming [76]. Some research has shown that diesel exhaust particles enhance allergen-induced acute immune responses by promoting Th2-type cytokines (IL-4/IL-5) and antibody production [77,78]. Our epidemiological data provide novel evidence for this concept, suggesting that in cleaner environments, the immune system may be less preoccupied by competing stimuli, thereby increasing its propensity to mount a specific allergic response to pet dander.

We hypothesize that in heavily polluted environments, the pronounced immunomodulatory effects of high-level air pollution may mask or supersede the more subtle allergenic effects of pets. This implication is particularly relevant to public health trends in China. The nation's historically high levels of air pollution may have previously obscured the underlying risk of pet sensitization. Consequently, as China experiences two converging societal trends—rapidly rising pet ownership and steadily improving air quality—our findings suggest a significant, emerging public health challenge. The "clean air dividend" may be paradoxically accompanied by a substantial increase in pet sensitization, a phenomenon that warrants greater attention from public health authorities.

The findings of this study should be considered in light of several limitations. The primary strength is its basis in a large, multi-city cohort; however, the number of AS

cases in our specific sample (n = 48) was small, which limits the statistical power for interaction analyses and means that these particular findings should be interpreted as exploratory. Second, the AS outcome was based on parental-reported symptoms rather than clinical validation, which could have led to misclassification. Third, our exposure assessments lacked granularity; air pollution was estimated from ambient monitors, and pet exposure was not characterized by type or intensity. The limit of the reliance on outdoor data is partly mitigated by the local subtropical climate in Changsha, where frequent window opening likely strengthens the indoor–outdoor air quality correlation. Fourth, our use of dichotomized pollution data for the interaction analysis, while necessary for model stability with limited cases, sacrificed information on dose–response relationships. Finally, the cross-sectional nature of the data on current exposure and AS prevents us from establishing causality.

5. Conclusions

Our study found that exposure to animals or pets during the current period was significantly associated with the prevalence of AS to pets in children, particularly those who lived in areas with low levels of outdoor air pollution. The effect of the exposure to low levels of air pollution on AS associated with exposure to animals or pets may contribute to the rapid increase in childhood animal allergic sensitization, especially in high-income countries. Our findings highlight that current pet exposure is a key risk for childhood AS, and this risk is amplified in cleaner air environments. Our findings signal an emerging public health challenge for nations undergoing simultaneous improvements in air quality and increases in pet ownership. This suggests that public health strategies may need to shift from focusing solely on pollution-related illnesses to preparing for a higher burden of allergic diseases, developing targeted interventions for at-risk populations in these progressively cleaner environments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos16070833/s1, Table S1: Descriptions of and questions about confounding covariates related to childhood allergic sensitization to pets in this study; Table S2: Descriptive statistics of exposure levels for children aged 3–6 years (n = 2598); Table S3: Summary of mean concentration of air pollutants during current period and prevalence of current animal ownership and of allergic sensitization to pets among children in 7 cities in China (n = 39,782).

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Abbreviations

The following abbreviations are used in this manuscript:

AS	Allergic sensitization
CCHH	China–Children–Homes–Health
ETS	Environmental tobacco smoke
OR	Odds ratio
CI	Confidence interval

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