



ENVIRONMENTAL DETERMINANTS OF VEGETABLE ALLERGEN SENSITISATION IN A TEMPERATE CONTINENTAL REGION: EVIDENCE FROM POLAND

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ARTICLE INFO	ABSTRACT
Article History: Received: 12 January 2026 Revised: 1 April 2026 Accepted: 16 May 2026 Published: 15 September 2026 Keywords: Sensitisation, microparticles, soil contamination, indoor humidity, allergenic proteins, pesticide load	This study investigated the association between environmental factors and vegetable allergen sensitisation among adults residing in a temperate continental region A cross-sectional study was conducted between March 2023 and November 2023 involving 604 adults aged 18–65 years, living in urban and rural areas of Lublin Voivodeship. Standardised questionnaires, individual interviews, specific immunoglobulin E (IgE) testing to five vegetable allergens using ImmunoCAP, and environmental monitoring data on air quality and agrochemical load were utilised. The results showed that the overall prevalence of sensitisation was 28.5%, with urban residents exhibiting a higher rate (31.7%) compared to rural residents (25.8%, $p = 0.052$). Statistically significant positive correlations were found between sensitisation frequency and concentrations of particulate matter (PM_{2.5}) ($r = 0.41$, $p < 0.001$) and nitrogen dioxide (NO₂) ($r = 0.44$, $p < 0.001$), indicating the involvement of inhalant pollutants in modulating the immune response. In areas with intensive fertiliser use (up to 349.2 kg/ha/year), the sensitisation frequency reached 33.5%, especially with the application of nitrogen and phosphorus compounds. Increased indoor humidity ($> 65\%$) and a family history of allergies increased the risk of sensitisation to 36.7% and 41.8%, respectively. The architectural type of housing and the presence of pets had a combined influence depending on hereditary predisposition. The obtained data emphasise the importance of comprehensive environmental assessments when developing preventive programs and stratifying the risk of allergic diseases, especially in the context of urbanisation and intensive agricultural production.

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Introduction

The prevalence of allergic diseases continues to increase globally, affecting a significant portion of both adult and paediatric populations. Of particular concern is the increasing prevalence of allergies to plant-derived foods, including vegetables, specifically vegetables, which were previously considered predominantly hypoallergenic. This phenomenon is becoming increasingly relevant in light of changing environmental conditions, urbanisation, and

the transformation of agricultural practices. The prevalence of food allergies has more than doubled in recent decades, especially in industrialised regions, which calls for a rethinking of risk factors and mechanisms of sensitisation (Pilecka *et al.*, 2017; Dudarev & Kukhar, 2025). In moderately continental climates, typical for most territories of Eastern Europe, there is a combination of unfavourable atmospheric conditions, high agrochemical load,

and increasing air pollution levels, which can act as a catalyst for allergenic processes. However, the role of these factors in the development of vegetable allergies remains insufficiently studied, despite the growing number of clinical cases of sensitisation to crops such as carrots, celery, tomatoes, and cabbage.

Most epidemiological studies have focused on respiratory and seasonal allergies, whereas food allergen sensitisation has received comparatively less attention. Often, food allergies are treated as an isolated pathology, without considering interactions with variables such as air pollution levels, housing conditions, and agrochemical load in the region of residence. Sikorska-Szaflik and Sozańska (2025) investigated the relationship between air pollution and allergic reactions, establishing the impact of PM_{2.5} and NO₂ on the development of bronchial asthma. However, their study did not differentiate between allergen types, and food sensitisation was not considered, limiting the interpretation of the data in the context of food allergies.

An additional problem is the influence of agrochemicals used in agriculture on the allergenicity of plant-based products. It is hypothesised that excessive fertiliser application, especially those based on nitrogen and phosphorus, may alter the protein composition of vegetables, increasing their immunogenicity. Knyziak-Mędrzycka *et al.* (2024) studied the agrochemical load on soils and its impact on the composition of plant products, finding a correlation between nitrate content and changes in the protein profile of vegetables. However, their study lacked data on the human immune system's response to such products, making it impossible to assess the real allergic risk.

An important aspect is the role of microclimatic conditions inside homes such as humidity levels and the presence of allergen sources. Increased humidity promotes the growth of mould and dust mites, which can enhance Immunoglobulin E (IgE)-mediated immune responses and increase the frequency

and severity of allergic symptoms, particularly respiratory manifestations (Klimenko *et al.*, 2009; Kyryk *et al.*, 2021). Kuźniar *et al.* (2024) analysed the impact of household conditions on the severity of allergic symptoms in children living in megacities, finding that humidity above 65% significantly correlates with respiratory symptoms, but did not consider the possibility of cross-sensitisation or interaction with food allergens.

A family history of allergic diseases is traditionally considered one of the key risk factors. Genetic predisposition may modify the immune response to antigens, including plant-based ones (Irgashev *et al.*, 2020; 2021). Frei *et al.* (2022) conducted a cohort study of families with a high allergy background, finding that children from such families exhibited a more pronounced reaction to household allergens. However, the influence of heredity on the development of food allergies in the context of an aggressive external environment was not part of their analysis.

Modern urbanisation processes also contribute to changes in the allergenic load on humans, understood in this study as the combined exposure to environmental factors capable of inducing or enhancing allergic sensitisation, including air pollutants, agrochemical agents, and indoor environmental conditions. Air pollution, population density, and architectural design—all affect immune status (Gudkov *et al.*, 2017; Hussain *et al.*, 2022a). Sozener *et al.* (2022) studied urbanisation factors and their impact on allergic diseases, showing that city residents are more likely to experience sensitisation. However, they did not conduct a comparative analysis between urban and rural areas, which prevents an assessment of the degree of environmental modulation of risk.

The combination of external and internal factors is particularly significant when pets are present, which can both be sources of allergens and modulators of immune responses. Lu *et al.* (2023) investigated the impact of contact with animals on the level of sensitisation in children,

identifying both protective and provoking effects depending on the age at which contact began. However, this study did not consider food allergens and did not perform stratification by allergen type.

The type of housing construction and its interaction with other variables such as population density and agrochemical load, remains a little-studied topic. Zhang *et al.* (2023) analysed architectural solutions and ventilation systems in the context of asthma prevalence in adults, finding a link between closed ventilation systems and a high frequency of allergic symptoms. However, their study did not address food allergies as a separate phenomenon.

Finally, a significant gap remains in the lack of a comprehensive analysis combining data on environmental pollutants, agrochemical indicators, and individual risk factors. Peters *et al.* (2022) attempted to create an integral model for assessing the risk of allergic diseases, incorporating air quality monitoring data, but their model did not differentiate allergens by type and food triggers were generalised without specific reference to vegetables.

Thus, in the face of growing environmental pressures and changes in dietary patterns, including increased consumption of raw and minimally processed vegetables and greater dietary diversity, there is a need for targeted research into the mechanisms by which environmental factors may contribute to the development of vegetable allergies. The goal of this study was to determine the nature of the relationship between environmental conditions and the frequency of sensitisation to vegetable allergens among the adult population. The objectives of the study included identifying differences in the prevalence of sensitisation depending on place of residence, determining the degree of impact of atmospheric pollutants and agrochemical load on allergic risk, and assessing the contribution of domestic conditions and hereditary predisposition to immune reactivity.

Materials and Methods

The study was conducted from March 2023 to November 2023 in the Lublin Voivodeship (Poland), a region characterised by a combination of urban centres (Lublin) and rural agricultural areas (the communes of Wojciechów, Końskowola, Kraśnik) subjected to varying degrees of industrial and agrochemical activity. The region lies in a temperate continental climate zone, with a mean annual temperature of 8.2°C and an annual precipitation level of approximately 580 mm (Climate Data, 2026). The predominant soil types are grey forest and sod-podzolic soils, which are often affected by anthropogenic transformation due to intensive farming practices and the use of nitrogen fertilisers.

The region is characterised by multiple sources of ecological stress, including emissions from residential heating based on solid fuels, road transport, and agricultural activities. Air pollution is mainly linked to PM_{2.5} and nitrogen oxides generated by domestic heating and vehicle emissions, particularly during the heating season (Nazar & Niedożytko, 2022; IQAir, 2026). In addition, the Lublin Voivodeship is an intensively agricultural area with substantial use of mineral fertilisers and pesticides, contributing to environmental exposure through both air and soil pathways.

The study included 604 participants selected using stratified cluster sampling. Regional medical facility records were used solely to identify eligible participants and were not involved in data collection or analysis, which were used to identify potential participants and were not involved in data collection or analysis. The participants were men ($n = 257$; 42.5%) and women ($n = 347$; 57.5%) aged 18 years to 65 years (mean age 38.9 ± 11.1 years), all of whom had been permanent residents of the region for at least five years. Inclusion criteria comprised the absence of current specific immunotherapy, acute infectious conditions, malignant neoplasms,

and autoimmune diseases. Exclusion criteria included pregnancy, severe neuropsychiatric disorders, and lack of informed consent. Ethical approval was obtained from the Bioethics Committee of the Medical University of Lublin (Protocol No. 7/2023, dated 14 February 2023).

Participants completed a standardised questionnaire validated for the Polish population, which included sections on clinical symptoms, food tolerance, frequency of vegetable consumption, living conditions, presence of pets, indoor humidity levels, and family history of allergic diseases in first-degree relatives. The questionnaire was supplemented with individual interviews conducted by allergists to clarify medical histories and minimise false-positive responses.

To objectively assess sensitisation, venous blood samples were collected, and specific IgE levels were measured for five vegetable allergens—*Daucus carota* (carrot), *Apium graveolens* (celery), *Solanum lycopersicum* (tomato), *Spinacia oleracea* (spinach), and *Capsicum annuum* (bell pepper)—using enzyme-linked immunosorbent assay (ELISA) with ImmunoCAP test systems (Thermo Fisher Scientific, Sweden). These vegetables were selected due to their widespread consumption in the region and their known allergenic potential, including cross-reactive proteins [e.g., pathogenesis-related (PR)-10 proteins and lipid transfer proteins (LTPs) associated with pollen-food syndrome. A level of ≥ 0.35 kU/L was interpreted as a positive sensitisation, in accordance with standard clinical thresholds for ImmunoCAP-based diagnostics. This cut-off value was adopted from standard clinical practice and was not derived specifically for the study population, and was not defined specifically for this study population. Skin prick testing was additionally performed in a subset of participants population classification; however, these results were not included in the statistical analysis due to limited coverage.

Environmental exposure was assessed using data from automatic air quality monitoring

stations (Aeroqual Series 500, Aeroqual, New Zealand) installed at the participants' places of residence. PM_{2.5}, NO₂, and tropospheric ozone (O₃) were selected as key indicators of air pollution due to their prevalence in the region and their well-documented role in modulating respiratory and immune responses in urban and agricultural environments. These stations recorded concentrations of PM_{2.5}, PM₁₀, NO₂, and O₃ at 30-minute intervals. Pesticide exposure and agrochemical use in rural areas were evaluated based on official statistics from the Institute of Soil Science and Plant Cultivation in Puławy (2026) and Ministry of Agriculture and Rural Development of Poland, reports (2026). Meteorological and phenological data, including pollen activity, were provided by local aerobiological stations and the Vantage Pro2 monitoring system (Davis Instruments, United States of America). These variables were used as proxies to characterise the overall allergenic load in the study environment.

Statistical analysis was performed using Statistica 13.3 (StatSoft, USA) and R 4.2.2 (The R Foundation for Statistical Computing, Austria). Descriptive statistics were applied alongside Student's t-test, the Mann-Whitney U-test, Pearson's chi-squared test, and Spearman's and Pearson's correlation coefficients. Stepwise multiple logistic regression was used to identify predictors of sensitisation. Results were considered statistically significant at a $p < 0.05$.

Results

The study included 604 participants from the Lublin Voivodeship. The sample was characterised by a predominance of women (57.5%) and a mean age of 38.9 ± 11.1 years. Overall, 45.9% of participants resided in urban areas and 54.1% in rural areas. Sensitisation to at least one of the investigated vegetable allergens was identified in 28.5% of participants ($n = 172$). No significant differences were found by sex ($p = 0.186$), although sensitisation tended to be more common among urban residents.

Table 1: Demographic structure of the sample and level of sensitisation to vegetable allergens

Parameter	Value
Total number of participants	604
Men/women (%)	42.5% (n = 257)/57.5% (n = 347)
Average age (years)	38.9 ± 11.1
Age range (years)	18 to 65
City/village (%)	45.9%/54.1%
Sensitised to ≥1 allergen (%)	28.5% (n = 172)
Sensitisation: Men/women (%)	30.3%/27.1%
Sensitisation: City/village (%)	31.7%/25.8%
Sensitisation to carrot	15.7% (n = 95)
Sensitisation to celery	13.4% (n = 81)
Sensitisation to tomato	10.6% (n = 64)
Sensitisation to spinach	7.8% (n = 47)
Sensitisation to bell pepper	5.3% (n = 32)

The demographic characteristics of the participants revealed several significant aspects shaping the epidemiological context of food sensitisation under the conditions of a temperate continental climate and agro-industrial environmental transformation. The analysed sample comprised 604 individuals. The representative distribution by sex (men: 42.5%; women: 57.5%) and age (range 18 years to 65 years, mean 38.9 ± 11.1) allows the data to be extrapolated to the adult population of the region as a whole.

The overall prevalence of sensitisation to at least one of the five investigated vegetable allergens was 28.5%, which can be considered high in a population context. This is particularly relevant given the absence of active specific immunotherapy among participants and the exclusion of individuals with severe immunopathologies, rendering the sample clinically significant yet not biased towards patients with severe allergic conditions.

The distribution of sensitisation to the five key vegetable allergens revealed a clear hierarchy in the frequency of immune responses, reflecting both biological characteristics of the antigens and differences in their consumption frequency and cross-reactivity. The most

commonly identified allergen was *Daucus carota* (carrot) to which 15.7% of participants were sensitised. Sensitisation to *Daucus carota* was identified in 15.7% of participants, representing the highest prevalence among the investigated vegetable allergens, the primary birch pollen allergen, making carrot a typical component of the pollen-food syndrome. The second most frequent sensitising agent was *Apium graveolens* (celery) with 13.4% of cases. Celery contains not only PR10 proteins but also thermostable LTP, which increases the risk of severe clinical manifestations.

Solanum lycopersicum (tomato) sensitisation was observed in 10.6% of participants, which may be related to both its widespread consumption and the presence of specific profilins and peroxidase antigens. *Spinacia oleracea* (spinach), despite its high biological activity, induced sensitisation in 7.8% of participants, likely due to its less frequent consumption and lower cross-reactivity with inhalant allergens. The lowest number of positive reactions was detected for *Capsicum annuum* (bell pepper) with 5.3%.

A comparative analysis by sex did not reveal statistically significant differences (30.3% among men vs. 27.1% among women, $p =$

0.186), indicating a comparable level of immune reactivity regardless of gender. Nevertheless, the observed trend toward higher sensitisation rates among men warrants further analysis considering occupational exposure, frequency of outdoor activity, and dietary patterns. Men engaged in agriculture or construction may experience increased exposure to inhalant and contact allergens, potentially influencing the development of cross-reactive sensitisation (Shahini *et al.*, 2023; 2024).

Place of residence had a more pronounced impact on sensitisation prevalence. Among urban residents, sensitisation was identified in 31.7% of cases, compared to 25.8% among rural residents ($p = 0.052$). Although this difference borders on statistical significance, it highlights the potentially important role of urban-related factors. Possible explanations include chronic exposure to air pollutants (PM_{2.5}, NO₂, O₃), limited childhood exposure to diverse microbiota, and reduced immune system adaptation to natural antigens. Moreover, urban environments are more often characterised by high indoor insulation and increased humidity, which may enhance allergen load through moulds and household dust, both of which act as adjuvants in the development of allergic responses.

Thus, the obtained results emphasise the importance of considering demographic and geographical factors when assessing the risk of sensitisation. These variables provide the basis for more accurate risk stratification in clinical practice and epidemiological forecasting, as well as for the development of primary prevention programmes for allergic diseases that take local living conditions into account.

The relationship between air pollution levels and the frequency of sensitisation to vegetable allergens was analysed by comparing environmental monitoring data with allergological screening results (Table 2). All study participants were categorised according to the degree of environmental pollution in their residential areas. This classification was based on average concentrations of priority air pollutants, including PM_{2.5}, O₃, and nitrogen oxides. The comparison revealed a clear trend of increasing sensitisation rates among residents of areas with higher anthropogenic burden. The most consistent associations were observed for pollutants that penetrate the lower respiratory tract and exhibit strong pro-inflammatory potential. These findings confirm the relevance of assessing environmental exposures when interpreting allergological status, particularly in urban settings.

The results of the analysis investigating the relationship between atmospheric pollution levels and the prevalence of sensitisation to vegetable-derived food allergens revealed a consistent and statistically significant association, particularly pronounced in relation to pollutants such as PM_{2.5} and NO₂. When participants were stratified according to levels of anthropogenic exposure – calculated based on data from automated air quality monitoring—a clear trend emerged: As the concentrations of these pollutants increased, so too did the proportion of sensitised individuals. Participants residing in areas with the highest levels of pollution exhibited nearly twice the rate of sensitisation compared to those living in relatively clean environments.

Table 2: Frequency of sensitisation depending on the level of atmospheric pollution

Pollution Level	Mean PM _{2.5} Concentration (µg/m³)	Mean NO ₂ Concentration (µg/m³)	Mean O ₃ Concentration (µg/m³)	Sensitisation Rate (%)
Low	16.2 ± 3.1	21.7 ± 4.2	62.5 ± 7.4	18.2
Moderate	26.8 ± 4.6	31.4 ± 5.3	55.8 ± 6.9	27.4
High	37.0 ± 5.8	42.1 ± 6.7	48.2 ± 8.1	38.9

Correlation analysis confirmed the presence of a moderately strong but statistically significant positive relationship between PM_{2.5} concentration and sensitisation levels (correlation coefficient $r = 0.41, p < 0.001$), as well as between NO₂ levels and sensitisation ($r = 0.44, p < 0.001$). These findings are consistent with current understanding of the role inhaled pollutants play in modulating immune responses. Both PM_{2.5} and NO₂ possess marked pro-oxidant properties, stimulate the production of pro-inflammatory cytokines, compromise the epithelial barrier of the respiratory tract, and may facilitate trans-epithelial allergen migration. In addition, they enhance antigen presentation and promote activation of the Th₂ immune response, which underpins allergic sensitisation.

Particular attention should be paid to the fact that PM_{2.5} and NO₂ not only increase sensitivity to airborne allergens but may also indirectly heighten the likelihood of developing cross-sensitisation to food components—especially vegetables that contain proteins homologous to pollen allergens. For example, sensitisation to *Apium graveolens* (celery) and *Daucus carota* (carrot) may develop in individuals previously sensitised to tree pollen, facilitated by the adjuvant effects of polluted air.

An interesting finding was the observed inverse pattern in the relationship between O₃ concentration and the prevalence of sensitisation. Unlike PM_{2.5} and NO₂, higher ozone levels were associated with a somewhat lower prevalence of sensitisation. This may be due to the destructive effect of ozone on the protein structures of

allergens, reducing their immunogenicity, or to shifts in the microbial environment and seasonal vegetation dynamics. However, this relationship warrants further investigation, as the impact of ozone on allergic reactivity remains inconclusive in the current scientific literature.

Thus, the findings highlight the crucial role of environmental conditions—particularly air quality—as key predictors in the development of allergic sensitisation among the adult population. These results underscore the need to incorporate environmental exposure indicators into allergy screening and prevention programmes, especially in urbanised areas with high anthropogenic burden. Moreover, the data may inform the tailored development of preventive interventions based on the pollution levels in specific localities.

The rural areas of the Lublin Voivodeship, encompassing the communes of Wojciechów, Końskowola, and Kraśnik, are characterised by intensive agrochemical usage, including nitrogen-based fertilisers, insecticides, and herbicides (Table 3). According to the Institute of Soil Science and Plant Cultivation (2026), agrochemical load in these regions during 2022–2023 exceeded average European levels, particularly with respect to nitrate and phosphorus compound application. The analysis revealed that zones with high mineral fertiliser usage reported significantly higher rates of positive sensitisation results compared to areas with moderate agrochemical activity. Soil characteristics were also considered—predominantly grey forest and sod-podzolic

Table 3: Agrochemical load in rural areas and level of sensitisation of the population

District	Fertiliser Use (kg/ha/year)	Main Compounds	Soil Type	Sensitisation (%)
Wojciechów	312.4	NPK, phosphorus-based pesticides	Grey forest soils	29.1
Końskowola	278.7	Ammonium salts, herbicides	Sod-podzolic soils	24.8
Kraśnik	349.2	Urea, potassium nitrate	Grey forest/ podzolised soils	33.5

Note: NPK fertilisers: Nitrogen, phosphorus, and potassium.

soils, which are vulnerable to transformation under fertiliser exposure. This may contribute to the accumulation of allergenic and immunomodulatory compounds in plant-based food products.

The analysis of agrochemical conditions in rural areas of the Lublin Voivodeship revealed a clear association between the intensity of mineral fertiliser application and the prevalence of sensitisation to vegetable allergens. The most pronounced allergic burden was observed in areas with intensive agricultural activity, particularly in the Kraśnik commune, where more than one-third of participants exhibited positive sensitisation results. This figure substantially exceeds those recorded in regions with less intensive agrochemical use such as Końskowola, where sensitisation rates did not exceed 25%.

The agrochemical load in these regions ranged from 278.7 kg to 349.2 kg of active substance per hectare per year, surpassing the average levels reported for Central Europe. The most frequently applied substances were complex NPK fertilisers, urea, ammonium salts, and organophosphate-based herbicides. These compounds are widely used in the cultivation of vegetable crops, including *Daucus carota*, *Apium graveolens*, *Solanum lycopersicum*, and *Capsicum annum*, which were included in the allergological assessment protocol of the study.

Current evidence indicates that agrochemicals can exert both direct and indirect effects on human health by altering the biological properties of plants. Chemical stressors induce the synthesis of defence-related proteins, including PR proteins, particularly PR10 and profilins. These proteins possess stable epitopes and frequently trigger cross-reactive sensitisation in individuals already sensitive to pollen allergens, particularly Bet v 1 homologues. Hence, the increased production of PR proteins in response to nitrogen exposure and pesticide stress may significantly elevate the allergenic potential of vegetables, especially when consumed raw.

Soil characteristics also played a significant role in this process. The study areas were predominantly characterised by grey forest and sod-podzolic soils, which are prone to rapid leaching and possess low buffering capacity. As a result, these soils accumulate mobile ions such as nitrates, ammonium, and residual pesticides, thereby increasing biotic stress on plant root systems. The agro-induced transformation of soil conditions leads to the enhanced expression of stress-induced proteins, including allergenic ones (Bardule *et al.*, 2018; Hussain *et al.*, 2022b). Kraśnik, identified as the most agro-intensively utilised commune, also exhibited the highest level of allergenic activity, which aligns with the hypothesis of a pathophysiological link between agrochemical exposure and allergen sensitisation.

Dietary behaviours of rural residents should also be taken into account, especially in agriculturally active areas. Consumption of homegrown produce—often without thermal processing—minimises the degradation of thermolabile allergens such as profilins and LTP (Montayeva *et al.*, 2023; Mukhametov *et al.*, 2023). Consequently, the combined impact of agrochemical exposure and dietary intake routes of allergens intensifies the risk of sensitisation.

Taken together, these findings support the consideration of agrochemical burden as a significant environmental marker of allergological risk. They highlight the importance of interdisciplinary oversight of agricultural practices, particularly in ecologically vulnerable regions with intensive farming operations.

Analysis of the participants' living conditions also revealed the influence of several non-medical factors on the prevalence of sensitisation to vegetable allergens (Table 4). The study included variables potentially affecting immune modulation in the domestic environment such as the presence of pets, household humidity levels, type of housing (apartment buildings vs. individual houses), and family history of allergic diseases among first-degree relatives. The data indicated that the highest susceptibility to sensitisation was

observed among participants living in homes with signs of chronic dampness (humidity > 65%) and those with a positive familial history of allergies. The presence of pets exhibited a dual effect: In the absence of a hereditary predisposition, it was associated with a lower rate of sensitisation, whereas in individuals with a positive family history, it increased the risk. Moreover, residents of apartment buildings demonstrated higher sensitisation rates compared to those living in detached houses, possibly due to poorer ventilation and allergen accumulation in enclosed spaces.

The final stage of analysis revealed a strong association between several domestic and anamnestic factors and the prevalence of sensitisation to vegetable-derived allergens. The findings confirm that individual living conditions, microenvironmental characteristics, and hereditary predisposition constitute a critically important background for the development of allergic sensitisation in the population. The most significant predictor was found to be family history: The presence of allergic diseases among first-degree relatives significantly increased the likelihood of sensitisation (41.8% vs. 22.7%), supporting the view that genetic factors are fundamental in the development of IgE-mediated responses. This is consistent with the widely accepted concept of the polygenic nature of allergic pathology, whereby genes regulating IgE synthesis, cytokine receptor expression (notably interleukin, IL-4 and IL-13), and mast cell activation are inherited with varying

penetrance and are expressed in interaction with environmental triggers.

Another potent risk factor was high indoor humidity. When relative humidity exceeded 65%, sensitisation rates increased by more than 12 percentage points compared to normal levels. Excessive humidity not only fosters the growth of microflora (especially moulds such as *Aspergillus* and *Penicillium*) but also leads to the accumulation of PM_{2.5}, increasing the allergenic burden. Prolonged exposure to such conditions impairs innate immune regulation, reduces the functional integrity of the respiratory epithelial barrier, and enhances the production of pro-inflammatory cytokines. This environment promotes systemic predisposition to allergic sensitisation, including to food antigens, particularly in individuals with polyvalent sensitivities.

Architectural features of dwellings also played a role: Respondents living in multi-family buildings exhibited a higher rate of sensitisation (31.5%) than those in individual houses (25.2%). This difference may stem from limited ventilation, greater population density, and the presence of shared air ducts, all of which facilitate allergen circulation. Moreover, restricted access to the natural environment reduces immune variability and adaptability: An important consideration when evaluating sensitisation risks in the context of urbanisation.

The role of household pets proved dualistic. On average, participants living with animals

Table 4: Household and anamnestic factors and their association with the incidence of sensitisation

Factor	Category	Frequency of Sensitisation (%)
Presence of household pets	Yes	26.2
	No	30.4
Chronic indoor humidity	> 65%	36.7
	≤ 65%	24.1
Type of housing	Multi-unit building	31.5
	Detached house	25.2
First-degree family history of allergy	Present	41.8
	Absent	22.7

showed slightly lower sensitisation rates, partially supporting the hygiene hypothesis, which posits that early and continuous exposure to microbial and zoonotic antigens contributes to the development of immunological tolerance. However, among individuals with a hereditary predisposition to allergy, such exposure acted as a trigger, increasing the incidence of sensitisation. This suggests that genetic factors may modify the effect of environmental exposures. Thus, the presence of animals in the home may serve as either a protective or risk factor depending on the individual's immunological baseline.

Taken together, these findings underscore the importance of comprehensive assessment of indoor environmental conditions and personal medical history in predicting allergic diseases. Such considerations should be integrated into screening algorithms and early identification strategies for sensitised individuals, particularly within preventive healthcare systems oriented towards environmental and behavioural risk modification.

Discussion

The discussion of the results obtained in the study of food sensitisation among the adult population of the Lublin Voivodeship facilitates an analysis of the demographic, ecological, and domestic factors influencing the prevalence of allergic reactions. The overall rate of sensitisation to vegetable allergens (28.5%) underscores the significance of this issue in the studied region and warrants comparison with international data.

The observed sensitisation prevalence was comparable to that reported by *Lu et al.* (2024), who investigated the prevalence of food allergy among urban populations in Central Europe and documented a similar sensitisation rate (27.8%). The authors highlighted the substantial role of urbanisation-related factors, which is consistent with the findings of this study. However, unlike the present investigation, *Verscheure et al.* (2023), who studied a comparable sample in Southern Europe, reported lower rates

(approximately 19.4%), may be attributable to differences in climatic conditions, environmental exposures, and dietary patterns.

No statistically significant differences were found in sensitisation rates by sex, consistent with findings from population-based studies showing no clear association between sex and immunoglobulin E (IgE)- to food allergens, as reported by *Melén et al.* (2020). Nevertheless, *Montoro et al.* (2024) proposed that men may be more susceptible to sensitisation as a result of inhalation exposure to pollutants, particularly in occupational settings—a finding indirectly echoed in the present study and warrant further investigation through longitudinal and cross-sectional studies.

The difference in sensitisation rates between rural and urban residents (31.7% vs. 25.8%) contrasts with the conclusions of *Morita et al.* (2023), who reported an increased allergic burden in urbanised areas owing to increased air pollution and reduced microbial diversity. Conversely, *Lu et al.* (2023) argued for a protective effect of the urban environment owing to improved hygiene standards and greater access to diagnostic services, although this view appears less substantiated in light of the current data supporting the detrimental influence of urban factors on immune tolerance.

The identified correlation between air pollution levels and sensitisation prevalence is of particular importance. The association between PM_{2.5} and NO₂ concentrations and sensitisation observed in this study is supported by *Moran* (2023), who demonstrated a similar pattern in industrialised regions. *Zhang et al.* (2025) demonstrated that these pollutants exert their effects via pro-inflammatory activation of respiratory epithelium and enhanced trans-epithelial migration of allergens. These mechanisms provide a plausible biological explanation for the associations observed in the present study.

The observed associations between environmental exposures and vegetable sensitisation can be interpreted through several

immunological mechanisms. As highlighted by Sozener *et al.* (2022), PM_{2.5} and NO₂ induce oxidative stress and disrupt epithelial barrier integrity in the respiratory tract, increasing permeability to allergens. These pollutants stimulate the release of pro-inflammatory cytokines, including interleukin (IL)-4, IL-5, and IL-13, and enhance antigen presentation by dendritic cells, promoting a T-helper 2 (Th2)-skewed immune response characteristic of allergic sensitisation. In addition, air pollutants may act as adjuvants, facilitating the penetration and immunogenicity of cross-reactive plant proteins. Peters *et al.* (2022) further emphasise that environmental exposures play a key role in modulating sensitisation pathways. Agrochemical exposure may further contribute by inducing stress-related protein expression in plants, including PR proteins and profilins, thereby increasing their allergenic potential. These mechanisms provide a plausible explanation of the relationship observed between environmental factors and sensitisation to vegetable allergens.

The inverse association observed between ozone concentration and sensitisation prevalence should be interpreted cautiously because causality cannot be inferred from the present cross-sectional design. That said, the correlation between ozone concentration and sensitisation rates aligns with the conclusions of Agache *et al.* (2024), who observed reduced allergenic activity at high O₃ concentrations under laboratory conditions. This effect may stem from oxidative degradation of allergenic protein epitopes, which lowers their immunogenicity and capacity to induce specific IgE production. Additionally, ozone may alter the structure and composition of airborne pollen and microbial particles, modulating their allergenic potential. However, these effects are highly dependent on seasonal fluctuations in temperature, humidity, and vegetation activity. Mélen *et al.* (2023) also highlighted the possibility of seasonal artefacts and variability in plant allergen levels, necessitating further research and longer observation periods. This should include

biomonitoring parameters, exposure modelling, and meteorological data to ensure reproducible and valid results.

Agrochemical exposure in rural areas was shown to significantly influence sensitisation prevalence, particularly in areas with intensive fertiliser application. This finding is consistent with the conclusions of Aldakheel (2021), who observed increased expression of PR proteins in plants exposed to nitrogen-based compounds, accompanied by heightened product allergenicity. Feng *et al.* (2023), however, disputed this effect, citing the degradation of allergenic proteins during cooking as a mitigating factor. In the present study, raw vegetable consumption predominated, suggesting that the findings are more relevant under these conditions.

Soil type and its susceptibility to agrochemical contamination were found to be significant modifiers. The study by Beltrán-Cárdenas *et al.* (2021) confirms the role of sod-podzolic and grey forest soils in accumulating agrochemicals and altering the phytochemical composition of plants. This corresponds with the highest sensitisation rates observed in Krašnik. Meanwhile, Lu *et al.* (2022) argue that the influence of soil factors is secondary to the volume of chemical inputs, a view partially supported by the correlation data in the present analysis.

Domestic living conditions proved to be an important background determinant in the development of sensitisation. Family history of allergic disease demonstrated the most robust association with positive skin test results, aligning with the findings of Huang *et al.* (2021). These authors emphasise the polygenic inheritance of allergic pathology and the essential role of gene-environment interactions. Seastedt and Nadeau (2023) expand on this by identifying molecular markers such as IL4RA polymorphisms associated with enhanced immune responses.

High indoor humidity (> 65%) also showed a statistically significant association with sensitisation prevalence, confirming

the findings of Xing and Wong (2021), who highlighted the role of microbial flora and indoor PM_{2.5} as adjuvants in allergic responses. Elevated humidity promotes the growth of moulds such as *Aspergillus*, *Penicillium*, and *Cladosporium*, which produce airborne spores and metabolites with high sensitising potential (Kozyatnyk *et al.*, 2013; Ismailova *et al.*, 2024). Moreover, excessive moisture disrupts epithelial barrier function in the respiratory tract, increases permeability to allergens, and stimulates pro-inflammatory cytokine production, thereby contributing to a chronically activated immune state. This effect may be exacerbated by poor ventilation and the use of synthetic building materials that emit volatile organic compounds with adjuvant properties. However, Leung *et al.* (2024) suggest that this association may be secondary, reflecting poor housing quality, overcrowding, and the related psychophysiological stressors that can affect immune homeostasis. These findings call for the inclusion of socioeconomic modifiers in future studies, with emphasis on a comprehensive evaluation of living environments, encompassing both hygienic parameters and psychosocial context.

Architectural characteristics of dwellings were reflected in the higher sensitisation rates observed among residents of multi-unit buildings. This supports the observations of Bellinghausen *et al.* (2022), who highlighted allergen circulation in enclosed spaces where poor ventilation and high population density promote the accumulation of allergenic particles. Additionally, such buildings often have shared ventilation systems that may serve as conduits for allergen transmission between residential units, exacerbating exposure in sensitised individuals. These mechanisms represent an important pathway for domestic exposure, particularly when combined with other risk factors such as humidity or the presence of pets. At the same time, Ogawa *et al.* (2021) argue that these differences can be mitigated by effective ventilation and adherence to sanitary norms, including the regular maintenance of air filters. This underscores the importance of evaluating

both architectural and operational aspects of residential buildings.

An intriguing finding was the dual role of household pets: Reduced sensitisation in individuals without a hereditary predisposition and increased rates among those with a family history of allergy. These results are consistent with the hygiene hypothesis articulated by Knol and Van Neerven (2024) and suggest a complex interaction between environmental exposures and individual immune profiles. Botha *et al.* (2019) further emphasise that exposure to animal-derived antigens may either induce tolerance or act as a trigger for allergic cascades in genetically predisposed individuals.

Overall, the results of this study illustrate the multifactorial nature of sensitisation to vegetable allergens, shaped by demographic, ecological, agrochemical, and domestic factors. The identified associations underscore the need of a multifactorial approach to diagnosis, prevention, and epidemiological forecasting of allergic diseases, particularly in the context of a transforming environmental landscape and growing urbanisation.

Conclusions

This study identified complex relationships between demographic, environmental, and household factors and the prevalence of sensitisation to vegetable allergens among the adult population of the Lublin Voivodeship. The overall sensitisation rate to at least one of the five tested allergens was 28.5%, underscoring the public health relevance of this issue in the context of a temperate-continental climate and the region's ongoing agro-industrial transformation. The data indicate no significant differences in sensitisation prevalence between sexes, whereas place of residence and the degree of anthropogenic influence emerged as more important predictors. A statistically significant positive association was established between air pollution levels (PM_{2.5} and NO₂) and sensitisation prevalence, supporting the proposed immunomodulatory role of inhaled

pollutants. The highest rates (up to 38.9%) were recorded in areas characterised by substantial industrial exposure.

Similarly, rural communes with intensive use of nitrogen and phosphorus fertilisers exhibited elevated allergic sensitisation rates, reaching 33.5% in the most agriculturally saturated areas. This association may be related to alterations in plant protein expression induced by intensive agrochemical exposure; however, mechanistic studies are required to confirm this hypothesis. Among domestic factors, chronic indoor dampness and a history of allergic disease had the strongest associations, increasing sensitisation risk to 36.7% and 41.8%, respectively. The modifying role of pets was also identified, with their presence either appearing to either increase or decrease the prevalence of sensitisation depending on genetic predisposition. The practical significance of the results lies in the potential to develop targeted preventive strategies in areas with high anthropogenic and agrochemical exposure, as well as the need to integrate household environmental assessments into early allergy screening and prevention programmes. Future research should focus on the investigation of mechanisms by which environmental factors transform the allergenicity of food products.

The main limitation of this study is its cross-sectional design, which precludes the establishment of causal relationships. Additionally, seasonal variations in allergen exposure and individual dietary patterns were not accounted for, potentially affecting the interpretation of some findings.

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Author Contributions Statement

Maria Zofia Lisiecka contributed to the conceptualisation of the study, the development of the research design, and the formulation of the theoretical framework. Maria Zofia Lisiecka was responsible for data analysis and interpretation, as well as for drafting the main sections of the manuscript. Joanna Luczak contributed to the literature review, methodological refinement, and critical revision of the manuscript. Joanna Luczak also participated in the interpretation of results and provided substantial intellectual input that improved the overall coherence and academic quality of the study. Both authors reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Conflict of Interest Statement

The authors declare that they have no known competing financial or non-financial interests regarding the publication of this work.

Ethical Conduct

Ethical approval for this study was obtained from the Bioethics Committee of the Medical University of Lublin (Protocol No. 7/2023; dated 14 February 2023)

Declaration of AI-usage

Artificial Intelligence (AI) was used for:

- Grammar checking
- Sentence formulation and readability improvement
- References formatting

Data Availability Statement

Available from the corresponding author upon reasonable request.

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