

Patterns of vegetable allergy and their public health implications in urban and rural populations

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ABSTRACT

Objective: To analyse the clinical and immunological characteristics of vegetable allergy and to summarise age-related, molecular, and urban-rural patterns reported in the scientific literature.

Methods: This study was conducted as a structured narrative review with secondary synthesis of published epidemiological evidence and theoretical modelling. Published studies indexed in Scopus, Web of Science, and PubMed were analysed to compare age-related patterns of sensitisation, allergen characteristics, and urban-rural differences. No primary clinical data were collected.

Results: Published evidence suggests that vegetable allergy is more frequently reported in early childhood, whereas severe systemic reactions tend to occur more often during adolescence. Published evidence suggests that molecular characteristics of allergens influence the clinical phenotype, with lipid transfer proteins being more commonly associated with severe systemic reactions than thermolabile proteins. Secondary data synthesis also indicates differences between urban and rural settings regarding diagnostic practices, dietary behaviour, and access to allergy care.

Conclusion: Vegetable allergy represents a complex clinical and public health issue influenced by age, molecular sensitisation, and environmental factors. The integration of published epidemiological evidence and theoretical modelling

may support risk stratification and the development of preventive and dietary management strategies. Further multi-centre studies based on primary clinical data are needed to validate the identified patterns.

KEYWORDS

Food sensitisation; allergic epidemiology; PR-10 proteins; lipid transfer proteins; IgE-mediated food allergy; cross-reactivity; immunopathogenesis; plant allergy.

ABBREVIATIONS

ACE: Angiotensin-Converting Enzyme.

OAS: Oral Allergy Syndrome.

NSAIDs: Nonsteroidal Anti-Inflammatory Drugs.

PR-10: Pathogenesis-Related protein, class 10.

Sol I 4: *Solanum lycopersicum* allergen 4.

Sol I 3: *Solanum lycopersicum* allergen 3.

Dau c 1: *Daucus carota* allergen 1.

Api g 1/4: *Apium graveolens* allergen 1/4.

Bet v 1: *Betula verrucosa* allergen 1.

IgE: Immunoglobulin E.

LTP: Lipid Transfer Protein.

FPIES: Food Protein-Induced Enterocolitis Syndrome.

WAO: World Allergy Organization.

EAACI: European Academy of Allergy and Clinical Immunology.

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INTRODUCTION

Allergy to vegetables is a separate clinical and immunological phenotype of food hypersensitivity, accompanied by sensitisation to profilins, LTPs and PR-10. The relevance of the problem is growing due to the recording of clinically significant reactions in all age groups – from young children, who are mainly characterised by primary sensitisation with generalised manifestations, to adolescents and adults, who are more likely to experience cross-allergy caused by pollinosis. In the context of urbanisation, changing eating habits and the growing popularity of vegetarian diets, sensitisation to vegetable components has been increasingly reported. In clinical practice, this is accompanied by diagnostic difficulties in distinguishing between isolated and cross-allergies, as well as the widespread use of elimination diets without laboratory confirmation. These factors together necessitate a systematic study of the pathogenesis, clinical forms, and dietary risks associated with vegetable allergies.

Leading international organisations make a significant contribution to the study of the prevalence of food allergies, the mechanisms of their development, and the body's response to plant proteins. WAO¹ coordinates global initiatives aimed at standardising the diagnosis and monitoring of food allergies in different regions of the world, including multicentre studies covering both urban and rural populations. In turn, EAACI² systematically implements clinical guidelines for the management of patients with food allergies and funds research related to the allergenic properties of vegetable proteins, mechanisms of cross-sensitisation and the interpretation of geographical characteristics of the allergy profile. Thanks to the activities of these organisations, a global evidence base is being formed that allows the evaluation of the impact of food allergens, including those of vegetable origin, on public health in the context of spatial and demographic factors.

The spatial distribution of allergic diseases, particularly those associated with vegetables, indicates that the level of sensitisation depends on the environment. One of the few studies that has conducted a comprehensive analysis of urban and rural populations in the context of allergies is the work of Tizek et al.³. It emphasises that the frequency of self-reported allergies varies depending on the type of locality, occupational activity and level of industrialisation. Peters et al.⁴ outlined a list of environmental factors associated with an increase in the prevalence of food allergies, among which the level of urbanisation plays a leading role. In the Polish context, the study of food allergies is presented in the study by Rymarczyk et al.⁵, which analyses the barriers to maintaining a healthy lifestyle in people with food hypersensitivity; attention is drawn to the high level of undiagnosed allergies and insufficient awareness of the risks associated with "healthy" foods, particularly vegetables. In turn, the work of Lisiecka⁶, conducted in Poland on a sample of children and adolescents, outlines typical clinical manifestations and risk factors, parti-

cularly in the early stages. The author points to the importance of regional monitoring of symptoms, prevention and elimination of allergens before treatment begins, confirming the need for an adapted approach within specific environmental conditions.

A rational dietary structure largely determines individual sensitivity to protein components in vegetable crops. In a study by Leung et al.⁷, this aspect is presented through the prism of dietary patterns that modulate the immune response. The innovative aspect of this approach lies in the attempt to interpret food allergies not only as a clinical syndrome, but also as a derivative of cultural and economic food behaviour. Li et al.⁸ conducted a differentiated analysis of the paediatric population with vegetable allergies, covering both clinical manifestations and concomitant atopy. The study opens up a new direction in the stratification of patients by type of sensitisation: primary or cross-sensitisation. In contrast, the work of Takemura et al.⁹ focuses on the insufficient diagnosis of pollen-vegetable allergies in children, where cross-reactions are masked by non-specific food intolerance. This creates a risk of chronicity due to the lack of targeted therapy.

Scientific literature confirms that allergic risk is formed even before birth, largely under the influence of the mother's nutritional status. The work of de Castro Mendes et al.¹⁰ proves that increased consumption of vegetables is associated with a decrease in the frequency of inflammatory diseases of the respiratory system in children. This allows vegetables to be interpreted not only as potential allergens, but also as a factor with preventive potential. Ogawa et al.¹¹ hypothesised that a mother's vegetable diet plays a protective role against allergies in her offspring, which was confirmed in a large sample in a prospective cohort study. A significant advantage is the standardised control of food content during pregnancy. In turn, the study by Adineh et al.¹² suggests an inverse relationship between vegetable and protein nutrition in pregnant women and the risk of allergies in young children. The authors also point to a methodological problem: the clinical diagnosis of allergies in infants still lacks adequate validity, which makes it difficult to confirm the observed trends.

The lack of comprehensive epidemiological assessments of vegetable allergies in urban and rural environments, taking into account age, types of sensitisation and specific food consumption, remains a problem. The aim of the study was to identify spatial patterns in the spread of vegetable allergies and to characterise the clinical and epidemiological differences between urban and rural populations. Within the scope of the objective, the following tasks were set: to conduct a comparative assessment of the frequency of vegetable allergies among residents of urban and rural areas; to analyse the relationship between age, type of sensitisation and dietary factors; to establish the characteristics of the clinical course depending on the socio-geographical context.

MATERIALS AND METHODS

During the study, a theoretical analytical model was developed based on the method of systematic analysis and comparative structural modelling. The model consisted of three consecutive stages:

- geographical – for analysing spatial differences in the prevalence of allergies depending on the level of urbanisation;
- age – for stratification by biological age and identification of changes in immune reactivity within the life cycle;
- molecular – for systematisation of vegetable-derived allergens, taking into account their stability, cross-activity and clinical significance.

Geographical and age data were analysed separately, as the former reflect external socio-ecological conditions and the latter reflect internal biological characteristics of immune reactivity, which makes it impossible to combine them without losing analytical accuracy.

The study was designed as a structured narrative review combined with secondary synthesis of published epidemiological evidence and theoretical modelling. The literature search was conducted in the Scopus, Web of Science, and PubMed databases and covered publications from January 2020 to December 2025. The search strategy combined terms related to vegetable allergy, plant allergy, food sensitisation, IgE-mediated food allergy, PR-10 proteins, LTPs, cross-reactivity, urban environment, and epidemiology using Boolean operators (AND/OR). Only peer-reviewed publications in English reporting clinical, epidemiological, molecular, or public health aspects of vegetable allergy were considered. Case reports without analytical relevance, conference abstracts, duplicate records, and studies lacking sufficient methodological information were excluded. The selection was based on title and abstract screening followed by full-text assessment. After duplicate removal and eligibility assessment, 37 sources were included in the final synthesis. Because of the heterogeneity of study designs and reported outcomes, a formal meta-analysis was not performed.

The selected studies provided information on age-related and geographical patterns of vegetable allergy, the clinical structure of allergic reactions (OAS, anaphylaxis, FPIES, and other manifestations), and molecular characteristics of food allergens. Particular attention was paid to publications addressing the impact of vegetable allergy on healthcare systems, access to diagnosis, and dietary management.

Data extraction focused on study characteristics, population age groups, geographical setting, molecular profile of allergens, reported clinical manifestations, and indicators related to access to diagnosis and dietary management. Methodological quality was assessed descriptively by considering the

clarity of diagnostic criteria, study design, and completeness of reported outcomes. The synthesis was intended to identify recurring patterns across heterogeneous sources rather than to estimate pooled epidemiological parameters.

To ensure the reliability of regional comparisons, three representative territories were selected from each group of urbanised and rural regions. Among urban regions, the analysis covered New York (USA), Tokyo (Japan) and Warsaw (Poland), which are characterised by high levels of urbanisation, access to a wide range of food products, intensive medical surveillance and the presence of food allergy monitoring systems. These cities were selected because they are representative of the North American, East Asian and European regions, respectively. For comparison, rural areas in Hidalgo County in South Texas (USA), the city of Yokote in Akita Prefecture (Japan) and the municipality of Istebna in the rural part of the Silesian Voivodeship (Poland) were selected. These regions have a limited level of urbanisation, a traditional food structure with a high proportion of locally grown vegetables and lower availability of specialised allergy care. This stage corresponds to the geographical block of the model, the main purpose of which was to identify spatial patterns of vegetable allergy prevalence, its clinical severity, and the frequency of anaphylactic reactions in different community environments. The selected territories were used as representative examples of different socio-environmental settings rather than as directly comparable epidemiological cohorts. Differences in healthcare systems, diagnostic practices, environmental exposure, dietary traditions, and population characteristics were taken into account during interpretation. Consequently, the geographical comparisons presented in this study should be understood as narrative and conceptual observations and not as evidence of causal relationships.

Within the theoretical model, the age of the subjects constituted a separate analytical category, which was considered as a determinant of immunological reactivity, clinical severity of symptoms, and sensitisation structure; the relevant data were obtained by analytical generalisation of numerical indicators presented in scientific sources. Age stratification was carried out according to four main categories: preschool children (0-5 years), school-age children (6-12 years), adolescents (13-17 years), and adults (18 years and older). This distribution is based on the physiological stages of immune system development, maturation of the epithelial barrier, hormonal changes in the body, and transformation of eating habits throughout life. The preschool period is considered a critical stage of primary sensitisation to vegetable proteins, due to the high permeability of the mucous membranes and the imperfection of IgE-mediated regulation. At school age, a stable allergenic profile is formed and the likelihood of cross-sensitisation increases. Adolescence is particularly important due to hormonal influences on immune reactivity, changes in behavioural patterns and the risk of reduced adherence to

dietary recommendations. In adulthood, the allergic process often becomes chronic, may manifest *de novo* and be accompanied by an increased risk of systemic complications. This stage implemented the age component of the model in order to identify critical periods of sensitisation development and predict severe clinical forms.

The analysis focused on food allergens of vegetable origin, which have recognised immunogenicity and most often appear in clinical protocols^{13,14}. These are primarily PR-10 proteins (Dau c 1 in carrots, Api g 1 in celery), which are associated with cross-sensitisation to birch pollen; profilins (found in tomatoes, cucumbers, spinach), which have a high frequency of reactivity and are unstable to heat treatment; LTPs, in particular from eggplant, zucchini and bell pepper, which belong to the group of stable allergens with potential anaphylactogenicity¹⁵⁻¹⁷. Sol I 4 molecules, characteristic markers of tomato allergenicity, and potato glycoproteins, which are relevant mainly in paediatric practice, were also taken into account¹⁸. Each of these allergens was evaluated not only in terms of clinical severity, but also in terms of stability, cross-reactivity and potential dietary significance. Because the original studies reported heterogeneous sample sizes and different outcome measures, a standardised descriptive framework based on a theoretical distribution of 100 published cases within each allergen category was used exclusively for comparative visualisation of clinical phenotypes. This approach was intended to facilitate structural comparison between allergen groups and does not represent real prevalence, absolute risk, or pooled epidemiological estimates.

This multifactorial methodological approach made it possible to form a generalised analytical model of possible associations between settlement type, age, food structure, and the reported prevalence and severity of vegetable allergy. The theoretical model was developed to organise and interpret published evidence and was not intended to replace primary epidemiological research. No inferential statistical procedures, confidence interval estimation, or formal comparative tests were performed. The findings should therefore be interpreted within the framework of secondary evidence synthesis and theoretical modelling. Potential sources of bias, including underdiagnosis, differences in diagnostic criteria, age heterogeneity, cultural variation, and methodological diversity among the original studies, were considered during interpretation of the results.

RESULTS

Geographical Patterns of Vegetable Allergy Prevalence

The prevalence of vegetable allergies in urban areas is consistently higher than in rural areas. In New York City in 2023, 8% of the total population had a diagnosed vegetable allergy, while in Hidalgo County, South Texas, the rate was 4.3%¹⁹. In

Japan, in the same year, the prevalence of food allergies to vegetables among children in Tokyo was 6.4%, while in Yokote it was 3.2%^{20,21}. In Poland, according to data for 2024, the proportion of food sensitisation to vegetable proteins in Warsaw reached 5.1%, compared to 3.9% in the municipality of Istebna²². These data suggest a possible association between the level of urbanisation and reported patterns of allergic manifestations; however, differences in healthcare access, diagnostic practices, environmental exposure, dietary habits, and population characteristics should be taken into account when interpreting these findings. Potential explanatory factors discussed in previous studies include air pollution, dietary habits, environmental exposure, gut microbiota composition, access to healthcare, diagnostic practices, pollen exposure, and socioeconomic conditions. The present study does not allow the independent contribution of these factors to be determined.

An even more significant indicator is the incidence of anaphylaxis induced by vegetable allergens. This parameter in urban areas exceeds similar values in rural areas by more than half. These estimates are averaged based on data obtained from current epidemiological studies. In New York in 2023, the frequency was 12.3 per 100,000 people, while in Hidalgo County it was 4.6¹⁹. In Tokyo, it was 10.1 per 100,000, and in Yokote, it was 3.3^{20,21}; in Warsaw, it was 8.5, compared to 2.7 in Istebna²². These differences may reflect a greater reported clinical severity of the allergic process in urban settings, although variations in diagnostic coverage and reporting practices may also contribute. Factors that may contribute to this pattern include polysensitisation to PR-10 and profilin proteins, cross-reactivity with Bet v 1 pollen antigens, early exposure to oral allergens, as well as underestimated social and organisational factors, in particular, varying access to diagnostic services and levels of medical vigilance.

The analysed evidence suggests a consistent trend towards a higher reported prevalence of vegetable allergy and greater reported clinical severity in urbanised regions. Accordingly, the type of environment may be considered a contextual factor potentially associated with differences in the clinical and epidemiological profile of vegetable allergy; however, the available evidence does not allow causal relationships to be established. To illustrate the key interregional differences in the clinical and epidemiological profile of vegetable allergies, a graphical visualisation has been created that illustrates selected indicators in three geographically contrasting countries. The values presented in Figure 1 represent a conceptual synthesis of heterogeneous published evidence and are intended solely for comparative illustration; they should not be interpreted as directly comparable epidemiological estimates because of differences in study design, healthcare systems, and population characteristics.

The Figure 1 illustrates differences between urban and rural regions in terms of the frequency of both registered vege-

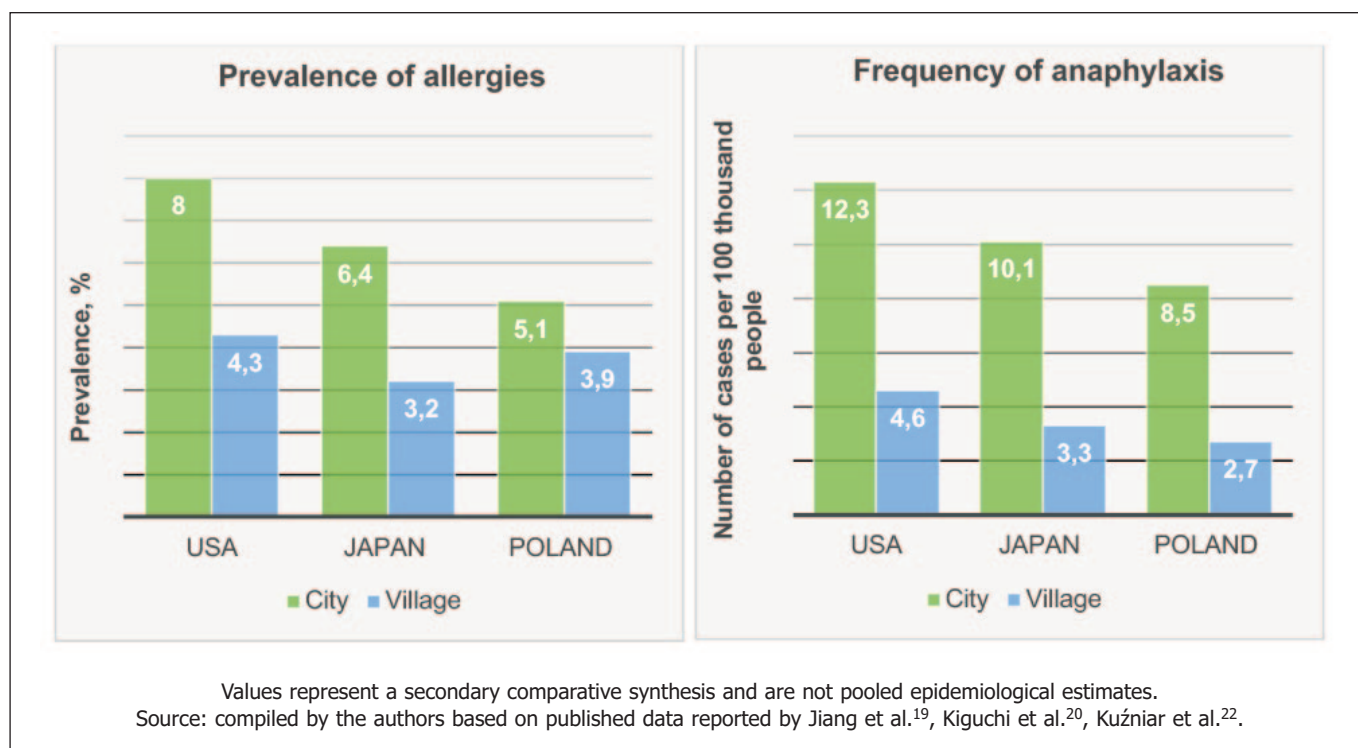


Figure 1. Theoretical comparison of selected published indicators of vegetable allergy in urban and rural settings

table allergies and cases of anaphylaxis. In the first graph, a higher reported proportion of detected sensitisation is shown in urban settings: in the United States, the difference is almost 4 percentage points, in Japan more than 3, and in Poland about 1.2. This pattern may be related to earlier contact with allergens in urban environments, variation in immune reactivity associated with environmental conditions, and greater access to medical diagnostics. Thus, the urban environment may be associated with a higher reported frequency of food sensitisation, although this relationship is likely to be influenced by multiple interacting demographic, environmental, and healthcare-related factors.

The second graph shows the incidence of anaphylaxis, the most severe clinical form of allergic reaction. In all three countries, the urban population shows significantly higher rates: in the United States, these figures are more than twice as high as in rural areas, and in Japan and Poland, they are almost three times higher. This pattern may reflect differences in immune response, cross-sensitisation, dietary exposure, diagnostic practices, and healthcare accessibility across regions. This difference is also likely to be partly explained by uneven diagnostic capacity across regions, with cases of anaphylaxis in rural areas potentially being underestimated or underreported. Taken together, these data support consideration of the living environment as a contextual variable associated with differences in the reported clinical profile of vegetable allergy.

The synthesised evidence suggests regional variation in vegetable allergy with respect to both frequency and clinical severity. This supports considering the type of environment during epidemiological assessment and public health planning, while recognising the limitations associated with heterogeneous source data.

Because the analysed data were derived from heterogeneous published sources, the observed urban-rural differences should be interpreted as comparative narrative patterns rather than direct epidemiological evidence. Variations in healthcare access, diagnostic criteria, environmental exposure, dietary habits, genetic background, pollen distribution, and socioeconomic conditions may contribute to the reported differences.

Age-related Aspects of Sensitisation and Clinical Course

Within the theoretical model developed in this study, the age of the participants constituted a separate analytical category, which was considered as a determinant of immunological reactivity, clinical severity of symptoms, and sensitisation structure.

In the 0-5 age group, primary sensitisation to vegetable proteins predominates. Previous studies have associated this period with immature mucosal barriers, limited secretory IgA activity, increased intestinal permeability, and the ongoing de-

velopment of the gut microbiota. At this stage, contact with profilin and PR-10 proteins in carrots, beets, tomatoes, or potatoes often leads to the production of IgE antibodies, even with minimal dietary exposure. The prevalence of vegetable allergy in this group reaches 6.2%, which is the highest rate among all age groups. At the same time, clinical reactions in children of this age usually do not go beyond local manifestations: erythema, itching, angioedema or mild gastrointestinal syndrome. The frequency of registered cases of anaphylaxis remains moderate – about 2.1 per 100,000 people, which is probably due to the general immaturity of the effector mechanisms of the immune response and the limited range of contact with triggers^{18,23}.

At the age of 6-12 years, the clinical and immunological situation becomes more complicated. The formation of a school food environment, the expansion of the range of foods consumed, and increased contact with external allergens contribute to the formation of persistent polysensitisation. It is at this age that a significant proportion of patients experience cross-reactions to pollen proteins for the first time, especially in children with concomitant allergic rhinitis or atopic dermatitis. The prevalence of vegetable allergy is about 4.8%, while the incidence of anaphylaxis increases to 3.3 per 100,000 people. Hypersensitivity to profilins in carrots, beets and tomatoes, as well as weak immune control over secondary reactions, are key risk factors^{24,25}.

Adolescence (13-17 years) is characterised by a significant increase in the severity of clinical manifestations of vegetable allergy. The incidence of anaphylaxis peaks at 7.6 per 100,000 population, which is more than three times higher than the corresponding rate in preschoolers. Although the prevalence of sensitisation remains high (about 5.7%), the key complication is the clinical significance of these reactions. Hormonal changes and other biological and behavioural factors have been proposed as possible contributors of the increased risk of anaphylaxis. Severe forms of oropharyngeal syndrome, combined with a bronchial obstructive component or gastrointestinal complications, are often observed at this age. In addition, adolescents are less likely to report symptoms or deliberately ignore recommendations for an elimination diet^{20,26}.

In adult patients (18 years and older), there is a tendency towards a decrease in the frequency of sensitisation – to 3.9%, but the severity of clinical forms often exceeds similar indicators in other age groups. Anaphylaxis is registered with a frequency of 5.2 per 100,000 people. On the one hand, this has been discussed in the literature in relation to intestinal permeability disorders, hyperreactivity of immune cells, metabolic changes, chronic inflammation, as well as the use of pharmacological drugs that potentially lower the reactivity threshold (e.g., non-steroidal anti-inflammatory drugs or ACE inhibitors). On the other hand, adult patients are less likely to

regularly visit an allergist, are less likely to follow a diet, and often do not associate their symptoms with the consumption of a specific product. That is why clinical diagnosis in this group is often delayed for years^{27,28}.

To illustrate the age-related patterns of sensitisation and clinical reactivity, the graph below shows the relationship between the prevalence of vegetable allergy and the frequency of anaphylaxis in four age groups. The age-related model is theoretical and integrates published evidence from studies with different populations and methodologies; therefore, the displayed values do not represent actual pooled population rates (Figure 2).

Analysis of the theoretical model presented in the graph reveals a discrepancy between the prevalence of sensitisation and clinical risks. Despite the highest prevalence of allergies in children under 5 years of age, the incidence of anaphylaxis in this group remains the lowest, while in adolescents, on the contrary, there is a peak in severe systemic reactions with a slightly lower overall prevalence of allergies. This pattern may reflect age-related changes in immune response – from predominantly localised or mild forms in early childhood to clinically aggressive manifestations in puberty, followed by a moderate decrease in severity in adults. This trajectory suggests that even with a decrease in the level of sensitisation with age, the need for clinical supervision does not disappear, as the proportion of cases of a systemic nature increases. The correlation of the curves also indicates a change in the clinical significance of IgE-mediated reactions with age, which strengthens the arguments in favour of an age-specific approach to the diagnosis, prevention and medical management of food allergies.

The synthesised evidence suggests that age may act as an important modifier of the clinical and immunological profile of vegetable allergy. Each age group has a specific risk configuration, which necessitates a differentiated approach to diagnostic criteria, choice of therapeutic tactics, and determination of the frequency of dispensary supervision. The observed age-related patterns provide a deeper understanding of the biological dynamics of the allergic process and may also serve as a basis for early-intervention strategies, taking into account the sensitivity of each period of development to external allergenic influences. At the same time, the synthesised evidence suggests a potential interaction between age and territorial factors: the association between living environment and the reported frequency and severity of allergic reactions appears more pronounced in younger age groups, which is probably associated with critical periods of immune system development and increased sensitivity to urban environmental factors. This cross-effect requires further stratified evaluation to develop effective preventive and clinical algorithms.

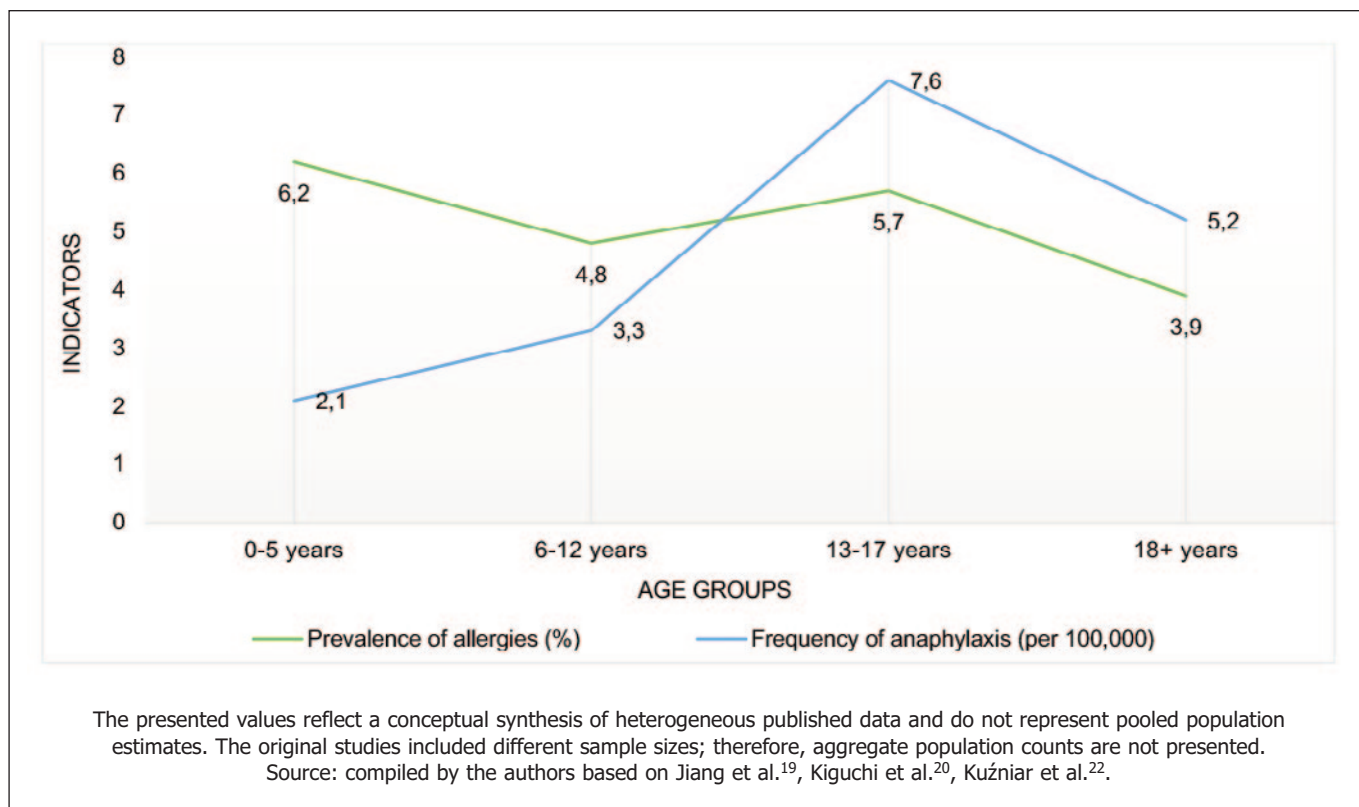


Figure 2. Theoretical age-related model based on secondary synthesis of published evidence

Immunopathogenetic and Clinical Features of Vegetable Allergy

The immunopathogenesis of vegetable allergy involves a complex interplay between plant-derived allergenic proteins and the immune system. In sensitised individuals, this leads to an IgE-mediated response. Key proteins involved in this allergic response include PR-10 proteins (like Dau c 1 in carrots), profilins (such as Api g 4 in parsley), and LTPs, particularly Sol i 3 in aubergine. Other important allergens with a high degree of cross-reactivity are also involved, like Sol i 4 or Bet v 1-homologues^{15,16}. PR-10 proteins are thermolabile and easily broken down by stomach acids, which is why reactions often stay within the mouth, leading to OAS. In contrast, LTPs are thermostable and resistant to digestive enzymes, increasing the risk of more severe, systemic reactions, including anaphylaxis¹⁵. Profilins sit somewhere in the middle – they're thermolabile but can still cause systemic symptoms with repeated exposure or if someone is also sensitised to pollen¹⁷.

Cross-sensitisation is a big part of how vegetable allergies develop. Profilins and PR-10 are pan-allergens, meaning their structure is similar across various plant species. This can cause reactions even if there's no direct contact with a specific vegetable. For example, someone allergic to birch pollen might react to carrots or celery because of these similar pro-

teins¹⁷. Heat processing of food is another key factor. Most PR-10 and profilin allergens are destroyed by heat. However, LTPs remain stable even after cooking, which means people can still have reactions to cooked foods, such as stewed tomatoes or baked aubergine¹⁶.

The symptoms of vegetable allergy can range from mild to severe. The most common is OAS, which causes itching, lip swelling, and a swollen mouth lining. With more severe sensitisation or if LTPs are involved, people can experience systemic reactions like hives (urticaria), angioedema, and anaphylaxis²⁹. A distinct condition is FPIES. This isn't IgE-mediated but is linked to vegetable allergens, particularly pumpkin or courgette. FPIES causes delayed, severe gastrointestinal symptoms like repeated vomiting, diarrhoea, and lethargy several hours after eating the offending food. There have been documented cases of FPIES in children being weaned onto courgette³⁰. Vegetable-induced anaphylaxis is rarer but can be very serious. For instance, individuals sensitised to pollen might experience a drop in blood pressure, bronchospasm, and even fainting after eating raw carrots, especially if they're exercising or taking NSAIDs at the same time³¹. Anaphylaxis to beetroot has also been reported, making diagnosis tricky due to its rarity and non-specific symptoms²⁹. The immunopathogenetic mechanisms of vegetable allergy show some regional differences. In southern areas, LTP reactions are more

common, while in northern regions, PR-10 and profilin reactions are more prevalent. This is down to climate, local diets, and pollen exposure³². Other factors like atopic dermatitis, asthma, or allergic rhinitis significantly increase the risk of systemic reactions. There's also a link between diet quality, the epithelial barrier, and the severity of symptoms. For example, a poor diet quality in children is associated with more pronounced immune inflammation and higher IgE levels³³.

To better understand the connection between allergen type and the clinical forms of vegetable allergy, the frequency of key symptoms for the main protein groups has been summarised and compared. The percentages presented in Table 1 are based on conditional normalisation for comparative modelling and should not be interpreted as real epidemiological frequencies.

Analysis of the theoretical comparative model suggests differences in clinical manifestations according to allergen type. Carrots (Dau c 1) and celery, which contain mainly thermolabile PR-10 proteins, cause mostly mild localised reactions, in particular OAS, while thermostable allergens in zucchini, eggplant and tomato, which contain LTP and profilins (in particular Sol I 4), are more often associated with severe systemic damage – anaphylaxis or FPIES. Thus, zucchini and tomatoes show the highest frequency of severe reactions among all vegetables included in the analysis, which may reflect the role of molecular stability in shaping the clinical phenotype. In addition, beetroot, rich in anthocyanins and glycoproteins, is characterised by latent sensitisation with a potential systemic reaction upon repeated contact. Vegetables with a predominance of stable allergens pose a greater clinical risk, while allergens with less structural stability cause mainly local, reversible manifestations.

The synthesised evidence suggests a complex, multi-level interaction between the biochemical properties of allergens and the nature of the individual immune response. The observed differences in severity of the course depending on the type of

vegetable are of direct importance for allergological prognosis, the choice of diagnostic methods and the formation of risk-oriented dietary recommendations. Taking into account the molecular stability, cross-reactivity, and local prevalence of certain crops allows for more accurate, pathogenetically sound management of food sensitisation. The generalisation of clinical forms of allergy by type of vegetable allergen is particularly important in the context of spatial analysis: the frequency of severe reactions is more often associated with urbanised regions, where highly processed foods or imported vegetables with altered allergenicity dominate. This approach may help to identify regional risk groups and can be integrated into public health strategies for the prevention of food allergy complications.

Dietary Behaviour and Adaptation: A Secondary Synthesis of Published Evidence

The dietary behaviour of individuals with vegetable allergies is influenced by a wide range of factors, from personal experience and awareness to cultural eating traditions and the availability of medical advice. Allergies to vegetable proteins, especially PR-10, LTP and profilins, force patients to make decisions about eliminating individual foods or entire food groups, which affects their quality of life, nutritional status and social adaptation.

Published studies suggest that self-diagnosis is a common adaptation strategy among some patients with vegetable allergy. In the absence of access to specific molecular tests or when symptoms are underestimated, patients often self-diagnose based on repeated reactions after eating a particular vegetable. Such actions often lead to overdiagnosis or, conversely, to underestimation of potentially dangerous proteins. In urban areas, where medical care is more accessible, patients are more likely to consult allergists to confirm their diagnosis and develop an individual diet. In rural areas, there is still a strong focus on traditional ideas about "intolerance" and the common classification of vegetables as "heavy" or "dangerous," which sometimes has no immunological basis³⁴.

Table 1. Theoretical distribution of clinical manifestations of vegetable allergy by allergen type based on secondary synthesis of published evidence (conditional normalisation for 100 cases in each group)

Type of allergen	Oral allergic syndrome, %	Anaphylaxis (%)	FPIES (%)	Mild generalised reaction, %
PR-10 (Dau c 1)	68.2	3.1	0.0	28.7
Profilins	59.5	2.4	0.0	38.1
LTP	27.4	41.3	4.8	26.5
Sol I 4 (tomato)	33.9	29.7	6.2	30.2
Other allergens	44.1	11.6	3.7	40.6

Source: compiled by the authors based on data analysis Asero et al.¹⁵, Berghi et al.¹⁶, Włodarczyk et al.¹⁸.

Data show that the availability of educational programmes has a positive effect on the formation of rational dietary behaviour. In studies conducted in schools, after the introduction of systematic information campaigns among teachers and students, the frequency of unjustified exclusion of foods from the diet decreased, while the number of requests for qualified assistance increased³⁵. The educational level of the family also correlates with the quality of dietary management: parents with higher education are more likely to follow doctors' recommendations, keep food diaries, and refrain from radically restricting the diet without clinical grounds³⁴. An analysis of dietary behaviour in a cultural context indicates that vegan or vegetarian diets create additional challenges for patients with vegetable allergies. In such cases, excluding even a few foods can significantly limit protein sources, leading to the risk of nutritional deficiencies. Adolescents and young adults who change their eating habits for ethical or environmental reasons are particularly vulnerable, unaware of possible hidden sensitisation to thermostable vegetable proteins³⁶.

The duration of dietary restrictions should be considered separately. Most patients diagnosed with allergies in childhood maintain restrictions for years, regardless of changes in the level of sensitisation or tolerance. This is often due to fear of anaphylaxis, even if the risk of systemic reactions is low. On the other hand, some patients gradually expand their diet after negative provocation tests, which highlights the importance of monitoring tolerance over time and reassessing the diagnosis³⁷. The rural context involves other adaptation mechanisms. Patients often replace "problematic" vegetables with local varieties with lower allergenic potential. Such practices can be effective, but there is no objective laboratory control, which creates risks of latent sensitisation and accumulation of immune load. According to epidemiological cohort data, rural regions have fewer referrals for specialised allergy care and higher levels of self-imposed dietary restrictions, which are not always confirmed by objective diagnosis³⁵.

Published evidence indicates that psycho-emotional factors may influence dietary behaviour. Fear of recurrent anaphylaxis has been reported to affect food confidence, causes social anxiety, avoidance of eating together, and behavioural disorders in children and adolescents. In such cases, adaptation strategies often take the form of hyperreactive caution, which significantly reduces quality of life. Educational interventions, particularly when combined with cognitive-behavioural support, have been reported to improve adaptation while reducing unnecessary dietary restrictions³⁴.

The reviewed evidence suggests that dietary behaviour in vegetable allergy is influenced by the interaction of medical, cultural and psychological factors. Its effectiveness is determined not only by the degree of sensitisation, but also by the availability of information, the level of support from the medical system, personal experience and the social environment.

In an urban context, clinically justified adaptations prevail, while in a rural context, independent strategic restrictions prevail, which are not always confirmed by objective diagnostics. These differences need to be taken into account when developing national guidelines for the management of patients with food allergies, with a focus on individualising advice within a specific social and cultural environment.

DISCUSSION

Vegetable allergy has a complex multifactorial structure, combining immunopathogenic mechanisms, age-related dynamics of reactivity, and external modifying factors, including dietary behaviour and sociocultural context. The clinical significance of this type of allergy is determined not only by the frequency of manifestations, but also by the high variability of symptoms, ranging from localised forms to severe systemic reactions. Comparison with the results of other studies has made it possible to better define the extent to which the characteristics of sensitisation and clinical severity established in this analysis are universal or, conversely, contextually determined by regional, age or cultural factors.

The analysis identified apparent spatial differences in the frequency of severe clinical manifestations of vegetable allergy. Thus, the highest reported rates of anaphylaxis were observed in megacities: 12.3 cases per 100,000 people in New York, 10.1 in Tokyo, and 8.5 in Warsaw. In contrast, in less urbanised areas (South Texas – 4.6; Akita – 3.3; Silesia – 2.7), the frequency of severe systemic reactions is significantly lower. This is consistent with the findings of Ota et al.²¹, who found a higher prevalence of OAS in children living in large cities in Japan, which is explained by higher reported allergen exposure in urban environments. Similar conclusions are presented in the work of Protudjer and Mikkelsen²⁴, which states that eating habits in megacities are accompanied by more frequent contact with new or exotic foods, which may increase the risk of cross-sensitisation. Additional evidence is provided by Jardim-Botelho et al.²⁶, who analysed the relationship between a vegetarian diet and the development of hypersensitivity to legumes, vegetables and plant proteins in vulnerable populations. Accumulated exposure to LTP proteases, profilins and other stable allergens as a result of frequent consumption of raw vegetables in an urban context has been suggested as a potential contributor to more severe clinical forms. Vieths²⁵ systematised the structure of allergens in plant products and noted that it is the urban population, which consumes a wide range of vegetables, including imported ones, that is exposed to a greater number of potentially active molecular determinants.

The synthesised evidence indicates a high level of sensitisation among the child population – up to 6.2% under the age of 5, with a subsequent slight decrease in older age groups. At the same time, the highest frequency of anaphylactic reactions was recorded in adolescents – 7.6 per 100,000 population. A

comparative analysis shows that a similar age dynamic is described in the work of Jiang et al.¹⁹, where the authors emphasise variations in the clinical course of food allergies by age and ethnic group, in particular the higher frequency of severe forms in adolescence. A study by Kuźniar et al.²² also found that adolescents show higher clinical activity than younger children, despite lower levels of sensitisation, which is consistent with the patterns identified in the present synthesis. Similar age paradoxes are reflected in the analysis by Sompornrat-naphan et al.²⁷, which shows an increase in the number of severe forms in adults with an overall decrease in the frequency of sensitisation, which is also recorded in our theoretical modelling. At the same time, the study by Skoczylas et al.²³ demonstrates a link between vegetable allergy and multimorbidity in childhood, especially in patients with bronchial asthma and atopic dermatitis, which may explain the high rates in the age group up to 5 years.

The analysed evidence demonstrated differences in clinical severity according to allergen type, which may be related to the molecular stability of protein components. The highest level of systemic reactions, in particular anaphylaxis, was recorded for LTP proteins, which are found in zucchini, tomatoes and eggplants. Within the theoretical comparative model, LTPs were associated with the highest proportion of anaphylaxis (41.3%), supporting their potential clinical relevance. At the same time, oral allergic syndrome in this group was found in only 27.4% of cases, indicating the predominance of severe over localised forms. This trend is consistent with the findings of Asero et al.¹⁵, which emphasise the anaphylactogenicity of LTPs as thermostable proteins that retain their allergenic properties even after culinary processing. A similar danger is demonstrated by Sol I 4 proteins specific to tomatoes: the level of anaphylaxis is 29.7%, and the frequency of FPIES is 6.2%, reflecting a multifactorial immune response. The data are consistent with the study by Berghi et al.¹⁶, which emphasises pronounced cross-reactivity and the potential for severe systemic manifestations.

In contrast, PR-10 proteins (in particular Dau c 1 in carrots) and profilins cause mainly mild reactions: oral syndrome was recorded in 68.2% and 59.5% of cases, respectively, while the proportion of anaphylaxis did not exceed 3.1%. This difference may reflect the role of epitope stability in shaping the clinical course, as summarised in the work of de Martinis et al.¹⁷. The data also correlate with the results of Jacob et al.²⁸, who found a lower allergenic potential of unstable Dau c 1 isoforms, emphasising their predominant involvement in the formation of localised symptoms. It is also worth paying attention to betroot, the frequency of systemic reactions to which remains moderate, but with a high potential for exacerbation upon repeated contact, as described by Tekeli et al.²⁹ as an example of hidden, subclinical sensitisation. These findings support the potential value of molecular typing of vegetable allergens as a basis for clinical risk assessment.

Analysis of the synthesised evidence identified a separate category of atypical reactions, in particular FPIES, which was mainly observed in sensitisation to zucchini and tomato proteins. The frequency of FPIES in these cases reached 4.8% and 6.2%, respectively, indicating the need to differentiate such forms from classic IgE-mediated mechanisms. A similar clinical scenario is described in a case study by de la Fuente et al.³⁰, where the reaction to zucchini was accompanied by a delayed immune response characteristic of FPIES. In addition, the work of Hirai et al.³¹ emphasises the role of physical activity as a trigger for food-dependent anaphylaxis when consuming carrots, which broadens the understanding of pathophysiological mechanisms, in particular involving not only the antigen but also additional environmental factors. The identified patterns are also in agreement with the conclusions of Präger et al.³⁶, which point to the emergence of new sources of vegetable allergens in connection with dietary trends (veganism, raw foodism) that potentially increase the risk of severe reactions.

The reviewed evidence indicated differences in adaptation strategies depending on the type of settlement. In rural areas, situational elimination prevailed, combined with a lack of systematic medical support, while in urban areas, long-term dietary restrictions were more common, even without laboratory confirmation of allergy. A similar trend is described in Kostecka et al.³³, who note uneven compliance with dietary recommendations among children with allergies in families with different levels of education. The work of Kourosh et al.³⁵ emphasises that the awareness of school staff directly affects the prevention of exacerbations in children, which is consistent with the importance of educational components in an urban context. In turn, Rethemiotaki³⁴ notes that the effectiveness of adaptation strategies is also related to the cognitive characteristics of patients, including the presence of learning disabilities, which can complicate compliance with dietary restrictions. Bayır et al.³⁷ also note an increase in risks for allergy sufferers in the absence of clear algorithms for managing food allergies, especially in conditions of limited access to specialised care.

Comparison with previous studies showed broad agreement with the patterns identified in the present synthesis and highlighted several aspects relevant to clinical practice, in particular the need for an age-specific approach to diagnosis and prevention. The integration of clinical, molecular and social parameters allows vegetable allergy to be considered not only as an isolated immune response, but as a complex phenomenon requiring multidisciplinary support.

CONCLUSIONS

The study developed a theoretical model intended to summarise possible associations between age, living environment, and dietary structure with the clinical and epidemiological characteristics of vegetable allergy. The model provides

a conceptual framework for stratifying potential risks, describing spatial and age-related differences, and identifying benchmarks for regionalised prevention strategies. The analysed evidence suggested differences between urban and rural populations in terms of reported prevalence, clinical severity, and adaptive behaviour in vegetable allergies. In cities, clinically confirmed forms are reported more frequently, which may partly reflect better access to diagnostics and higher awareness. This highlights the need to adapt prevention to regional characteristics.

The reviewed evidence suggests age-related variation in both the frequency of sensitisation and the clinical severity of reactions. The maximum level of sensitisation is recorded in children under 5 years of age (6.2%), which may reflect increased immunological susceptibility reported during early immune development. Although the prevalence of sensitisation declines after early childhood, it remains high in adolescence (5.7%), while the frequency of severe reactions, particularly anaphylaxis (7.6 per 100,000), increases significantly. In adults, the prevalence of sensitisation decreases to 3.9%, whereas the level of systemic reactions remains relatively high (5.2 per 100,000). These findings support the need for age-specific surveillance that takes into account not only prevalence but also potential clinical risk.

The synthesised evidence suggests that the molecular structure and stability of allergens may be associated with the severity of the clinical course and overall clinical risk. PR-10 (Dau c 1) and profilins were predominantly associated with local reactions (68.2% and 59.5%), while the proportion of anaphylaxis was only 3.1% and 2.4%, respectively. In contrast, LTPs found in zucchini, eggplant, and tomato were more frequently associated with systemic forms, including anaphylaxis (41.3%) and FPIES (4.8%). Sol I 4 in tomatoes had an intermediate risk profile, with 29.7% anaphylaxis and 6.2% FPIES.

Thermolabile PR-10 proteins were predominantly associated with local reactions, whereas thermostable LTP and Sol I 4 were more frequently associated with severe systemic manifestations. In addition, the reported sensitisation to beetroot and other vegetables with latent epitopes indicates the importance of molecular diagnostics. Thus, the pathogenetic properties of these proteins may represent an important factor in clinical risk assessment.

Limitations. A limitation of the study was the theoretical nature of the analysis, which did not fully take into account individual clinical variations. The theoretical models proposed in this study were developed to organise and compare heterogeneous published evidence and are not intended to replace primary epidemiological data or formal meta-analytic estimates. Future studies should focus on multicentre validation of the identified patterns using molecular diagnostics and stratified clinical groups.

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