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The effect of food processing on the allergenic potential of common vegetables

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ABSTRACT

Introduction: Food allergies to common vegetables have become an increasingly relevant issue in clinical nutrition and public health.

Aim: The aim of this study was to determine the impact of various food processing methods on the allergenic potential of common vegetables and to develop recommendations for reducing the risk of allergic reactions.

Materials and Methods: The study is a comparative systematic review that included a critical evaluation of clinical and empirical data on the allergenic potential of vegetables like carrots, celery, tomatoes, and potatoes. Literature published between 2018 and 2025 was queried from PubMed, Scopus, and Web of Science, focusing on in vitro and in vivo studies.

Results: The results showed that thermal processing (boiling, baking) led to the denaturation of allergenic proteins, particularly thermolabile profilins, but did not ensure the complete destruction of thermostable pathogen-related proteins. It was found that fermentation in acidic environments promoted the breakdown of proteins into shorter peptides with reduced immunogenicity, while non-thermal methods (ultrasound, high pressure, cold plasma) altered protein configurations without heating. The study revealed a phenomenon of cross-reactivity, whereby structural similarities between proteins of different vegetables triggered simultaneous allergic responses to related plant species. The most effective approach proved to be the combination of technologies (boiling with fermentation, pH alteration with heating), which enabled multilevel degradation of antigenic epitopes. A correlation was established between the individual sensitisation profile of a patient, the state of gastric secretion (with increased pH levels from the physiological range of 1-2), and the effectiveness of the processing methods.

Conclusion: The findings demonstrated the need for a personalised approach to selecting vegetable processing methods for individuals with food allergies and highlighted the importance of multidisciplinary collaboration between allergologists, gastroenterologists, and food technologists. The study's outcomes allowed for the development of practical recommendations on selecting optimal processing methods for vegetables in allergic individuals, contributing to dietary expansion and improved quality of life.

KEYWORDS

Molecular allergology, food matrix interactions, thermolabile profilins, pathogen-related proteins, cross-reactivity, protein denaturation, gastrointestinal digestion.

ABBREVIATIONS

IgE: immunoglobulin E.

IL8: Interleukin 8.

PFAS: Pollen-Food Allergy Syndrome.

pH: Potential of Hydrogen.

PR: Pathogenesis-Related.

rApi: Recombinant *Apium Graveolens.*

rBet: Recombinant *Betula Verrucose.*

INTRODUCTION

Food allergy is becoming an increasingly significant issue in today's world, as the number of individuals experiencing allergic reactions to food continues to rise. Vegetables, in particular – despite being an integral part of a healthy diet – can provoke undesirable immune responses in sensitive individuals. In the context of modern diets, where processed foods comprise a substantial portion of daily intake, it is essential to understand how various processing methods influence the allergenic potential of vegetables. This knowledge is critical for the development of safer food products, particularly for vulnerable groups such as children and individuals with multiple allergies. Furthermore, understanding the mechanisms underlying changes in allergenicity will enable the creation of more effective product labelling strategies and improved consumer information, both of which are key components in safeguarding public health.

The impact of food processing on allergenicity has attracted considerable scientific interest. López-Pedrouso et al.[1] focused on the role of Omics technologies – comprising high-throughput molecular analysis methods such as genomics, proteomics, metabolomics, and transcriptomics – in detecting and quantifying food allergens. The authors emphasised that the diversity of isoforms, post-translational modifications, and other structural alterations occurring during processing can either enhance or reduce a food's allergenic properties. They concluded that proteomic analysis using mass spectrometry offers powerful tools for detecting and quantifying allergenic proteins, but that standardised methodologies and reliable assessment techniques are necessary for accurate and rapid detection at the industrial level.

A significant contribution to understanding the effects of novel processing methods on food allergenicity was made by Dong et al.[2], who compared conventional thermal treatments (boiling, steaming) with emerging non-thermal technologies such as high-pressure processing, ultrasound, pulsed light, cold plasma, fermentation, and pulsed electric fields. Their research demonstrated that these innovative approaches generally preserved original food characteristics better and enhanced the efficiency of allergen removal. The authors stressed that a deeper understanding of allergen modification mechanisms could help design strategies for reducing the immunoreactivity of foods in the food industry.

Gonzalez et al.[3] addressed clinical aspects of how industrial and domestic processing methods affect food allergenicity. They reviewed studies evaluating the allergenicity of processed products using clinically accessible tools such as oral food challenges, skin prick tests, and measurements of specific immunoglobulin E (IgE) levels. Their findings showed that different processing methods (baking, boiling, canning, fermentation, pasteurisation, peeling, powdering, and frying) had varied effects on the likelihood of reactions in patients allergic to eggs, milk, peanuts and other legumes, nuts, fruits, and seafood. The authors underlined that recognising food allergy as a spectrum of hypersensitivity – rather than a binary phenomenon – has led to the development of dietary expansion approaches involving processed, less allergenic foods, and their application in food allergy immunotherapy.

A noteworthy study on the influence of cultivation methods on the allergenic properties of fruit was conducted by Aninowski et al.[4], who examined the effects of organic, integrated, and conventional farming on the allergenic potential and flavonoid content of strawberries. Their findings indicated that organically grown strawberries were the safest, containing the lowest levels of Bet v 1 and profilin allergens compared to those grown under integrated and conventional systems. The researchers concluded that organic strawberries are safer and offer greater health benefits due to their reduced allergenicity.

Liu et al.[5] conducted a comprehensive analysis of how components of the food matrix affect allergenicity. They investigated the modifying effects of water, non-allergenic proteins, carbohydrates, and lipids, as well as the impact of wet and dry processing on the interaction of matrix components with allergenic potential. A three-component mechanism of matrix influence was identified: modulation of biological processes of sensitisation and allergic response induction; modification of structural-functional properties of allergenic proteins and their extractability from the matrix; and interference with analytical detection of residual allergens. Meanwhile, Włodarczyk et al.[6] studied tomatoes as a food with high allergenic potential. They found correlations between tomato sensitisation and reactivity to grass pollen and latex allergens. Despite numerous studies, the scientific basis for characterising tomato allergens was found to be insufficient. The authors identified limitations in immunological detection methods due to cross-reactivity, which may result in false-positive outcomes.

A significant contribution to the understanding of the role of fermentation in reducing the allergenicity of food products was made by El Mecherf et al.[7]. They examined the impact of lactic acid bacteria, used as starter cultures in dairy products, on the fermentation of plant proteins. The authors concluded that, in addition to their nutritional value, fermented foods offer additional health benefits. However, they emphasised the need for further research to draw scientifically substantiated conclusions regarding the actual influence of fermentation on food allergenicity. The researchers also highlighted the importance of studying the molecular structures of allergens and their fate during fermentation to better understand the effects of this process.

Albuquerque et al.[8] investigated the nutritional and safety aspects of technologically modified alimentary products within the public health system. They postulated the necessity of an in-depth analysis of consumption patterns in order to predict population-level effects. Conceptualising public health as a set of preventive measures aimed at optimising biopsychosocial well-being, the authors justified the priority of studying processed foods. The systematisation of scientific data enabled the identification of the impact of various processing methods on the modification of allergenic potential, with a particular focus on thermal, non-thermal, enzymatic technologies and agrotechnological factors. At the same time, the molecular mechanisms underlying changes in the structure of specific vegetable allergens during different types of processing remain underexplored, and there is a lack of standardised methodologies for assessing the allergenicity of processed products under industrial conditions.

The aim of the study was to determine and characterise the effects of various food processing methods on the allergenic potential of common vegetables, in order to develop recommendations for reducing the risk of allergic reactions. The research objectives were as follows:

- to examine changes in the structure and bioavailability of allergenic proteins in common vegetables (potatoes, carrots, celery, tomatoes) under the influence of thermal processing, fermentation, and mechanical treatment;
- to identify the molecular mechanisms through which different food processing methods affect vegetable allergenicity, with a focus on protein denaturation, glycosylation, and the formation of new epitopes;
- to evaluate the clinical significance of changes in the allergenic potential of processed vegetables using in vitro and in vivo testing, and to develop recommendations on optimal processing methods that minimise allergenicity while preserving nutritional value.

MATERIALS AND METHODS

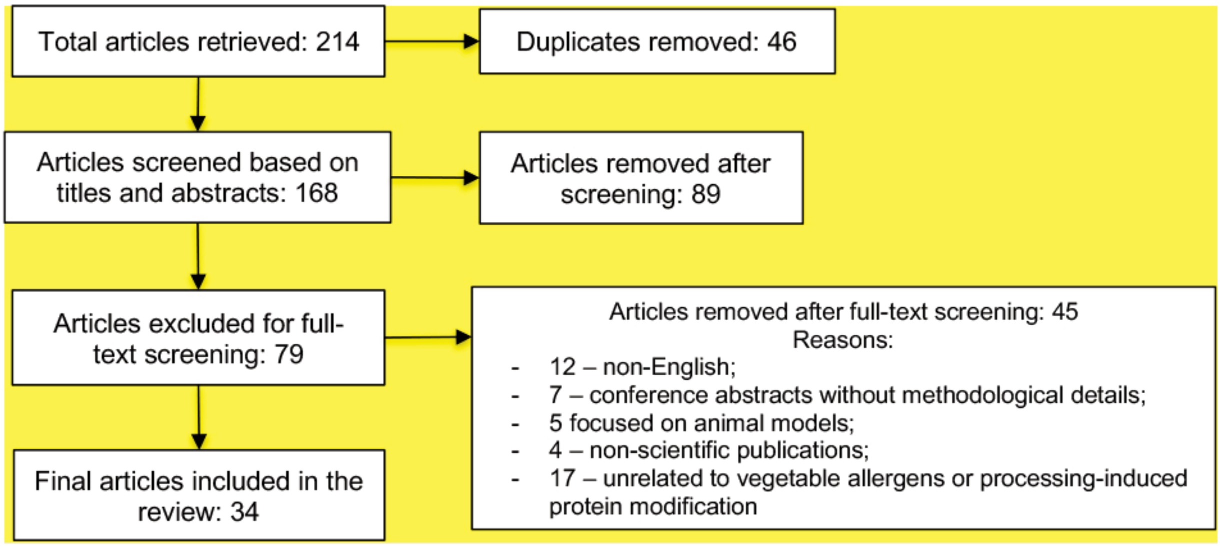
The study was designed as a comparative systematic review incorporating critical analysis of empirical and clinical findings. Research on the allergenic properties of common vegetables and methods of reducing their allergenic potential was conducted within a comprehensive systemic approach, utilising a range of general scientific and specialised methods. The work was based on the molecular allergology concept, which considers food allergenicity through the lens of the structural properties of protein components and their interactions with the human immune system. The theoretical foundation of the study included the concepts of protein cross-reactivity and the thermostability of allergenic epitopes, which explain the phenomenon of preserved immunogenic properties in certain proteins even after thermal processing.

The review was conducted as a comparative systematic synthesis of literature published between 2018 and 2025, using the databases PubMed, Scopus, and Web of Science. This method enabled the identification of key molecular factors of allergenicity in various vegetable species based on the analysis of peer-reviewed publications. The search strategy combined relevant keywords and MeSH terms, including "vegetable allergenicity," "profilins," "PR proteins," "food processing," "thermal processing," "fermentation," "non-thermal technologies," "IgE reactivity," and "protein denaturation."

Inclusion criteria consisted of peer-reviewed studies published in English between 2018 and 2025 that focused on food allergenicity in human populations or used in vitro methods relevant to allergenic protein characterisation. Experimental research, clinical trials, systematic reviews, and technological assessments of food processing techniques that affect the possibility for allergies were among the papers that qualified. Studies based only on animal models without direct relevance to human allergenicity, conference abstracts without complete methodological details, non-English publications, non-scientific sources, and studies not concentrating on vegetable allergens or processing-induced protein modifications were all excluded. These standards made ensuring that evidence that was directly related to the objectives of the current analysis and supported by science was included.

Initially, 214 publications were found in the chosen databases (Figure 1); after duplicates were eliminated, 168 items were left. After screening by title and abstract, 79 studies were found to match the initial relevance requirements. 34 studies were kept for in-depth analysis after full-text appraisal and the application of inclusion and exclusion criteria. A sufficiently strong and varied body of data was provided for the review's thematic and methodological goals by these, which included 14 experimental research, 8 clinical investigations, 8 technological or biochemical evaluations, and 4 systematic reviews. Three additional sources were authoritative clinical and informational resources, not peer-reviewed research articles. They were used solely to provide background context, definitions, and clinically verified descriptions of allergy-related conditions and allergens.

A comparative method was used to assess the effectiveness of thermal processing (boiling, baking, frying), enzymatic processing (lactic acid fermentation, enzymatic hydrolysis), and non-thermal methods (ultrasound treatment, high pressure, cold plasma) in terms of changes in protein immunogenicity, degree of denaturation, and preservation of nutritional value. This analysis was based on technological studies. A method of systematisation and classification of experimental and clinical research allowed the organisation of findings into structured tables that reflect the biological and immunological factors of allergenicity in carrots, celery, tomatoes, and potatoes, as well as technological methods for reducing their allergenic potential. A total of 34 studies were included, with 8 focusing on carrots, 7 on celery, 9 on tomatoes, and 10 on potatoes. The data extraction process was conducted independently by two reviewers to minimise selection bias, and any discrepancies were resolved through discussion to ensure consistency



Source: compiled by the authors.

Figure 1. Flowchart of literature search and selection process

and accuracy. To reinforce reliability, this review adhered to the PRISMA guidelines for systematic reviews, ensuring a transparent and rigorous approach to data extraction and analysis.

The method of critical analysis was applied to assess the reliability and clinical relevance of results obtained by different research groups. This enabled the identification of the most substantiated data on the effectiveness of various processing methods, based on such criteria as reduction in IgE reactivity, degree of antigen epitope degradation, consumer safety, and technological feasibility. To describe the clinical manifestations of allergic reactions and evaluate the effectiveness of different vegetable processing methods, clinical studies were analysed. The impact of gastric secretory status on the formation of allergic reactions was assessed using biomedical research data. To develop criteria for assessing the allergenicity of food products, regulatory documents of the European Food Safety Authority were used[9]. Recommendations on current approaches to the diagnosis and treatment of food allergies were drawn from informational resources of professional medical organisations[10-12].

RESULTS

Review and theoretical justification of the allergenic properties of common vegetables

A total of 34 studies were analysed, including 8 clinical investigations, 14 in vitro experimental studies, and 8 technological or biochemical evaluations. Allergic reactions to vegetables are based on complex mechanisms of interaction between the protein components of these foods and the human immune system, which has already been sensitised to similar antigenic structures. In the case of commonly consumed vegetables such as carrots, celery, tomatoes, peppers, or root vegetables (beetroot, parsley), specific types of proteins – particularly profilins and so-called pathogenesis-related (PR) proteins – play a central role in the onset of allergic responses. These protein molecules are part of the natural defence mechanisms of plants against stress factors, infections or mechanical damage. At the same time, they possess antigenic determinants capable of triggering an immune response in the human body. When allergenic proteins enter the mucosal surfaces of the gastrointestinal tract in sensitised individuals, they provoke the production of IgE antibodies. These antibodies bind to the surface of mast cells and basophils, which subsequently release histamine, leukotrienes, and cytokines. These inflammatory mediators give rise to the characteristic clinical manifestations of food allergy – ranging from localised symptoms such as oral itching or mucosal swelling to systemic complications such as anaphylactic shock, requiring urgent medical intervention. It has been established that even a minute amount of plant protein may elicit an active immune response if sensitisation has already occurred[10].

An important factor in determining the allergenic potential of vegetables lies in the structural characteristics and thermal stability of their proteins. Certain allergens, including some profilins, are altered or degraded during heating, which reduces the likelihood of acute allergic reactions after consuming boiled or stewed vegetables. However, heat-stable proteins

– common among PR proteins – retain their antigenic properties even after thermal processing. Therefore, individuals with heightened sensitivity to raw carrots or celery may still experience symptoms after consuming soups or sauces prepared with these vegetables. In addition, there is the phenomenon of cross-reactivity, whereby proteins from different vegetable species share similar amino acid sequences or spatial configurations with pollen allergens or other plant-derived proteins. As a result, in sensitised individuals, the immune system may recognise these familiar determinants and initiate an immune cascade, clinically manifesting as an allergy to several related plant sources simultaneously[1,3] (in vitro findings).

Celery holds a particular place among vegetables with a high risk of allergenicity, with allergic reactions most frequently observed in individuals with cross-sensitivity to birch and mugwort pollen. In clinical studies, 30-40% of individuals with pollen allergies report sensitivity to celery[12]. Carrots are also commonly cited in clinical practice as a trigger of oral allergy syndrome, which includes symptoms such as swelling of the lips, tongue, palate, and throat itching. Tomatoes and peppers often exhibit sensitising potential due to the preservation of protein structures even after cooking and the presence of additional compounds that may irritate the mucosal lining. Research indicates that approximately 15% of individuals allergic to pollen also experience sensitivities to tomatoes or peppers[13,14] (experimental and in vivo findings). Although most epidemiological assessments indicate that the overall prevalence of vegetable allergy is lower compared to other food allergens (such as nuts or milk), the true incidence is likely underestimated. This is largely due to the fact that mild to moderate reactions are frequently misdiagnosed or attributed to other gastrointestinal conditions. Such cases typically do not appear in official statistics and are not subjected to proper differential diagnosis with other allergic or non-specific food reactions (experimental findings). The key biological and immunological factors influencing the allergenicity of vegetables are summarised in Table 1.

Table 1 summarises the multifactorial model of the pathogenesis of allergic reactions to vegetable allergens, demonstrating the interplay between the molecular-biological characteristics of plant proteins and the physiological features of the patient's gastrointestinal tract.

This systematisation of factors is essential for a differentiated approach to the diagnosis and dietary management of patients with food allergies, as it enables the prediction of clinical responses to various culinary processing methods of vegetables. Taking these pathogenetic characteristics into account in clinical practice enhances the effectiveness of therapeutic and preventive measures by allowing for personalised selection of thermal processing schemes, fermentation, or other methods of plant material modification according to the individual sensitisation profile of the patient. This becomes particularly important in the presence of cross-reactivity between food and inhalant allergens (experimental findings).

To reduce risks associated with the consumption of potentially allergenic vegetables, many countries have introduced labelling standards for food products containing the most common allergens. Such labelling helps improve consumer awareness, especially for individuals with confirmed allergies to specific dietary components. However, since certain vegetable proteins are not yet included in the list of major aller-

Table 1. Biological and immunological factors affecting the allergenicity of vegetables

Factor	Specific example/condition	Mechanism of action	Clinical significance
Type of vegetable protein	Profilins, PR proteins	Determine thermal stability and immunogenic potential	Necessitates personalised selection of food processing methods
Cross-sensitisation	Birch or mugwort pollen, peanuts	Similarity in amino acid sequences	Induces allergic reactions to multiple related sources simultaneously
Gastric secretion status	Hypoacidity (pH>4)	Impaired protein hydrolysis→preservation of antigenic structures	Increases risk of allergy even to proteins with low inherent allergenicity
Form of the vegetable	Raw/processed/fermented	Varies in the degree of preservation of active epitopes	Patients may exhibit reactions only to specific forms (e.g., raw vegetables)
Individual IgE profile	Sensitisation to specific proteins (e.g., rApi g 1.01, rBet v 2)	Targets thermolabile or thermostable proteins	Enables prediction of post-processing protein tolerability

Source: created by the author on the basis of[14,15] (in vivo findings).

gens, food manufacturers are not always required to indicate them on product labels. This creates specific challenges for individuals with confirmed or potential sensitivities, as well as for healthcare professionals striving to develop safe dietary plans[3] (in vitro findings).

It should be noted that the development of a robust national policy in the field of food allergy prevention must be based on reliable scientific evidence, including studies assessing the impact of different vegetable processing methods on reducing allergenic potential[16] (technological/industrial findings).

Specialised clinical observations and in-depth studies conducted in allergy centres have shown that reactions to common vegetables can occur in various age groups, from preschool children to the elderly[17] (in vivo findings). Some evidence points to increased sensitivity to raw root vegetables (notably carrots, celery, or beetroot), manifesting as oral itching, lip or tongue swelling, or even clinically pronounced oral allergy syndrome. In such cases, it is believed that the vegetable's protein components may remain active in saliva and are not broken down during the initial stages of digestion. Up to 30% of individuals with oral allergy syndrome showed persistent IgE binding to proteins in raw vegetables after saliva incubation[18] (in vivo findings). In patients prone to pollinosis (allergies to tree or grass pollen), these symptoms may be exacerbated due to the presence of cross-reactivity, where the immune system "confuses" structurally similar proteins[18,19] (in vivo findings). The pollen-food allergy syndrome (PFAS) arises from an IgE-mediated immune response to specific proteins found in inhaled allergens (pollen) that cross-react with plant-derived food proteins present in some raw fruits, vegetables, and nuts[20] (in vivo findings). At the same time, cases of allergic reactions to thermally processed vegetables have also been reported, where a formally reduced level of thermolabile allergens does not guarantee complete elimination of immunological risk due to heat-resistant molecular fragments. While cooking alters many food proteins, exceptions exist – including heat-stable proteins found in celery, soybeans, and peanuts – that retain their allergenicity even after heat treatment. Studies have shown that up to 40% of patients with celery allergies continue to react to cooked celery[18] (in vivo findings).

Research shows that the functional activity of gastric secretion plays a critical role in the proper breakdown of dietary proteins. When gastric acidity is reduced (i.e., when pH rises from the natural level of 1-2 to higher values), the activation of pepsinogen into pepsin is significantly impaired, which is necessary for the effective hydrolysis of protein molecules. In clinical tests, a pH increase above 4 in the stomach significantly impairs protein digestion in 60-70% of patients[19,1] (in vivo and in vitro findings). Specific vegetable proteins may retain their structural integrity in the absence of sufficient acid hydrolysis, allowing them to bypass the stomach barrier and reach the small intestine virtually intact. Clinical observations confirm that patients with hypochlorhydria are more likely to exhibit IgE-mediated immune reactions to dietary proteins[21] (in vivo findings). Gastroenterological examinations have revealed a correlation between reduced gastric secretion and the incidence of allergic reactions, as undigested vegetable proteins retain their antigenic properties and can directly interact with immune cells of the intestinal mucosa[19] (in vivo findings). Considering these factors, practitioners and patients suspected of vegetable allergies are advised to employ extended diagnostic protocols (including skin prick testing and specific IgE assays) and to carefully monitor dietary habits, particularly in terms of preparation methods. In the long term, such detailed evaluation may substantially improve the current medical care system for patients with food allergies and help develop more accurate recommendations for the safe consumption of commonly eaten vegetables.

Main methods of vegetable processing and their impact on allergenic activity

The method of vegetable preparation and processing can significantly influence their allergenic potential. This primarily includes thermal processing (boiling, stewing, frying, baking), blanching, fermentation, as well as specific industrial techniques such as drying, ultrasonic treatment, or altering the pH environment. A common feature of all these methods is their ability to modify the spatial structure of proteins, making them either less active immunologically or, conversely, preserving allergenic determinants in a stable form[16,22] (experimental and technological/industrial findings). In controlled experiments, thermal treatment at 100°C for 20 minutes resulted in a 50% reduction in IgE binding in carrot proteins, while in tomatoes, the reduction was approximately 30%[23]. Table 2 systematises the main technological methods for reducing the allergenic potential of vegetables, taking into account their effectiveness and practical applicability.

The systematisation of technological approaches presented in Table 2 demonstrates a gradation of methods according to their impact on protein allergenic structures, safety coefficient, and feasibility of practical application in clinical settings and the food industry. Boiling vegetables for 15-20 minutes typically results in a 20-40% decrease in allergenicity, while more intensive methods like high-pressure treatment can reduce allergenicity by up to 70%[23]. A differentiated approach to selecting a processing method should consider the patient's individual sensitisation profile, the type of allergenic determinants, and the availability of technological equipment. Particular attention should be given to the parametrisation of processing conditions that ensure an optimal balance between the preservation of nutritional value and the disruption of immunogenic epitopes. The integration of these methods into clinical practice allows for the development of personalised dietary recommendations that account for the specific pathogenesis of allergic reactions in individual patients. Recent trials indicate that personalised dietary adjustments

Table 2. Technological methods of reducing the allergenic potential of vegetables

Processing method	Technological conditions	Expected effect on proteins	Practical application
Thermal processing (boiling, baking)	Temperature>100°C, duration≥20 min	Denaturation, partial degradation of thermolabile proteins	Effective for unstable proteins; does not ensure complete safety
Fermentation	Acidic environment, involvement of microorganisms	Hydrolysis into shorter peptides→reduced immunogenicity	Promising approach, though further clinical validation is required
Non-thermal methods	Ultrasound, high pressure, cold plasma	Alteration of protein conformation without heating	High cost and lack of standardisation limit current application
Combined technologies	Boiling+fermentation, pH adjustment+heating	Multilevel degradation of antigenic epitopes	Most promising for the development of hypoallergenic food products
Mechanical fragmentation	Chopping or grinding prior to cooking	Increased surface area→more effective denaturation	Recommended as an auxiliary method in household food preparation

Source: created by the author on the basis of [3,23,24] (technological/industrial findings).

based on processing methods result in 30-40% improved tolerability among patients with food allergies[2,3]. A crucial aspect of implementing such technologies is a multidisciplinary approach that brings together the expertise of allergologists, gastroenterologists, food technologists, and molecular biologists to achieve optimal therapeutic outcomes.

Boiling and blanching for 15-20 minutes are considered basic methods commonly employed in domestic settings, public catering, and the food industry. When vegetables are immersed in hot water, protein structures may undergo denaturation (unfolding of protein chains) and aggregation (clumping), often leading to a loss of their original antigenic configuration. This may reduce the risk of acute reactions, particularly when consuming thermally processed carrots or celery[25] (in vitro findings). However, heat-stable allergens found in certain root vegetables, solanaceous and umbelliferous species may partially retain their structure even after prolonged boiling. For instance, studies have shown that heat-stable allergens in tomatoes and celery retain 30-40% of their allergenic properties after boiling for 30 minutes[6]. Consequently, some individuals with heightened sensitivity may still experience allergic symptoms after consuming soups or sauces. This phenomenon may be attributed to the fact that thermal processing does not always affect the critical IgE-binding sites of protein complexes (experimental findings). This underlines that the reduction in allergenic potential through heating is not universal and depends on the type of vegetable and its specific protein components.

Frying and baking at high temperatures may promote more intensive protein denaturation. However, in dense vegetable tissues, zones may form where heat penetration is slower, allowing the primary structure of certain allergens to remain intact. Additionally, Maillard reactions (interactions between amino acids and sugars under elevated temperatures) may produce novel chemical compounds that can aggravate irritation of the oral and gastrointestinal mucosa. Studies have shown that Maillard reactions increase irritation by up to 40% in patients consuming thermally processed peppers[26] (in vitro findings). Therefore, thermal processing of varying intensity can exert a dual effect: on the one hand, protein denaturation may reduce their availability for immunoglobulin binding; on the other, side thermal reactions or uneven heat distribution may preserve or even enhance specific allergenic molecular fragments.

Fermentation involves the action of microorganisms (bacteria, fungi) or endogenous plant enzymes in transforming the chemical composition of a product. Examples include sauerkraut, pickling, and other prolonged vegetable preparations in acidic environments. Fermentation has been shown to reduce allergenicity by 20-30% in vegetables like carrots and cabbage, as pH changes and enzymatic activity play key roles in altering protein structure: certain fragments may break down into shorter peptides that are less detectable by the immune system[26] (in vitro findings). In clinical trials, fermented carrots exhibited 25-40% less IgE binding compared to raw carrots[25] (in vitro findings). Some observations have shown that fermented vegetables may elicit milder allergic reactions; however, these findings require further confirmation across different crop types[24] (technological/industrial findings). In some cases, fermentation serves as an additional means of decontamination from microorganisms and toxins. Fermented vegetables may reduce microbial load by 50-60%, but the persistence of certain allergenic determinants in fermented products remains a potential risk factor for hypersensitive individuals[27] (technological/industrial findings).

Non-thermal processing methods, such as mechanical grinding, vacuum packaging, or ultraviolet radiation, may variably alter allergenic activity. For instance, grinding and processing carrots at 60-80°C for 15 minutes increases the surface area of vegetable proteins exposed to digestive enzymes, potentially facilitating their breakdown and potentially reducing their allergenicity by 20-30% in comparison to raw vegetables[2] (experimental findings). However, under certain conditions, small protein fragments may more readily reach deeper segments of the gastrointestinal tract and sensitise the immune system, especially if pH levels and enzymatic activity do not ensure adequate allergen degradation[5] (technological/industrial findings). In industrial settings, where controlled lighting, drying, or the use of chemical stabilisers is applied, the preservation of allergenic proteins depends on a combination of factors: temperature, duration of processing, humidity levels, and the structure of the vegetable cells themselves (experimental findings).

Clinical observations suggest that in some patients with allergies, the allergenicity of celery and carrots significantly decreases after prolonged thermal processing. This can be attributed to high temperatures (about 150°C) degrading proteins responsible for allergic reactions[13] (in vivo findings). For patients with specific types of protein sensitivity (particularly to components rApi g 1.01 and rBet v 2), thermally processed celery is often tolerated without symptoms. These specific proteins are sensitive to both high temperature and digestive processes, allowing certain individuals with celery allergy to safely consume the cooked form. It is important to note, however, that the tolerance of thermally processed celery depends on the individual's sensitisation profile to particular allergenic proteins[12]. In contrast, those with cross-sensitisation to heat-stable structures (associated with homologous proteins in tree or weed pollen) may still exhibit allergic responses even after boiling[22] (technological/industrial findings). These findings reinforce the notion that no universal processing method currently exists that guarantees the elimination of allergic risk. Nonetheless, an optimal combination of heating duration and intensity, pH alteration, and enzymatic treatment may significantly reduce the allergenicity of many vegetables.

Contemporary technologies such as high-pressure processing, ultrasound, and cold plasma treatment are currently in the experimental research stage. Studies indicate that cold atmospheric plasma can generate various reactive oxygen species capable of modifying protein structures and influencing their immunogenicity (experimental findings). Experimental data using IL8 and insulin models demonstrate that plasma-treated proteins markedly increase the expression of surface markers and alter cytokine secretion profiles in antigen-presenting cells[28]. Notably, these effects cannot be replicated by simple hydrogen peroxide treatment, indicating the unique influence of short-lived reactive compounds on protein structures. Despite their promise, such methods have yet to gain widespread use in clinical practice due to their economic impracticality for mass consumption and the lack of large-scale clinical trials confirming their safety and efficacy[29] (experimental and in vitro findings).

Different vegetable processing methods not only influence taste and nutritional properties but can also significantly alter the allergenic profile of the product. Accordingly, healthcare providers and dietitians working with allergy-prone patients must take into account the relationship between the type of processing and the nature of the protein components involved.

Comparative analysis of results and prospects for practical application in the medical field

The most effective measures for reducing the allergenic potential of vegetable raw materials are those that directly influence the structural organisation of proteins and, accordingly, their ability to elicit IgE-mediated immune responses. In this context, the combination of hydrothermal processing (such as boiling, stewing, or blanching) with additional technological techniques (fermentation, pH modification, ultrasonic or high-pressure treatment) plays a pivotal role. Leading allergological studies confirm that thermolabile proteins lose their antigenic activity at sufficiently high temperatures and with adequate heating duration[16] (technological/industrial findings). At the same time, in cases where thermostable allergens (mainly from the PR protein group) predominate, even prolonged boiling or frying may not guarantee complete elimination of clinically significant reactivity[30] (in vitro findings). Therefore, patients with confirmed sensitisation to thermostable proteins in carrots, celery, or tomatoes are advised to carefully select both the method and intensity of heat treatment, and in the presence of clinical manifestations, to consider alternative methods or completely avoid the consumption of certain vegetables in any form (experimental findings).

It is important to note that fermentation – particularly under conditions that promote active protein chain degradation (acidic environment, involvement of lactic acid bacteria) – has demonstrated promising results in reducing the allergenicity of various legumes, root vegetables, and cruciferous plants[31] (in vitro findings). Through enzymatic transformations, proteins undergo hydrolysis into lower molecular weight fragments, which hampers the formation of immunologically relevant epitopes. However, existing data remain limited to a series of individual experimental studies, and thus the widespread use of fermentation processing for safe consumption by allergic individuals requires further randomised trials (experimental findings). In contrast, non-thermal technologies, such as ultrasound or high-pressure treatment, can alter the spatial conformation of certain proteins without intense heating, thereby preserving vitamins and micronutrients. Despite the observed reduction in IgE-binding capacity of plant proteins[32] (technological/industrial findings), these methods are still rarely applied in industrial practice due to high investment costs for equipment and the lack of large-scale clinical trials validating their efficacy and safety.

A comparative analysis shows that, in medical practice, it is particularly important to differentiate patients according to the types of proteins to which they are sensitised. This is achieved through extended panels of specific IgE testing, as well as skin prick testing with various forms of vegetables (e.g., raw and heat-treated). Such diagnostics allow for a precise determination of whether additional processing of a product is meaningful or whether a given patient must completely avoid it[22] (technological/industrial findings). Patients who primarily react to thermolabile proteins can usually tolerate boiled or stewed vegetables relatively well[19] (in vivo findings). In cases of cross-sensitisation to stable antigens of plant or pollen origin, even intensive thermal processing may not ensure safety. Selective consumption of fermented products may be viable if clinical observations confirm a significant reduction in IgE reactivity as a result of fermentation processes.

The practical application of these findings encompasses two strategic directions. Firstly, in clinical practice, allergologists and dietitians should provide in-depth counselling to patients on how to process vegetables appropriately, depending on their individual sensitisation profile. Recommendations include either complete exclusion of raw vegetables from the diet (for individuals with severe allergies) or, alternatively, prolonged boiling combined with mechanical fragmentation of the product, which increases the protein's exposure to thermal factors and enhances its denaturation[33] (in vivo findings). Secondly, food manufacturers targeting allergy-prone consumers should develop technological schemes combining thorough heating with fermentative or acidic treatment. Multistage methods appear especially promising, in which rapid initial heating (blanching) is followed by fermentation in a controlled environment, further degrading any residual allergenic determinants. Such developments require thorough laboratory control and a multidisciplinary approach, encompassing both technical aspects (optimisation of temperature and pH parameters) and medical safety criteria (monitoring the persistence of thermostable epitopes)[16] (experimental and technological/industrial findings).

Overall, the data confirm that the greatest reduction in allergenicity is achieved when the processing method appropriately corresponds to the specific protein structure triggering the patient's immune response. Since no fully universal method exists, clinical practice must be based on individual approaches with careful evaluation of sensitisation and accompanying factors (e.g., gastric pH). Given the large body of findings from various research groups, the need arises for standardising protocols for assessing the allergenicity of vegetable proteins to determine which specific processing parameters (temperature, duration, pH, microbial composition in the case of fermentation) most effectively eliminate clinically significant reactions[9]. Food producers prioritising the development of allergy-safe products may benefit from advances in high-tech non-thermal methods (e.g., cold plasma), although the scalability of these technologies and their medical approval are still at the stage of scientific substantiation.

DISCUSSION

The conducted study comprehensively addresses the issue of how various processing methods influence the allergenic potential of common vegetables – an issue of considerable relevance for clinical practice, the food industry, and public health at large. The results obtained illustrate the complexity of allergic response mechanisms and confirm the necessity of a differentiated approach to vegetable processing depending on the type of protein allergens and the individual sensitisation profiles of patients.

The observed correlation between the molecular-biological characteristics of plant proteins and the specifics of the immune response aligns with the findings of Jacob et al.[25], who established that different carrot isoallergens (Dau c 1) retain allergenic activity even after thermal treatment. The study supports observations regarding the thermostability of specific proteins and the presence of sequential epitopes that are not destroyed even under heating in low-pH environments. Notably, according to these researchers, even the presence of a food matrix that may reduce the thermostability of carrot allergens does not guarantee the complete elimination of allergenic activity, thus reinforcing the conclusion that IgE-mediated reactions may persist after thermal processing of vegetables.

The developed systematisation of technological methods for reducing the allergenic potential of vegetables is consistent with the findings of Cuadrado et al.[30], who reviewed the effects of different processing methods on the immunoreactivity of allergenic nut proteins. Although the current study focuses on vegetables, there are observable parallels regarding how specific processing techniques affect the structural properties of allergenic proteins. In particular, the authors emphasise that molecular stability – associated with resistance to heating and proteolysis – is a key factor in the allergenicity of plant proteins, thus supporting the conclusion that protein thermostability must be taken into account when selecting the appropriate processing method.

The potential of fermentation for reducing the allergenic potential of vegetables is supported by the study conducted by Tan et al.[26], who analysed changes in nutritional components during vegetable fermentation and their impact on human health. According to the authors, fermentation leads to the degradation of soluble proteins into free amino acids, which is consistent with findings on the breakdown of proteins into shorter peptides that are less detectable by the immune system. However, as noted in both studies, fermented vegetables may contain potentially hazardous components, such as biogenic amines and nitrites, necessitating further research and the development of new technologies to ensure the safety of fermented products.

Systematised information on the biological and immunological factors influencing the allergenicity of vegetables is further supported by the findings of Lokya et al.[34], who examined the prevalence of allergies associated with various food products, including peanuts, tree nuts, wheat, and soy. The authors highlight a recent increase in cases of food allergies and emphasise the need for the development of improved methods for the detection, diagnosis, and treatment of allergic reactions. These findings align with the identified need for enhanced diagnostic approaches for patients with vegetable allergies.

The analysis of the effectiveness of different vegetable processing methods to reduce allergenic potential is consistent with the findings of Williams[16], who evaluated food processing technologies in the United States for their ability to reduce allergen content. According to the author, although thermal methods are traditionally used, emerging non-thermal technologies such as high-pressure processing and cold atmospheric plasma show promise in producing hypoallergenic foods. These methods modify allergenic proteins without applying heat, thus preserving product quality while reducing allergenic reactivity. This supports the notion that non-thermal processing methods are promising in reducing the allergenicity of vegetables.

The study demonstrates that integrated technological approaches combining various processing methods show the greatest potential for the development of hypoallergenic food products. These findings are consistent with the research of Sabaghi and Maleki[35], who examined strategies for reducing food allergenicity through the application of biopolymers, biologically active components, and food-derived enzymes. The study highlights that different enzyme, including proteolytic enzymes (such as pepsin, papain, and bromelain) and enzymes from the transferase group (e.g., transglutaminase), are capable of modifying protein structures in foods through processes such as degradation, cross-linking, and oligomerisation, which can alter the allergenic properties of dietary proteins.

The potential of fermentation as a method for reducing the allergenic potential of vegetables identified in this study is further confirmed by Siddiqui et al.[27], who report that fermentation facilitates the breakdown of compounds into more digestible forms and reduces the presence of toxins and pathogens in food. In addition, the authors note that fermented products contain probiotics that support digestion and nutrient absorption, which may offer added benefits for individuals with vegetable allergies.

The findings also highlight the necessity of a personalised approach to patient sensitisation profiles when selecting thermal processing methods for vegetables. This correlates with data presented by Gunal-Köroğlu et al.[21] concerning the allergenic potential of unconventional proteins. Key determinants of allergenicity were identified, including the conformational structure of proteins, immunological cross-reactivity, food modification technologies, and the state of the intestinal microbiome. It was established that dysbiotic changes in gut microbiota increase the risk of hypersensitivity reactions, supported by evidence on the role of gastrointestinal secretory enzymes in the proteolytic transformation of dietary proteins.

The study found that thermal processing is not always effective in reducing the allergenic potential of vegetables, as certain proteins retain their structure even after heating. This is consistent with findings by Pak[36], who observed that although thermal and chemical processing can reduce the allergenicity of some foods, they do not render them entirely non-allergenic. The author underscores that combining food processing with other treatment approaches opens new pathways for safer, more convenient, and effective management of food allergies.

Findings regarding tomato allergy and processing methods are corroborated by the study of Włodarczyk et al.[6], who identified tomatoes as one of the most common allergenic vegetables. The authors note that tomato allergy is also associated with other allergies, such as grass pollen and latex allergies, aligning with findings on cross-reactivity between food and inhalant allergens. The researchers emphasise that despite numerous efforts to identify and characterise tomato allergens, existing data remain insufficient, highlighting the need for further research in this area.

The study underlines the importance of understanding the mechanisms underlying allergic reactions and developing effective allergen detection methods. This is in agreement with the conclusions of López-Pedrouso et al.[37], who note that ensuring food safety is one of the greatest challenges in bringing new products to market. The authors stress the need for the development of novel high-throughput screening methods to identify potential allergens, particularly using protein databases and other online tools. They also suggest that targeted proteomics will become a powerful technology for quantifying hazardous proteins, which corresponds with current recommendations for expanded diagnostics, including skin prick tests and specific IgE analysis.

Research into the allergenic properties of commonly consumed vegetables and methods to reduce their allergenic potential is of considerable importance for clinical practice and the food industry. The analysis confirms that the effectiveness of various vegetable processing methods (thermal, enzymatic, and non-thermal) depends on the type and thermostability of allergenic proteins. The observed relationship between the molecular-biological characteristics of plant proteins and the immune response is consistent with the conclusions of leading researchers in the field, particularly the assertion that complete elimination of allergenicity is not achievable even after intensive processing.

However, several limitations of the study should be considered. The results' generalisability may be impacted by methodological variability among the examined research, which includes variations in experimental designs, processing settings, and sample sizes. Furthermore, a lot of research was done in vitro, especially on heat processing and reducing allergenicity, which made clinical extrapolation difficult because there was no real-world validation. Furthermore, the non-thermal processing techniques included, such high-pressure therapy and ultrasound, are still in the experimental stage and do not yet have controlled clinical trials to prove their safety and effectiveness for general use. Finally, potential publication bias may also be a worry, as research with good outcomes are more likely to be published, while negative or inconclusive findings can be underreported. These elements emphasise the need for more investigation, especially carefully monitored clinical studies, to fully comprehend how food processing affects the likelihood of allergies.

CONCLUSIONS

The conducted study comprehensively addressed the impact of various processing methods on the allergenic potential of commonly consumed vegetables, specifically potatoes, carrots, celery, and tomatoes. The research provided an in-depth characterisation of the molecular mechanisms that modify the structure and bioavailability of allergenic proteins under the influence of diverse technological processes, establishing their clinical relevance for patients with food allergies. A thorough analysis of the biological and immunological factors influencing vegetable allergenicity demonstrated the pivotal role of profilins and PR-proteins in eliciting immune responses. These protein molecules, which form part of plants' natural defence systems, are characterised by thermal stability, immunogenicity, and the ability to trigger IgE-mediated reactions. The study confirmed the presence of cross-reactivity, whereby structural similarities between proteins from different plant species or pollen led to allergic reactions to multiple related sources. This phenomenon is of critical importance for differential diagnosis and dietary management.

The research also examined the impact of different food processing techniques on vegetable allergenicity in detail. Thermal processing (boiling, baking, frying) induces denaturation and partial degradation of thermolabile proteins, though it does not ensure the complete elimination of thermostable allergens. Fermentation in acidic environments involving microorganisms leads to the breakdown of proteins into shorter peptides, reducing their immunogenicity. Non-thermal methods (ultrasound, high pressure, cold plasma) alter the spatial configuration of protein molecules without heating; however, their clinical relevance requires further verification. A systematic analysis revealed that the greatest reduction in allergenic potential can be achieved through the combination of different techniques – for example, integrating hydrothermal processing with fermentation or pH modification. This multi-level destruction of antigenic epitopes significantly reduces the IgE-binding capacity of plant proteins. A key finding of the study was the identification of a correlation between an individual's sensitisation profile and the effectiveness of specific vegetable processing methods, thereby underscoring the need for a personalised approach to dietary recommendations. The systematisation of technological approaches for reducing vegetable allergenicity – considering their efficacy and practical applicability – provides a robust foundation for implementing personalised dietary recommendations tailored to the pathogenetic features of allergic responses in individual patients. The integration of these methods into clinical practice requires a multidisciplinary approach involving allergists, gastroenterologists, food technology specialists, and molecular biologists.

The limitations of this study included the limited number of large-scale clinical trials investigating novel processing methods and the lack of standardised protocols for evaluating the allergenicity of vegetable proteins. Future research should focus on the development of such protocols and the exploration of genetic factors influencing individual sensitivity to vegetable allergens.

REFERENCES

1. López-Pedrouso M, Lorenzo JM, Gagaoua M, Franco D. Current trends in proteomic advances for food allergen analysis. Biology. 2020;9(9):247. https://doi.org/10.3390/biology9090247
2. Dong X, Wang J, Raghavan V. Critical reviews and recent advances of novel non-thermal processing techniques on the modification of food allergens. Crit Rev Food Sci Nutr. 2020;61(2): 196–210. https://doi.org/10.1080/10408398.2020.1722942
3. Gonzalez PM, Cassin AM, Durban R, Upton JEM. Effects of food processing on allergenicity. Curr Allergy Asthma Rep. 2025;25:9. https://doi.org/10.1007/s11882-024-01191-5
4. Aninowski M, Kazimierczak R, Hallmann E, Rachtan-Janicka J, Fijoł-Adach E, Feledyn-Szewczyk B, et al. Evaluation of the potential allergenicity of strawberries in response to different farming practices. Metabolites. 2020;10(3):102. https://doi.org/10.3390/metabo10030102
5. Liu Q, Lin S, Sun N. How does food matrix components affect food allergies, food allergens and the detection of food allergens? A systematic review. Trends Food Sci Technol. 2022;127:289–90. https://doi.org/10.1016/j.tifs.2022.07.009
6. Włodarczyk K, Smolińska B, Majak I. Tomato allergy: The characterization of the selected allergens and antioxidants of tomato (Solanum lycopersicum) – A review. Antioxidants. 2022;11(4): 644. https://doi.org/10.3390/antiox11040644
7. El Mecherfi K, Todorov S, Albuquerque Cavalcanti de Albuquerque M, Denery-Papini S. Allergenicity of fermented foods: Emphasis on seeds protein-based products. Foods. 2020;9(6): 792. https://doi.org/10.3390/foods9060792
8. Albuquerque TG, Bragotto APA, Costa HS. Processed food: Nutrition, safety, and public health. Int J Environ Res Public Health. 2022;19(24):16410. https://doi.org/10.3390/ijerph192416410
9. EFSA GMO Panel, Mullins E, Bresson J-L, Dalmay T, Dewhurst IC, Epstein MM, et al. Scientific opinion on development needs for

the allergenicity and protein safety assessment of food and feed products derived from biotechnology. EFSA J. 2022;20(1):7044. https://doi.org/10.2903/j.efsa.2022.7044

10. Food Allergy Research & Education. Food allergy facts and statistics for the U.S. [Internet]. 2024. Available from: https://www.foodallergy.org/sites/default/files/2024-07/FARE%20Food%20Allergy%20Facts%20and%20Statistics_April2024.pdf

11. Cleveland Clinic. Oral allergy syndrome (OAS): Symptoms & treatment. [Internet]. 2022. Available from: https://my.clevelandclinic.org/health/diseases/23996-oral-allergy-syndrome

12. AllergyInsider. Celery allergen fact sheet. [Internet]. 2022. Available from: https://www.thermofisher.com/allergy/us/en/allergen-fact-sheets/celery.html

13. Ballmer-Weber BK, Vieths S, Lüttkopf D, Heuschmann P, Wüthrich B. Celery allergy confirmed by double-blind, placebo-controlled food challenge: A clinical study in 32 subjects with a history of adverse reactions to celery root. J Allergy Clin Immunol. 2000; 106(2):373–8. https://doi.org/10.1067/mai.2000.107196

14. Sharma Y, Patil P. Biological and chemical factors influencing food allergies: A comprehensive review. J Sci Res Rep. 2024;30(6): 787–94. https://doi.org/10.9734/jsrr/2024/v30i62095

15. Lee MW, Lee HJ, Moon S, Shin KH. Usefulness of component-resolved diagnosis of pollen-food allergy syndrome. Ann Lab Med. 2024;44(4):378–80. https://doi.org/10.3343/alm.2023.0466

16. Williams E. Assessment of food processing technologies on allergen reduction in United States. Int J Food Sci. 2024;7(2):1–10. https://doi.org/10.47604/ijf.2540

17. Li S-K, Liu Z, Huang C-K, Wu T-C, Huang C-F. Prevalence, clinical presentation, and associated atopic diseases of pediatric fruit and vegetable allergy: A population-based study. Pediatr Neonatol. 2022;63(5):520–6. https://doi.org/10.1016/j.pedneo.2022.03.019

18. Carlson G, Coop C. Pollen food allergy syndrome (PFAS): A review of current available literature. Ann Allergy Asthma Immunol. 2019;123(4):359–65. https://doi.org/10.1016/j.anai.2019.07.022

19. Pali-Schöll I, Untersmayr E, Klems M, Jensen-Jarolim E. The effect of digestion and digestibility on allergenicity of food. Nutrients. 2018;10(9):1129. https://doi.org/10.3390/nu10091129

20. Kato Y, Morikawa T, Fujieda S. Comprehensive review of pollen-food allergy syndrome: Pathogenesis, epidemiology, and treatment approaches. Allergol Int. 2025;74(1):42–50. https://doi.org/10.1016/j.alit.2024.08.007

21. Gunal-Köroğlu D, Karabulut G, Ozkan G, Yilmaz H, Gültekin-Subasi B, Capanoglu E. Allergenicity of alternative proteins: Reduction mechanisms and processing strategies. J Agric Food Chem. 2025;73(13):7522–46. https://doi.org/10.1021/acs.jafc.5c00948

22. Vanga SK, Jain M, Raghavan V. Significance of fruit and vegetable allergens: Possibilities of its reduction through processing. Food Rev Int. 2018;34(2):103–25. https://doi.org/10.1080/87559129.2016.1239208

23. Dong G, Hinds LM, Soro AB, Hu Z, Sun D-W, Tiwari BK. Non-thermal processing technologies for allergen control in alternative protein sources for food industry applications. Food Eng Rev. 2024;16:595–617. https://doi.org/10.1007/s12393-024-09378-2

24. Pi X, Yang Y, Sun Y, Cui Q. Recent advances in alleviating food allergenicity through fermentation. Crit Rev Food Sci Nutr. 2021; 62(1):1–14. https://doi.org/10.1080/10408398.2021.1913093

25. Jacob T, Vogel L, Reuter A, Wangorsch A, Kring C, Mahler V, et al. Food processing does not abolish the allergenicity of the carrot allergen Dau c 1: Influence of pH, temperature, and the food matrix. Mol Nutr Food Res. 2020;64(18):e2000334. https://doi.org/10.1002/mnfr.202000334

26. Tan X, Cui F, Wang D, Lv X, Li X, Li J. Fermented vegetables: Health benefits, defects, and current technological solutions. Foods. 2024;13(1):38. https://doi.org/10.3390/foods13010038

27. Siddiqui SA, Erol Z, Rugjii J, Taşçi F, Kahraman HA, Toppi V, et al. An overview of fermentation in the food industry – looking back from a new perspective. Bioresour Bioprocess. 2023;10:85. https://doi.org/10.1186/s40643-023-00702-y

28. Pontes Silva T, Lacerda Cervantes de Carvalho AC, Liberato De Souza A, Caetano Chagas S, Paraiso Brandão De Miranda L, Ferreira Araújo Do Nascimento G, et al. Clinical and nutritional characteristics of children with food allergy attended on an ambulatory basis. Nutr Clín Diet Hosp. 2024;44(2):266-74. https://doi.org/10.12873/442pontes

29. Clemen R, Arlt K, von Woedtke T, Bekeschus S. Gas plasma protein oxidation increases immunogenicity and human antigen-presenting cell maturation and activation. Vaccines. 2022;10(11): 1814. https://doi.org/10.3390/vaccines10111814

30. Cuadrado C, Sanchiz A, Linacero R. Nut allergenicity: Effect of food processing. Allergies. 2021;1(3):150–62. https://doi.org/10.3390/allergies1030014

31. Verma AK, Kumar S, Das M, Dwivedi PD. Impact of thermal processing on legume allergens. Plant Foods Hum Nutr. 2012;67(4): 430–41. https://doi.org/10.1007/s11130-012-0328-7

32. Braspaiboon S, Laokuldilok T. High hydrostatic pressure: Influences on allergenicity, bioactivities, and structural and functional properties of proteins from diverse food sources. Foods. 2024;13(6):922. https://doi.org/10.3390/foods13060922

33. Fabbri ADT, Crosby GA. A review of the impact of preparation and cooking on the nutritional quality of vegetables and legumes. Int J Gastronomy Food Sci. 2016;3:2–11. https://doi.org/10.1016/j.ijgfs.2015.11.001

34. Lokya V, Parmar S, Pandey AK, Sudini HK, Huai D, Ozias-Akins P, et al. Prospects for developing allergen-depleted food crops. Plant Genome. 2023;16(3):e20375. https://doi.org/10.1002/tpg2.20375

35. Sabaghi M, Maleki SJ. Mitigating food protein allergenicity with biopolymers, bioactive compounds, and enzymes. Allergies. 2024;4(4):234–53. https://doi.org/10.3390/allergies4040016

36. Pak E. Food processing and its effects on allergenicity of food allergens. Am J Stud Res. 2024;2(4):23–8. http://dx.doi.org/10.70251/HYJR2348.242328

37. López-Pedrouso M, Lorenzo JM, Alché JD, Moreira R, Franco D. Advanced proteomic and bioinformatic tools for predictive analysis of allergens in novel foods. Biology. 2023;12(5):714. https://doi.org/10.3390/biology12050714