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Allergenicity of pollen grains and risk of pollinosis development in the light of changing environmental conditions

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Abstract

Introduction and Objective. Inhalant allergens, especially pollen grains, are an increasing threat to human health and are the most common cause of allergic rhinitis (AR). The increased prevalence of allergy is also incident to the interaction of various environmental factors. The aim of the study is to demonstrate the effect of climatic conditions, air pollution, and urbanisation on the dynamics of pollen grain production by plants and the increase in their allergenicity.
Review Methods. The literature review was based on selected key words. Scientific publications mainly from the last eight years available in PubMed, PLOS ONE and Google Scholar databases were used.
Brief description of the state of knowledge. Particulate Matters (PM), ozone O3, and nitrogen oxides NOx may induce changes in the structure of pollen grains, facilitating the release of allergens. Global warming, rising CO2 concentrations, and changing precipitation patterns have a direct impact on plant life cycles and pollen production. An earlier onset and elongation of pollen seasons leads to increased exposure to pollen allergens. Climate changes also favours the occurrence of new allergenic plant species and intensifies the production of pollen grains by existing species. In cities, pollen grains may be more allergenic than in less urbanised areas.
Summary. Environmental changes and air pollution significantly impact the allergenicity of pollen grains. The increased allergen production and modifications of their structure result in an increased risk of developing pollinosis and an intensification of allergic symptoms. Understanding these mechanisms is key to developing more effective treatments and prevention of pollen allergies, which is an important aspect of public health.

Key words
pollinosis, inhalant allergens, air pollution, health aspects, climate change

INTRODUCTION

Due to the dynamic development of civilisation – lifestyle changes, technological and industrial advances, and climatic changes – a continual increase in the incidence of allergic diseases has been observed worldwide. Studies conducted in recent years indicate a clear upward tendency in the incidence of allergies in the human population, also in Poland. According to data, the occurrence of allergic reactions is noted in even up to 30% of the population [1]. Particularly, inhalant allergies pose a significant health threat, caused mainly by allergens of natural origin, such as pollen grains, fungal spores, or house dust mites. Pollen grains produced by plants in enormous quantities are considered to be the largest source of allergens and the most common cause of allergic rhinitis (AR). This is due to their content of proteins that induce the body's immune response to specific IgE antibodies [2]. In consequence, there is a high risk of developing and intensifying symptoms of allergic diseases caused precisely by increased exposure to plant pollen grains and their allergens.

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Furthermore, pollen allergy is also related to some types of food allergies; therefore, changes in the spread of pollen grains and their allergenic activity may also affect these afflictions [3].

The intensification of allergy symptoms and increase in the incidence of pollen allergy cases are also associated with the interaction of a variety of climatic factors, such as temperature, wind speed, air humidity and precipitation, as well as environmental factors, with the most significant importance attributed to the increase in atmospheric air pollution.

OBJECTIVE

The aim of the review is to present the current state of knowledge on the relationship between pollen allergies, together with the amount of pollen grains in the environment and environmental factors. The analysis aims to show how climate change, atmospheric pollution, and urbanisation affect the dynamics of pollen grain production by plants, changes in their pollen seasonality, chemical composition, and allergenic potential associated with the risk of inhalant allergy development in humans.

MATERIALS AND METHOD

The literature review, carried out using databases such as PubMed, PLOS ONE, and Google Scholar, was conducted in September 2024. In order to find appropriate articles, the following key words were used: plant allergens, respiratory allergies, pollen grains, environmental changes, climate changes, and air pollution. Particular attention was focused on publications from the last eight years.

STATE OF KNOWLEDGE

Characteristics of the principal plant allergens. The allergenic proteins synthesised in pollen grains that have been identified to date are divided into seven main groups. These include prolamins, cupins, profilins, expansins, LTP proteins, polcalcins, and plant stress proteins. They usually occur in significant amounts and perform essential life functions in plants, including initiation of the growth of the pollen tube and participation in plant defensive and adaptive responses to environmental factors [2].

The superfamily of cupins and prolamins includes storage proteins and enzymes occurring in all seed plants. Cupins constitute the most diverse multifunctional group of plant proteins among pollen grain allergens, e.g. enzymatic proteins from the group of α-ketoglutarate dehydrogenases involved in the Krebs cycle and associated with other key metabolic pathways. The enzyme-like proteins of the cupin group catalyse between 50 – 100 different biochemical reactions, are involved in the biosynthesis of plant antibiotics and associated with plant defence reactions. Moreover, they are characterised by high thermal stability and resistance to digestive enzymes, which is important for the allergenicity of these proteins [2].

Prolamins are proteins with a relatively low molecular weight of around 20 kDa and with high proline and glutamine content. They are known primarily for their occurrence in wheat, barley, rye, and oats, characterised by high resistance to digestive enzymes which makes them essential in digestive disorders, such as coeliac disease and food allergy. These proteins are associated with the plant response to biotic and abiotic stress and have a variety of functions related to plant protection against stress factors, e.g. high temperature, unfavourable pH, and the effects of various digestive enzymes or detergents [2, 4].

Profilins, so-called panallergens, are cytoplasmic proteins characterised by the ability to induce sensitisation via both inhalation and ingestion. Profilins, present in all eukaryotic cells, are responsible for cross-reactivity, for instance, between pollen, latex, and plant foods. Proteins from this family may exhibit up to 75% similarity to each other, contributing to the wide range of their cross-allergic reactions with various pollen allergens and food allergens (e.g. from apples, peaches, oranges, strawberries, and many others). The participation of profilins in basic life processes explains their omnipresence and multidirectional aspect of action [5, 6].

Expansins are another group of proteins playing a crucial role in the germination, growth, and development of plants. Their activity is essential at various stages of the plant's life, from germination to fructification; they also play an important role in the tolerance of plants to stress, including drought, heat, and salt stress. Expansins play a key role in the remodelling of the plant cell wall during growth and response to environmental factors. Expansins are present in the pollen grains of many plant species; hence, their involvement in the development of sensitisation reactions is prominent. Additionally, these proteins may react with allergens occurring in food, leading to the development of numerous cross-reactions [7].

In turn, Lipid Transfer Proteins (LTP) are a group that is widely recognised as being food allergens, especially in Mediterranean regions. They have the ability to penetrate cell walls and are resistant to heat treatment and the action of digestive enzymes, which means they can trigger allergic reactions even after the consumption of processed foods. These proteins are classified as plant stress proteins inducing severe allergic reactions, including anaphylaxis. They are present in pollen grains, fruit, nuts, and algae [8].

Polcalcins are small, often acidic proteins that bind calcium ions and are commonly found in pollen grains. They take part in the regulation of various physiological processes in plant cells, including the transmission and processing of intracellular signals. The functions they perform are extremely important for the growth of the pollen tube. Their activity is dependent on the influence of environmental factors and stress. The amino acid sequences of polcalcins show 60 – 90% similarity with analogous proteins from other allergenic sources. This significant amino acid sequence homology between polcalcins of different species may contribute to the high cross-reactivity observed within this group of proteins [1, 2].

Another group of proteins comprises plant stress Pathogenesis-Related Proteins (PR), which play a key role in the plant response to various forms of stress, both biotic and abiotic, including air pollution. They account for approximately 14% of all proteins involved in pollen grain germination, and their content varies depending on the degree of exposure of a given plant to stress conditions. These proteins are involved in intracellular metabolic processes, cytoskeletal structure, and transport of energy. According to the current classification, there are 19 different classes of PR proteins, of which as many as eight can cause allergic reactions in humans. It has been shown that approximately 25% of plant allergens are actually plant stress proteins. The high allergenicity of PR proteins is the cause of increased hypersensitivity to tree pollen grains in particular. In addition to the induction of specific allergic symptoms, PR proteins can cross-react, thereby intensifying clinical symptoms of the disease. These proteins can be found not only in pollen grains but also in fruits and seeds, making them relevant in terms of the development of both inhalant and food allergies [2, 9, 10].

Each of the mentioned groups of proteins has unique structural and biochemical properties that determine their allergenic potential and provide a basis for research into the development of preventive and therapeutic strategies for allergy.

Climate changes influencing the allergenicity of pollen grains. In the era of the high variability of environmental conditions, it is becoming crucial to understand their impact on public health, including the allergenic potential of plant pollen grains. Analysis of the influence of climatic factors on the allergenicity of pollen grains is therefore important, not only for ecology and environmental biology, but also from the aspects of public health.

The emission of pollen grains by plants is a dynamic and multifaceted process, closely influenced by many environmental factors. In addition to the soil composition, plant cover, air temperature, humidity, and wind speed, which are commonly acknowledged to be determinants of pollen timing and intensity, recent research has also shown a significant effect of moderately extreme precipitation on the subsequent pollen release by plants [11]. Increased soil moisture is beneficial for the proper growth and development of plants, which may lead to more intensive pollen release. Moderate precipitation preceding the pollen season may promote better plant development and enhance their ability to produce pollen grains. Light rain can increase the spread of pollen grains by 20% through modulations of their shape and size [12]. On the other hand, too intensive precipitation or its absence at critical moments of plant development can disrupt this process, leading to postponement pollen release and a reduction in the number of pollen grains produced. Precipitation may also have a negative impact on the pollen grain concentration in the air, for example by damaging flowers or restricting the access of pollinating insects. Moreover, heavy rainfall may temporarily remove pollen grains from the air, reducing their concentration, followed by their re-accumulation once the rainfall subsides. In the context of climate change, changing precipitation patterns may therefore have long-term effects on pollen dynamics and intensity [12]. For example, the effect of lower precipitation and high air temperature in summer was the reduced annual sum of ragweed pollen grains observed in recent years in Lublin, eastern Poland by Piotrowska-Weryszko et al. [13].

Global warming, especially in combination with increasing CO_2 concentrations, alters the intensity and timing of flowering, causing a shift in the growing season and an increase in plant biomass. This results in a seasonally earlier onset of pollen release, an altered duration of the pollen season, high concentrations of pollen grains in the air, and the emergence of new allergenic plants and their pollen in Europe. Examples of such plants include common ragweed (*Ambrosia artemisiifolia*), which is considered a highly allergenic plant and species from the cypress family (*Cupressaceae*), such as commonly cultivated arborvitaes (*Taxodiaceae*) and certain grass species (*Gramineae*), e.g., California brome (*Bromus carinatus*) or Weeping lovegrass (*Eragrostis albensis*), which are becoming increasingly widespread in response to changing climatic conditions. In the context of these changes, the prognoses suggested by Lake et al. [14] indicate that ragweed pollen allergy will be a common health problem in most European countries, and ragweed sensitisation is expected to more than double between 2041 – 2060. Therefore, people allergic to ragweed will be likely to experience more severe allergic symptoms due to the increased concentration of pollen grains in the atmosphere and the extended pollen season of the plant. The predicted changes are mainly related to climatic conditions and the rate of spread of this plant on the European continent [14]. In addition, increased CO_2 concentrations and higher temperatures may increase the pollen production by plants, and further intensity allergic problems in the population. This affects both the time of the allergic reaction development and the severity of the disease symptoms [15].

Research conducted in Germany has shown that the start of the pollen season can differ significantly depending on the weather conditions in a given year. For example, early spring species, such as hazel and alder, can start flowering as early as at the end of December or as late as in March of the following year. The development and flowering of plants are strongly dependent on the air temperature since milder temperatures encourage plant development while lower temperatures inhibit this process. Thus, the onset of meteorological winter can coincide with the onset of phenological early spring. Due to cross-reactions between pollen of plants of the *Betulaceae* family (hazel, alder, and birch), people sensitised to birch pollen allergens may also show allergy symptoms in December [16, 17]. It has also been demonstrated that higher air temperatures may induce increased production of birch pollen grains [18, 19]. In addition, as air temperature increases, which influences the life cycle of plants through changes in water availability, nutrients, soil type, and day length, there is a trend towards increasing concentrations of aeroallergens in the air. Observations of an earlier start of the birch pollen season have been reported in European cities such as Brussels, London, Stockholm, and Vienna [20–22].

Ongoing observations show that plant phenology, including flowering, is changing in response to global warming. The extension of pollen seasons is closely associated with both earlier springs (i.e. earlier occurrence of the last spring frosts) and later autumns (i.e. delayed occurrence of the first autumn frosts) [23].

Climate change, such as an increase in CO_2 or drought, affects plants by causing disturbances in allergen-coding transcripts, protein profiles, and metabolites, which may consequently increase the allergenicity of pollen grains. Moreover, modifications in the chemical composition and properties of pollen grains may occur in response to higher temperatures and environmental changes, thus affecting their degree of allergenicity. For instance, certain surface proteins of pollen grains responsible for inducing allergic reaction pathways, may be more active or occur in greater quantities as a consequence of climate changes [17]. As a result of these changes, allergy sufferers may experience stronger or more prolonged allergic symptoms. This is particularly relevant in the context of public health and needs to be considered in health care planning and strategies for adaptation to climate change.

Air pollution and the allergenic potential of pollen grains. The European Environment Agency has reported that as much as 96% of the urban population is exposed by atmospheric pollution [24]. Air pollution also plays a significant role in altering the allergenic properties of pollen grains, and their adverse influence is particularly evident in urban areas. Interactions between pollen grains and air pollution, such as PM_{10} or $PM_{2,5}$, ozone (O_3), or nitrogen oxides (NO_x), can lead to changes in the chemical composition and surface structure of pollen grains, changing their allergenic potential.

Studies have demonstrated that air pollution may have an impact on the morphology and viability of pollen grains, which is relevant to their ability to transmit and store allergens. For example, air pollution can lead to the formation of microcracks on the surface of pollen grains, which facilitates the release of allergens [25]. In urban environments, where air pollution levels are often higher, pollen grains may be more allergenic than in less urbanised areas. This phenomenon requires particular attention, especially as it is usually urban residents who experience more severe symptoms of respiratory allergy. Therefore, the urban air pollution may contribute to an increased prevalence and severity of allergic symptoms [18].

Air pollution can affect the process of pollen release by plants in various ways. For example, increased concentrations of carbon dioxide (CO_2) and other gases influence the life cycle and pollen production by plants, directly affecting the duration and intensity of pollen seasons. Similarly, ozone (O_3) and nitrogen dioxide (NO_2) play an important role in plant growth and development, triggering changes in their life cycles and increased pollen grain production. These pollutants may also determine the chemical composition of pollen grains, potentially enhancing their allergenic properties. As a result, air pollution contributes to the severity of allergic problems, particularly in urban environments. In stressful conditions, plants produce defence proteins, including allergenic ones. For example, pollen grains of Arizona cypress (*Cupressus arizonica*), which grows in heavily polluted areas, produce higher amounts of the allergen *Cup a 3* [26]. However, pollen of rye (*Secale*) exposed to high concentrations of ozone (O_3) shows an increase in total proteins, including those with allergenic properties [27]. Nevertheless, the response of plants to stress conditions may vary depending on the species [28].

In the analyses carried out over the last few years, increased allergenicity of ragweed pollen has been also observed with the recorded elevated levels of air pollution. Rising CO_2 levels and stress connected with climate warming largely result in increased production of *Ambrosia artemisiifolia* pollen grains and increased concentration of the allergen *Amb a 1* [29]. In an environment with a high CO_2 concentration, the plant produces more biomass and 61% to 90% more pollen grains. This is possible thanks to faster growth of the plant in spring, resulting from higher temperatures during occurring this period. The main ragweed allergen *Amb a 1* is increasingly produced in these conditions, which enhances the allergenic activity of the pollen and may intensify clinical allergy symptoms [17, 28].

In turn, a study conducted in Munich indicated that birch pollen in regions with high atmospheric ozone showes stronger allergenicity, and the content of allergen *Bet v 1* was positively correlated with the amount of O_3 in the environment [30]. Plant allergen extracts from sites with high ozone levels caused stronger reactions in skin tests than those from sites with lower ozone concentrations. Samples of pollen grains revealed not only the presence of the major allergen *Bet v 1* but also adjuvant substances, such as pollen-associated lipid mediators (PALM), lipopolysaccharide (LPS), or adenosine. They regulate the inflammatory response and have immunomodulatory effects, and may therefore promote and exacerbate allergic reactions [19, 30]. Birch allergens cause symptoms of inhalation and cross-allergies in approximately 6.4% – 22.4% of the European population. The main allergen *Bet v 1* of birch is recognised by specific IgE in up to 95% of patients [28]. Studies conducted by Stawoska et al. [28] have also revealed that air pollution can affect the secondary structure of the *Bet v 1* protein, inducing a decrease in regular α and β helix structures and an increase in β-strands and antiparallel β-sheet structures. This modification of the protein structure may have considerable consequences for its functions and an increase in allergenic activity [19, 28].

Epidemiological studies, such as those conducted in Canada by Cakmak et al. [31], indicate an increased allergenic effect of pollen grains after exposure to air pollutants, leading to increased allergy symptoms. A relationship has also been shown between hospitalisations of patients for asthma and exposure to tree and herbaceous pollen grains, as well as fine particles $PM_{2.5}$ and PM_{10} [31]. Moreover, the pollen surface has the ability to absorb airborne particles, such as metals, gases, or tiny PM particles. This process disrupts the structure of pollen grains and leads to extensive release of sub-pollen cytoplasmic particles, which act as adjuvants, increasing the body's immune response to pollen allergens [28].

In addition, particulate matter, such as $PM_{2.5}$, PM_{10}, or particles containing the metals nickel (Ni), cadmium (Cd), arsenic (As), lead (Pb), and gaseous pollutants as sulphur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and ozone (O_3), may adhere to the surface of pollen grains and modify their morphological and protein structure, which further enhances their immunoreactivity [32]. Studies carried out in Kraków, Poland, by Ziemianin et al. [32], show a significant correlation between PM air pollution and the allergenicity of birch pollen grains. PM_{10} levels were shown to be significantly associated with the average concentration of the *Bet v 1* allergen in pollen grains, which was significantly higher in samples collected from more polluted sites. The research observed a complex interaction between environmental factors and tree genetics, suggesting that the allergenic potential of birch pollen grains may be influenced by both local levels of air pollution and individual plant characteristics [32].

Air pollution may also increase sensitisation to aeroallergens through their direct impact on the respiratory mucosa environment. The concentration of reactive oxygen species (ROS) increases in the airway epithelium, where pollen oxidases NADPH play a key role in the induction and development of inflammation caused by pollen antigens. Furthermore, air pollution may have an indirect effect on the development of allergies by combining aeroallergens with particulate matters, such as diesel exhaust particles (DEP), thereby modifying their properties [18]. DEP pollution plays an essential role in terms of both increased air pollutant emissions and public health. These particles, formed as a result of incomplete combustion of fuel in diesel engines, consist of a carbon core on which a variety of chemical constituents, e.g. carbon monoxide (CO), nitrogen oxides (NO, NO_2), sulphur dioxide (SO_2), hydrocarbons, and heavy metals, are deposited. Most DEP particles are classified as ultrafine particles with a diameter of less than 0.1 μm; hence, they can easily penetrate the lipid membrane of alveolar epithelial cells, ensuring rapid transcellular translocation and, in a subsequent stage, inducing inflammation of the respiratory tract and tissue damage. Another interesting aspect is the impact of DEP on allergens contained in pollen grains [19]. It has been found that DEP can act as carriers for allergens, as in the case of birch allergens and the *Lol p 1* allergen of perennial ryegrass (*Lolium perenne*) pollen grains [19]. Pollen allergens carried along with pollutant particles can be more easily transported to the lower respiratory tract. This may lead to their direct impact on the lungs and bronchi, increasing the risk of allergic and asthmatic reactions, especially in urban environments, where air pollution levels are often higher.

Environmental pollution can react with the surface proteins of pollen grains, altering their structure or increasing the expression of genes encoding specific allergens. Such changes may be responsible for higher immunological reactivity of pollen triggering stronger allergic reactions [33]. For

Table 1. Influence of selected environmental factors on pollen release variability, allergenic potential of pollen grains, and possible health consequences

Environmental factors	Impact on the quantity of pollen grains	Degree of allergenicity	Health consequences	Literature resources
Global warming	↑ On the number of pollen grains in the air; changes in plant phenology; emergence of new invasive species with high allergenic potential;	+++	Negative	[14, 23, 37, 38]
Atmospheric precipitation	Variable impact: ↑ on the number of pollen grains after moderate precipitation; ↓ on the number of pollen grains after heavy precipitation	++	Negative Positive	[11, 12, 39, 40]
CO_2	↑ in pollen grain production	+++	Negative	[17, 28, 29]
Nitrogen Oxides (NO_x)	Change in the life cycle of plants; ↑ in pollen grain production	+++	Negative	[36, 41]
Ozone (O_3)	Stress for plants; variable impact on the number of pollen grains	+++	Negative	[19, 30]
PM particles (PM_{10}, $PM_{2.5}$)	Changes in the morphology and viability of pollen grains; impact on the number of pollen grains	++++	Negative	[28, 31, 32]
Diesel exhaust particles (DEP)	Possible role as carriers for allergens; ↑ in their presence in the lower respiratory tract	++++	Negative	[19]

↑ – increase; ↓ – decrease; ++++/very big; +++/big; ++/medium

example, air pollution induces quantitative and qualitative changes in the structure of common mugwort (*Artemisia vulgaris*) pollen and changes in the structure of the allergenic proteins of this pollen, which may lead to the emergence of more aggressive allergens increasing the risk of pollinosis symptoms [34].

Air pollution, particularly the presence of nitrogen dioxide (NO_2), can cause post-translational modifications of pollen proteins, such as S-nitrosylation or nitration. A study conducted by Zhao et al. [35] showed that exposure of ragweed to higher NO_2 concentrations throughout the whole growing season leads to increased S-nitrosylation of proteins. S-nitrosylation then occurs the major ragweed allergen *Amb a 1* [35].

Another important aspect is the nitration of allergens in pollen. Literature data report an enhancement of the nitration of allergenic proteins in the presence of high concentrations of NO_2 and ozone [36]. Nitration of proteins – for example, the birch allergen *Bet v 1* – may lead to oligomerisation of the allergen, which increases its immunogenicity. These changes have a significant impact on the character and intensity of the resulting immune response of the body to pollen allergens. This is relevant in the context of the growing problem of pollen allergies in urban and polluted environments [28, 36]. Research has shown that nitrated *Bet v 1* can cause a stronger proliferation of T cell lines specific to this allergen. Moreover, IgE binds more strongly to nitrated *Bet v 1* than to the non-nitrated form of this protein [36].

The increased allergenic potential of pollen grains in urban areas has direct implications for public health (Tab. 1). It may lead to an increase in the number of pollen allergy cases and the intensification of symptoms in individuals suffering from this type of allergy, which highlights the need for further research and the implementation of measures aimed at reducing air pollution levels. Research on the interactions between the number of pollen grains, their allergenic potential, and air pollution are crucial for a better understanding and more effective treatment of pollen allergies in urban environments. Elucidation of the mechanisms by which environmental pollutants affect the allergenic potential of pollen grains may contribute to the development and implementation of more effective methods for the prevention of pollen allergies.

CONCLUSIONS

In the face of the ongoing environmental changes, it is becoming particularly important to understand their impact on public health, including the allergenicity of pollen grains (Tab. 1). Global climate warming, rising CO_2 levels, and changes in precipitation patterns have a considerable influence on the seasonality, intensity, and duration of pollen release, which may also influence the allergenic properties of pollen grains. The intensifying climatic phenomena, such as rising temperatures, result in the earlier flowering of plants and the appearance of new allergenic species in Europe.

Existing studies indicate that the allergenicity of pollen grains increases in conditions of higher rates of air pollution and climate change, leading to an increase in the incidence and intensity of pollen allergies. It has been established that variability in environmental conditions may disrupt the life cycle of plants, extend the pollen release season and, as a result, increase the content of pollen grains in the air and the risk of allergies. Air pollution may alter the chemical composition and the surface structure of pollen grains and disrupt the structural and functional profile of pollen proteins, thereby increasing the allergenic potential of pollen grains. This, in turn, may lead to an intensification of symptoms in individuals suffering from pollen allergies and an increase in the incidence of pollinosis. Additionally, air pollutants can disrupt the morphology of the pollen grains, causing microcracks facilitating the release of allergens. Therefore, in urban areas, where pollution levels are higher, pollen may be more allergenic than in rural areas.

In conclusion, climate change and air pollution have a direct impact on the increase in the allergenicity of pollen grains, which results in an increased frequency and severity of allergic symptoms, especially in urban environments. These changes have a significant impact on public health, especially in terms of the rising number of allergy sufferers. The results of existing studies indicate the need for further detailed analyses aimed at elucidation of the complex mechanisms affecting the allergenicity of pollen grains. This is crucial for developing effective strategies for diagnosing, treating, and preventing pollen allergies, especially in heavily urbanised and polluted areas.

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