Chapter

The Allergenic Potential of the Plants

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Abstract

The allergenic potential of pollen emitted by plants is one of the factors that need the most attention in urban greening because it has a high impact on the quality of air and the health of citizens. The most crucial problem is the lack of knowledge about the allergenic capacity intrinsic to cultivated or wild plants. This treatment of the allergenic potential of plants becomes a valuable tool for management and evaluation by allergologists or general practitioners. The result of this study is the allergenic potential of plants assessed from the most up-to-date literature references. This chapter aimed to focus on the allergenic potential of plants and other harmful or positive interactions between plants and human respiratory health, to treat and discuss the criteria most used in international literature for value and to show its value for the most frequent plants (botanical families, genera, species, varieties) in urban parks, school areas, sports areas, wild spaces, and forests near urban cities in some world areas. This is also a risk mitigation measure in planning urban spaces and green infrastructures for people affected by pollinosis and applying sustainable development goals for sustainable cities, good health, and well-being.

Keywords: allergenic plants, allergenic pollen, assessment of allergenic potential, airborne pollen, pollinosis, urban parks, green areas, invasive plants, climate change

1. Introduction

Shortly after the emerged lands were conquered, plants evolved into the appearance of superior plants (higher plants) that have cones or flowers with male and female parts in the same individual or distinct individuals. Pollen is released by the male organs of higher plants on the terrestrial surface to find the female ones for breeding, cross the genetic material, and thereby increase biodiversity and resilience to environmental impacts. Pollen emissions (PE) from plants can harm human health, particularly in respiratory diseases and in sensitive places such as schools, hospitals, or sports areas (**Figure 1**). Indeed, contact of pollen granules with the mucosae or eyes can cause allergic reactions or sensitisation in the human population [1]. Allergic respiratory diseases are serious public health challenges in many countries and regions. Asthma affects more than 350 million people worldwide and is



Figure 1.
Wind-dispersed pollen cloud emitted from Cupressus in a schoolyard in Perugia, Italy. (photo by Francesca Marinangeli).

the most common chronic disease in children, affecting at least 30 million children and young adults in Europe [2]. Not all types of pollen cause allergies in humans. There are several allergenic plants with varying grades or intensities, as well as non-allergenic plants. Studies on this topic are relatively recent, focusing on a few more impactful plants, and are not yet very widespread. The meaning and evaluation of allergenicity are much discussed in the scientific world. The interpretation of allergenicity can be considered in two main ways [3]: In botanical significance, a plant is highly allergenic when its pollen triggers very strong allergenic symptoms in some individuals, or in epidemiological significance, when many people suffer from pollen emitted by a plant. In Europe, one of the most vulnerable regions for air pollution effects on respiratory health [4], 35% of the population suffers from allergies to the Poaceae family, and during the last few decades, the prevalence of pollen allergies has increased [5], as has been observed in other continents (Africa, Asia, America). Pollen grains can also travel across countries or seas far from their emission source. In some cases (eg, in Michigan, USA, for *Ambrosia artemisiifolia*), scientists use satellite images to predict pollen diffusion or concentration [6]. It is possible to study the phenology of airborne pollen, including timing and duration,

and determine the direction and source area of PE [7, 8]. Data on the presence and prevalence of allergenic airborne pollen, obtained from both aerobiological studies and allergological investigations, make it possible to design pollen calendars with the approximate flowering periods of plants in the sampling area [5, 9]. The pollen map is changing, as shown by aerobiological and allergological studies by the same author in Europe, due to cultural factors (green area planning), globalisation and colonisation by alien plants, and climate change, which cause weather extremes, thunderstorms, windstorms, and increasing episodes of long-range transport of allergenic pollens or subpollen particles [10]. Therefore, it is essential to know and consider, also in diagnostics, the allergenic potential of a plant, even if it lives in other places (alien species). Concerning climate change, many studies carried out in the last decades have shown that the pollen season for taxa flowering in winter and spring in temperate regions has tended to occur earlier, probably due to the continuous rise in temperature. The flowering of one of the most allergenic families, the grass family, has been observed in Central Italy in a 33-year study [11]. Poaceae pollen is currently the leading airborne biological pollutant and the chief cause of pollen allergy worldwide [12]. It is also essential to consider the interaction between pollen and air pollutants to gain new insights into the mechanisms of respiratory allergic diseases, as specific weather conditions can modify pollen's allergenic potential [4]. The additional influence of urban pollution may prompt a more severe immunological response [12]. Some plants can cause adverse reactions even by ingesting fruits or other parts. There are also cross-reactions between common allergens in Mediterranean plants and commonly consumed fruits [13]. However, plants are not only hostile to the human respiratory system: They produce oxygen, purify the air with their leaves, and some plants can positively affect the respiratory system due to balsamic substances. Clean air is essential for our health, and sustainable development goals aim to create healthier cities. It is fundamental to spread knowledge in botanical allergology and correctly plan green areas.

2. Airborne pollen and allergy

Pollen is the male gametophyte of spermatophytes, higher plants that reproduce sexually, and its main function is fertilisation. Spermatophytes are subdivided into angiosperms and gymnosperms depending on whether or not the seed is protected by an ovary [14]. Allergy refers to the spontaneous and exaggerated reactivity of the body of a sensitive individual to substances that are harmless to the rest of the population [5]. The etiologic agent responsible for pollinosis is pollen, particularly its protein and glycoprotein components, both internal and membrane. Protein, lipid, and polysaccharide molecules, various enzymes, and microorganisms are found in pollen. Their interaction influences the corresponding cell receptors, causing inflammation [15]. Once pollen comes into contact with the nasal and/or oral mucous membranes, it undergoes initial lysis, which releases the allergenic protein fractions that can then act locally and at the level of the small airways. Once inhaled, pollen grains are attacked by enzymes in mucous secretions; the wall is dissolved, and allergenic molecules are released. The characteristic of the allergenic molecules present in the pollen granule is that they interact with the immune system of sensitive individuals, triggering allergic reactions. On the outside of the pollen wall (exine) are proteins and glycoproteins that have the critical function of

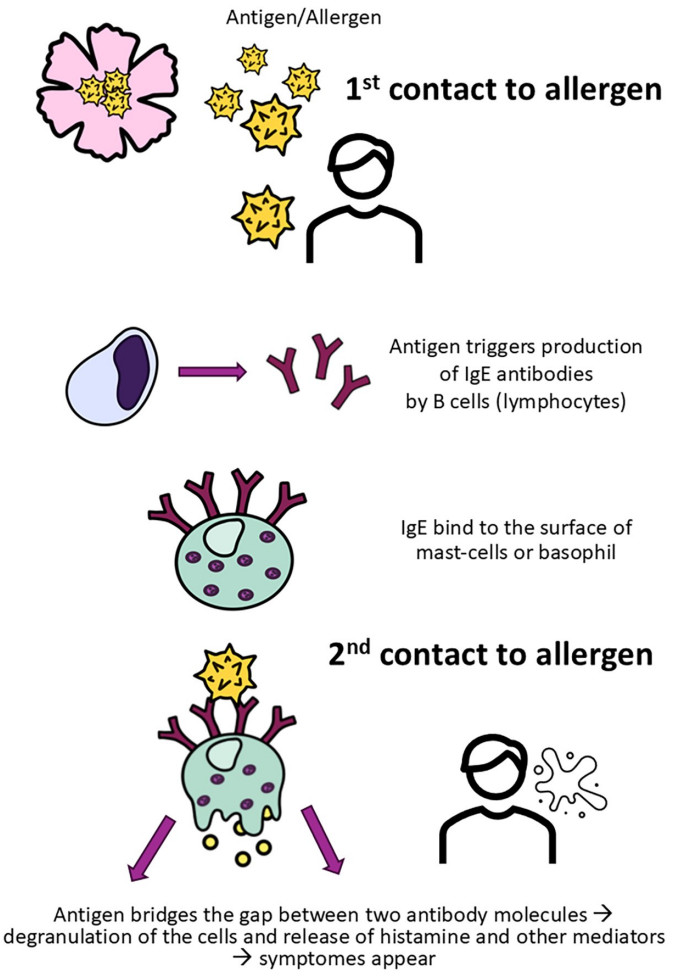


Figure 2.
The mechanism of allergic reaction: allergen (antigen)–antibody.

species-specific recognition. At first, it was thought that pollen allergens were only those located on the exine; later, it was ascertained that most of them are contained within the granule and that they escape from the openings (pores, colpi, colours) very quickly once in contact with a moist surface. Pollen allergy is a Type 1 hypersensitivity (IgE-immediate) reaction to specific allergens [16]. The allergic reaction consists of producing IgE antibodies in response to an antigen (pollen) and binding to receptors on mast cells (immune system cells) (**Figure 2**). On second contact, the allergen binds to IgE, which in turn binds to mast cells that release numerous chemical mediators (histamine, proteases, acid hydrolases, and proteoglycans) that, when released, result in allergy symptoms. Pollen grains can have multiple allergens. 'Major allergens' are defined as those that are capable of causing the production of specific IgE in more than 50% of patients allergic to that pollen. Meanwhile, 'minor allergens' are defined as those that cause IgE production in a lower percentage of patients [12, 17].

2.1 Pollination strategies

Pollination is the process that allows the pollen granule produced by the anthers of one flower to reach the stigma. Pollination strategies may be anemophilous (wind pollination), entomophilous (insect pollination), and amphiphilous (mixed pollination) (**Figure 3**). The oldest angiosperms are believed to be endogamous, that is, pollinated by the wind. Around 100 million years ago, as insects spread, plants gradually switched to entomogamous pollination. There was thus a continuous coevolution between plants and pollinating insects that led to a progressive transformation both morphologically, especially of the flowers and the insects' mouthparts, and biochemically, with the synthesis of chemical attractant compounds (pigments, odours, sugary substances) [18–20]. In some genera of Asteraceae, such as *Ambrosia* and *Artemisia*, environmental pressure has shifted from entomogamy to anemogamy. This is how plants respond to environments characterised by drought, sun, and wind, to avoid pollinating many flowers. In many trees in temperate climates, such as the hazel, flowers bloom early in the spring awakening or even in the middle of winter. The leaves will open after fertilisation has taken place: This is to encourage cross-pollination. Anemogamous plants have special characteristics: high pollen production, although the wind causes a huge loss of pollen, and the lack of all those parts of the flowers that are superfluous, such as brightly coloured petals. Although these interactions are frequently disregarded, pollinators visit wind-pollinated plants to gather pollen or for materials and nest locations [21]. Wind-pollinated flowers do not produce nectaries, have dull colours and

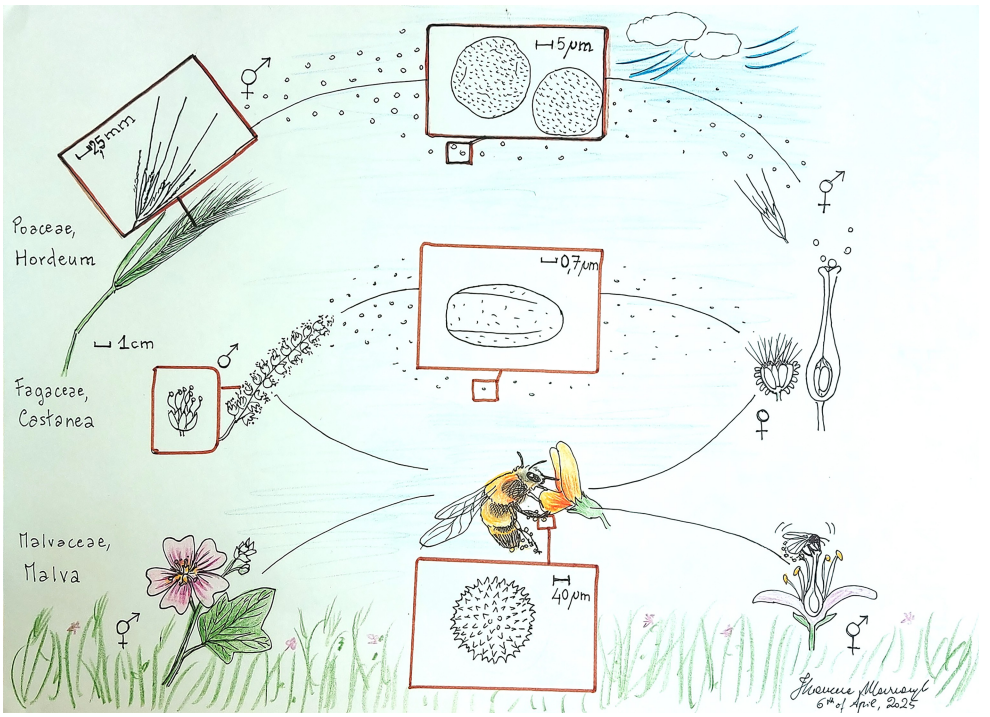


Figure 3.
Anemophilous, amphiphilous, and entomophilous pollination schemes in Hordeum *(Poaceae family),* Castanea *(Fagaceae family), and* Malva *(Malvaceae family) (illustration by Francesca Marinangeli).*

are generally odourless. In them, the pollen surface is smooth or slightly grained (eg, Poaceae: *Hordeum* sp., *Lolium* sp., Cupressaceae: *Cupress*us sp., *Juniperu*s sp.), and the shape is sufficiently aerodynamic to be carried over considerable distances. In some cases, the pollen grains have aerodynamic air pockets (Pinaceae: *Pinus* sp.) or are very small (Urticaceae: *Parietaria* sp., Fagaceae: *Castanea sativa*). In contrast, non-allergenic plants have showy, fragrant flowers (Malvaceae: *Malva* sp.). Poorly aerodynamic pollen sometimes has specific sculptures in chains or microchips. In addition, many pollen grains are covered with a viscous liquid, the 'pollenkitt', which plays an important role in pollen dispersal and adhesion (*Betula*, *Crocus* genera) [14].

2.2 Spread of anemophilous pollen

The relationship between wind and pollen release, concentration, and dispersion in the atmosphere is fundamental in aerobiology. For example, see [22–26]. The pollen dispersion in the atmosphere forms the so-called biological aerosol, which can be an etiological cause of disease [27, 28]. The aerosol is a biphasic system (a heterogeneous mixture of two or more components) that can be inhaled and is represented by a continuous gaseous phase (oxygen, nitrogen, etc.) and a discontinuous phase of individual particles with a diameter between 0.001 μm and 100 μm. The entire atmosphere can be defined as an immense biological aerosol containing the dispersion of viable and nonviable biological particles. The troposphere is the aeriform belt of the Earth's atmosphere in direct contact with the Earth's surface. It varies in thickness depending on latitude (at the poles, it is only 8 km thick, while at the equator, it reaches 16–20 km). The release of pollen into the atmosphere occurs when the particles manage to enter the turbulent layer of the troposphere. The release mechanism is passive in that it requires the action of external agents such as wind and rain [29, 30]. Pollen in environmental conditions of high relative humidity tends not to be released. The greater the wind speed, the easier it is for pollen grains to break free from their substrate. The pathway of the pollen is, therefore, due to physical forces acting on the pollen granule, such as friction with air molecules, the force of gravity, and gas displacements in the atmosphere. In addition, an important factor is the size of the pollen grain, as it is based on this that one can assess the tendency of the particles to deviate from their path and thus characterise their aerodynamics. Comparing the pollen grain to a sphere in laminar motion concerning a fluid, the viscous friction force it is subjected to is described by Stokes' law [31]. It follows from the equation that the smaller the particle size, the lower the settling velocity. The average diameter of pollen is about 25 microns, and their falling speed, under absolutely stable atmospheric conditions, according to Stokes' law, should be 7.5 cm/sec. The Earth's atmosphere has also been described as an ocean of agitated air; in fact, it comprises several heterogeneous layers, resulting in alternating layers of warm and cold, moving air that determines what is known as atmospheric turbulence. Long-distance transport can also be favoured during violent thunderstorms with vertical air movement [32]. In 80% of cases, pollen is deposited on the ground a few meters from its source. However, the distance travelled by pollen can vary depending on the height of the plant producing it and the wind speed [33, 34]. For long-distance transport (even hundreds of kilometres), favourable conditions are turbulent air conditions that drag the pollen upwards and stable air conditions for prolonged transport at high altitudes [35, 36]. At night, the decrease in ground temperature reduces the possibility of

pollen passing from the bottom to the top. During the day, the particles will be subject to convective motions that depend on the heating and cooling of the ground. During the sunny hours, the air close to the ground warms up more, and being less dense than the cold air, it tends to rise and drag the particles even to high altitudes. Here, the atmosphere is thinner, so the viscosity of the air decreases, allowing the particles to travel with greater stability. The ideal conditions for long-distance transport are turbulent initially to allow the pollen grains to be released, and subsequently stable conditions for prolonged transport.

2.3 Pollen seasons

Flowering and pollen transport are strongly influenced by environmental conditions [37]. The flowering phase is related to the number of daylight hours in the day and the thermal conditions of the period. The same species does not flower everywhere at the same time; it will generally flower earlier in the southernmost distribution areas and at lower altitudes. Flowering will be delayed or brought forwards depending on the climate and weather pattern of the distribution area. The start of pollination of each plant species depends on the botanical species, geographical area, altitude, and weather pattern of the growing season [38, 39]. Plants release their pollen only when the weather is dry and relatively warm. Pollen concentration varies during the day, usually being highest during the hottest hours of the day. During periods of good weather, airborne pollen is constantly present. Even during the night, there may be pollen in the air unless there has been heavy rainfall during the day. After heavy rain, allergy sufferers experience relief. After a rain shower, the increased humidity in the air rehydrates the pollen, which becomes more strongly allergenic. However, pollen broken up by rain can be just as harmful because it reaches the deep airways. Poaceae pollen decreases significantly on rainy days, while it is estimated that a birch tree can start releasing pollen into the air as early as an hour after it has stopped raining. The allergy-causing molecules present in pollen are proteins in nature and are characteristic of being released during the hydration of the pollen granule [40, 41]. These molecules can interact with the immune system of sensitive individuals, thus triggering allergic reactions. Considering the different abilities of each pollen to trigger an allergic response and the significant or minor allergens present, reference concentrations are indicated as low, medium, and high. In **Table 1**, the values and the colours denote standard concentration classes used in aerobiology: absent (white), low (yellow), medium (orange), and high (red). The assessment refers to the amount of pollen of the various anemophilous taxa in the air. It does not indicate the 'threshold' pollen concentrations triggering an allergic reaction. Ranges of pollen concentrations refer to the values reported in the Italian Society of Aerobiology Medicine Environment (formerly the Italian Association of Aerobiology) [42].

2.4 Aerobiological monitoring and networks

Aerobiology is a discipline that studies pollen and other particles dispersed in the atmosphere, their origin, their diffusion, and the effects they produce on the environment [43]. Pollen is collected using a volumetric Hirst-type trap to count pollen (**Figure 4**) [44, 45]. Aerobiology provides various contributions in different fields, such as medicine, specifically allergology, environmental science, plant

Family	Genera more representative	Null/non relevant	Low	Medium	High
Aceraceae	*Acer*	≤ 0.9	1–19.9	20–39.9	≥ 40
Amaranthaceae/Chenopodiaceae	*Amaranthus, Chenopodium*	0	0.1–4.9	5–24.9	≥ 25
Asteraceae (sin. Compositae)	*Ambrosia, Artemisia*	0	0.1–4.9	5–24.9	≥ 25
Betulaceae/ Corylaceae	*Alnus, Betula*	≤ 0.5	0.6–15.9	16–49.9	≥ 50
	Carpinus, Corylus, Ostrya	≤ 0.5	0.6–15.9	16–49.9	≥ 50
Cupressaceae/ Taxaceae	*Cupressus, Thuja*	≤ 3.9	4–29.9	30–89.9	≥ 90
	Juniperus	≤ 3.9	4–29.9	30–89.9	≥ 90
	Chamaecyparis	≤ 3.9	4–29.9	30–89.9	≥ 90
Cyperaceae	*Cyperus, Carex*	≤ 0.9	0.1–4.9	5–9.9	≥ 10
Euphorbiaceae	*Euphorbia*	≤ 0.9	0.1–4.9	5–9.9	≥ 10
Fagaceae	*Castanea, Fagus, Quercus*	≤ 0.9	1–19.9	20–39.9	≥ 40
Poaceae (sin Gramineae)	*Avena, Dactylis, Cortadelia, Calamagrostis, Miscanthus,* etc.	≤ 0.5	0.6–9.9	10–29.9	≥ 30
Moraceae	*Broussonetia*	≤ 2	2–19.9	20–69.9	≥ 70
	Morus	≤ 2	2–19.9	20–69.9	≥ 70
Myrtaceae	*Eucalyptus*	≤ 0.9	0.1–4.9	5–29.9	≥ 30
Oleaceae	*Fraxinus, Olea*	≤ 0.5	0.6–4.9	5–24.9	≥ 25
	Ligustrum	≤ 0.5	0.6–4.9	5–24.9	≥ 25
Pinaceae	*Pinus*	≤ 0.9	1–14.9	15–49.9	≥ 50
Plantaginaceae	*Plantago*	≤ 0.9	1–0.4	0.5–1.9	≥ 2
Platanaceae	*Platanus*	≤ 0.9	1–19.9	20–39.9	≥ 40
Polygonaceae	*Rumex, Polygonum*	≤ 0.9	0.1–4.9	5–9.9	≥ 10
Salicaceae	*Populus, Salix*	≤ 0.9	1–19.9	20–39.9	≥ 40
Ulmaceae	*Ulmus*	≤ 0.9	1–19.9	20–39.9	≥ 40
Urticaceae	*Parietaria, Urtica*	≤ 0.19	2–19.9	20–69.9	≥ 70

Table 1.
Pollen abundance classes (granules/m³ air/day) [42], mod.

science, meteorology, phenology, and climate change. Many countries must create an aerobiological monitoring network for pollen allergy sufferers. The network aims to offer a service that can provide real-time trends of allergenic pollen concentrations so users can resort to vaccines before rhinitis and asthma attacks occur. There are several monitoring networks around the globe. In 2020, 879 active pollen monitoring stations were found [46]. Pollen monitoring coverage is biased toward the Northern Hemisphere (mainly in Central America, Europe, and Asia); Europe has more than 500 spore traps, among which we cite, for example: 'Réseau National de Surveillance Aérobiologique' (RNSA), France; 'Red Española de Aerobiología' (REA), Spain; 'Rede Portuguesa de Aerobiologia' (RPA), Portugal; 'Rete Italiana Monitoraggio Aerobiologico' (R.I.M.A.®) and POLLnet, Italy; 'National Pollen and Aerobiology Research Unit' (NPARU), UK; and 'European Aeroallergen Network' (EAS),

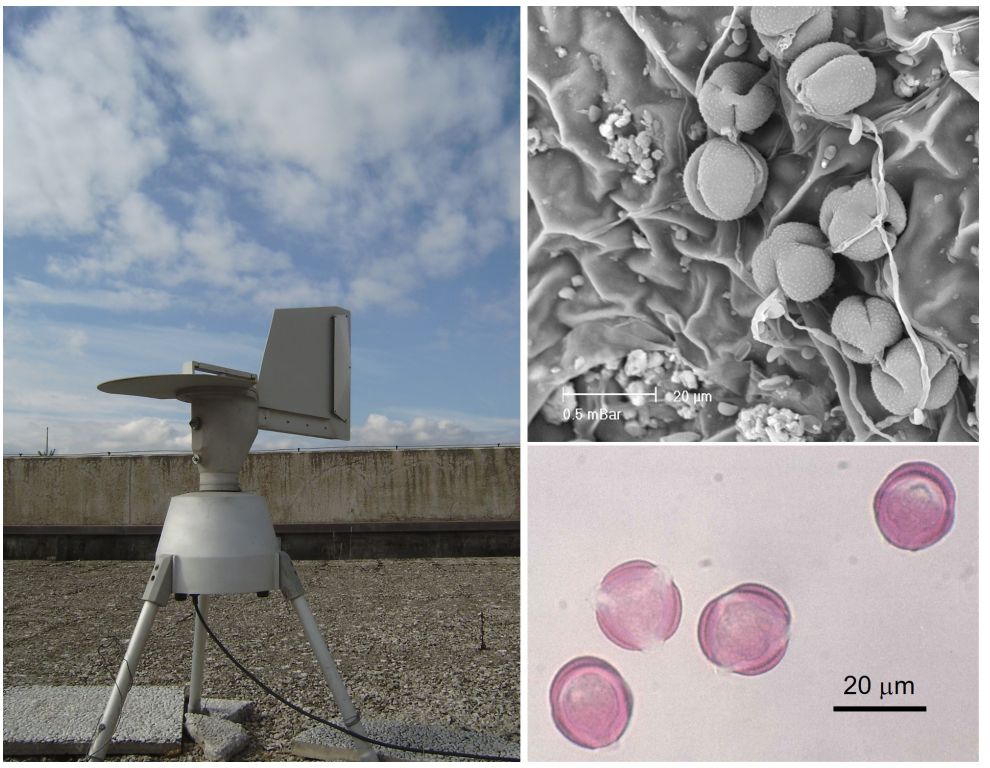


Figure 4.
Volumetric Hirst-type trap. Pollens of the genus Artemisia *observed by scanning electron microscope (above) and optical microscope (below) (photo by L. Pace).*

Austria. MedAeronet is a network linking Croatia, France, Italy, Spain, and Turkey [47]. Some spore traps are in Argentina and Australia. They are present almost only in South Africa, where the most extended annual monitoring exists for Cape Town (about 20 years), but the data series were not continuous. In 2019, a new network, the interdisciplinary network (SAPNET), was launched to monitor weekly variations of aerospora and provide online data [48] to establish regional pollen calendars [46].

3. The allergenic potential of the plants

3.1 Definition

Every plant known to provoke an allergic reaction in humans would be considered allergenic [3]. The plant's allergenic potential (also called ap) could be defined as 'the possibility of a plant triggering an allergy reaction in sensitive people'. The criteria to define an allergenic plant are four and are named Thommen's postulates in [3]:

I. The presence of an excitant (allergens) for hay fever and/or asthma in pollen grains is necessary.

II. Pollen grains have to be light and small enough to be carried by the wind for considerable distances.

III. Pollen grains must be wind-borne.

IV. Pollen grains should be produced in large quantities.

Some authors [3, 49] have proposed the addition of two other factors:

V. The plant mother must be abundantly distributed within a territory.

VI. The length of the pollen season defines the allergy impact.

In a multidisciplinary approach, other factors should be considered, as shown in a study conducted in Porto, Portugal (2005–2007) [50]:

VII. The population reactivity measurement (deducible from hospital admissions data for asthma or dyspnoea).

VIII. Immunochemical data (specific IgE to pollen extracts) about contemporary pollen dispersion (detectable by volumetric trap, microscope, or gel electrophoresis analysis).

For an allergic reaction, an interaction between an antigen (from a plant individual) and an antibody (in a human individual) is necessary. The allergenicity of plants (pollen, fruits, other parts) depends on several factors. Plant proteins can cause allergic diseases in susceptible people through immune-mediated reactions; for example, see [51]. Proteins, the antigens, and the essential building blocks of the plant organism may be contained in pollen granules, leaves, stems, fruits, roots, and all other parts.

3.2 Factors on which the allergenic potential depends

The expression of ap depends on several factors, of which the main ones are reported in this paragraph.

3.2.1 Immunogenicity 'Notes on the immunogenicity of pollen'

The presence of allergens in plants is defined as an immunogenicity factor important for the allergenic potential (ap) [3]. Allergens are defined by the World Health Organization/International Union of Immunological Societies (WHO/IUIS) in an official allergen nomenclature [52], which includes the taxon name (family, genus, species, variety) on the official website [53]. The website provides a database with all the proteins, in a standardised name, contained in various parts of plants that cause IgE-mediated (atopic) reactions in humans. The allergen nomenclature was created in 1986 in the USA [54] for highly purified, well-characterised allergens and nonpurified or partially purified allergenic extracts. For example, '*Lol p* I' refers to *Lolium perenne* allergen number one. The nomenclature criteria were revised in 1994 [55] with the inclusion of allergen genes, mRNAs, cDNAs, and recombinant and

synthetic peptides of allergenic interest. Subsequent revisions occurred in 1995–1996 [56], 2018 [57], and 2019 [52]. In the database, research can be limited to all allergens, such as food, airborne, contact, injection, and unknown allergens. In this section, only pollen allergens were addressed. The latest revision [58] includes 55 new allergens found in plants, defined between 2019 and 2021 (one due to contact, 38 for respiratory contact, and 16 via food), all tested on human patients. The respiratory allergens derived from plants include: *Artemisia vulgaris* (a profilin named Amb t 8, a protein found only in Asteraceae pollen), *A. absinthium, A. annua, A. argyi, A. californica, A. capillaris, A. frigida, A. gmelinii, A. ludoviciana, A. lavandulifolia, A. sieversiana, A. tridentata* (defensin-polyproline-linked protein (DPLP) and/or PR-1 proteins); *Cannabis sativa* (common name marijuana), which contains proteins such as Can s 2 (a profilin) and Can s 4 (oxygen-evolving enhancer protein and PR-10 homologue), causing immediate symptoms upon exposure; *Cryptomeria japonica* (reaction in cypress pollen-sensitised subjects); *Cupressus sempervirens* (Cup s 7, a GRP protein); *Juniperus ashei* (a GRP protein, causing reactions in subjects with peach allergy and subsequent cypress pollinosis); *Morus alba, from the* Rosaceae family (a cobalamin-independent methionine synthase protein); *Phleum pratense,* a grass (expansin-like protein), and an Asian grass, *Zoysia matrella* (a pollen expansin useful for stigma penetration); Tree pollen from *Populus nigra* (profilin), *Quercus acutissima* (PR-10 and profilin), *Quercus ilex* (PR-10), and *Quercus mongolica* (PR-10). The PR-10 proteins from birch (*Betula* genus) and related trees of the Betulaceae and Fagaceae families are cross-reactive and are major causes of allergic rhinitis. The GRP proteins (snakins, gibberellin-regulated proteins) interact with plant hormones and are involved in cross-reactions with peach (*Prunus persica*), plum (*Prunus domestica*), pomegranate (*Punica granatum*), or citrus fruits in individuals with Cupressaceae pollen allergy [58]. A list of the main allergenic plants and the presence of allergens in the IUIS database can be found in Section 5.1 on biodiversity and allergenic potential.

For pollen allergens, another library is published [59]. This collection was developed as another resource for allergy sufferers to aid in the identification and management of their allergies. It contains more than 1,100 species of plants, with information about their allergenicity, native country, life cycle (perennial, annual), description, if it is evergreen or deciduous, geographical distribution, seasonal pollination, maps of the countries where the plants are available and photographs to identify or recognise them. Searching a plant/genus for a common name, Latin name, or by alphabet is possible. An allergenic plant is described, if allergenic, in three classes: mild allergen, moderate allergen, and severe allergen (f.e. *Cupressus*).

The Allergome database [60] was developed and released on the web in 2003 by public and private institutions as part of a project to collect data on allergen proteins. It is possible to find a group of allergen proteins (eg, profilin) or a specific allergen linked to the sources citing it. More than 6,000 Allergome monographs have been published. In the latest update, 2,554 allergen sources were included in this library. The allergens are linked to the species containing them, with both common and Latin names.

3.2.2 Morphology, pollination strategy, and pollen production

Allergenic potential depends on the pollination strategy (mainly by wind, insects, or both in amphiphilous taxa), which is more important than morphology [3] and floral architecture [51]. In dioecious species (with separate female and male

individuals), only male individuals can produce and release allergenic pollen, while female individuals have zero potential [61]. Low ap is also found in cleistogamous (closed nuptial) flowers or ornamental cultivars, such as double-flowered cultivars, whose pollen will perform self-fertilisation [3]. The amount of daily airborne pollen is recorded at monitoring stations using pollen traps. Pollen-release intensity in wind-pollinated species is linked to plant size (trees and shrubs) and ground cover (herbs); greater crown volume means greater pollen release since larger species tend to have more branches, blossoms, and stamens per unit of surface area [62]. The amount of pollen released into the air is directly proportional to the number of individuals of a single species in any given area.

3.2.3 Life cycle and length of flowering phase

The plant's life cycle [63] is very important in determining the ap Perennial species, in general, produce more pollen than annual species, even though annual species can blossom again during the year in response to rising air temperatures caused by climate change. The phenology of the plant, as well as the climate and the specific weather trends of the seasons in a year, is very important in defining ap; in particular, the length of the anthesis period, also referred to as the principal pollination period (PPP), is defined in [49].

3.2.4 Distribution of plants in a territory

The chorological type (or chorotype) defines plants' genetic origin, spatial distribution, and ability to adapt to climate. This distribution indicates the adaptation of a taxon to the environment, soil, and climate, and the reaction to their changes depends on the chorotype. For example, increasing air temperature can favour Australian plants but not Panboreal plants. Chorotypes may directly or indirectly influence the adaptive potential (ap) of plants [64, 65]. The distribution of plants is also determined by other important factors such as the germination capacity of seeds, resilience to climate change, the strength of the plant population, and the invasiveness of habitats by alien species [66].

3.2.5 Abiotic factors

The extrinsic or abiotic factors on which the allergenic potential of plants depends are air temperature [67], air moisture, prevailing winds (determining the geographic distribution of airborne allergens), seasonal weather trends, rainfall, thunderstorm frequency (directly provoking severe asthma in some subjects) [68], climate change in general, length of day and night (influencing PE) [69], altitude and latitude (influencing the start and end dates of flowering), and geographical morphology, such as the presence of mountain ranges, lakes, or seas (influencing the diffusion of airborne pollen by wind over long distances). The increase in the atmosphere's carbon dioxide concentration and air temperature [3, 11, 49] has an impact on sources of airborne allergens and, consequently, on allergen exposure of the population and the manifestation of allergic respiratory diseases, such as allergic asthma and allergic rhinitis [69].

3.3 The assessment of the allergenic potential

The ap can be classified into several classes. Different plant taxa (family, genus, species, botanical varieties, or cultivars) can cause allergic symptoms ranging from non-allergenic to highly allergenic grades. The allergenic potential of the plants was evaluated by considering the characteristics of the plant and the aspects of pollination by spontaneous or cultivated flora. It can be assessed as a two-form qualitative value (yes/no) or through indexes in graded systems [3]. On a timescale, seven methods of evaluation, intrinsic or extrinsic to plant characteristics, qualitative/estimative or graded, are proposed in the following list:

Ogren plant allergy scale, a qualitative/estimative method proposed by Ogren [61], considers subjectively different plant-specific criteria based on studies about similarities between allergenic and non-allergenic plants. Characteristics include pollen weight and size, pollen moisture, flower fragrance, and the position of male flowers in monoecious species. The scale categorises species at 10 levels, with one being non-allergenic and 10 being highly allergenic. No formula was created to calculate this index. This index refers to plants regardless of the vegetation composition in a space.

Allergen index , a graded method proposed by Hruska [63], is based on information about the plant's life cycle, the length of its phenanthesic period, the presence of phenomena of cross-reactivity (CR), and species abundance. The literature has described a specific formula to calculate this index [63]. This index includes the vegetation composition of a space. Some cities in Central Italy [70] and schoolyards in Novi Sad, Serbia [71], have been investigated using this index.

Allergenic potential of plants (GRADE approach) was assessed in Italy by Ortolani [72], based on the existence of scientific evidence and risks that pollen exposure causes hay fever symptoms and that pollen grains can cause allergic sensitisation. A committee of experts used a GRADE approach (Grading Recommendations, Assessment, Development, and Evaluation) to clarify the allergenicity of the species in the list as high, moderate, or low. The assessment is qualitative, and no formula has been described to calculate this potential.

Urban green zone allergenicity index (I_{UGZA}), a graded method proposed by Cariñanos [49], calculates the allergenic potential index of urban green spaces, and at first, it was applied in some Mediterranean cities. This index is expressed as a ratio and compares an existing green space with a hypothetical space with maximum allergenicity. The index is based on the following assumptions: Plants that mature with a higher crown volume emit higher quantities of pollen, anemophilous trees produce more pollen than other trees, and pollen release is directly proportional to the number of individuals belonging to one species [51]. This index is obtained through a specific formula [49, 73]. It includes the vegetation composition of a space. The potential allergenic value (PAV, or VPA) of each plant in a park is calculated based on three primary parameters: pollination strategy, also named PEs (initially on a 0–3 scale, later simplified to a 1–3 scale), assigning the minimum value to only female-sex individuals (later simplified to a minimum value = 1 for entomophilous plants) and the maximum value to anemophilous plants (value 3); potential allergenicity (ap, estimated on a 0–4 scale) that the species provoke in humans (estimated through specific bibliographies in medicine and public health), assigning the maximum value to *Betula, Alnus*, Poaceae, and *Artemisia*; and the duration of the pollination period or

principal pollination period (DPP or PPP, ranging from 1 to 3 weeks). The PPP for species in the first study was established based on published data for the flowering periods of standard Mediterranean species and the pollen calendar for the city of Granada, developed using daily mean pollen data for over 10 years. The PAV, given by the product of the three parameters, ranges from 0 to 36. Five classes of allergenicity have been defined: nil (PAV = 0), low (PAV from 1 to 6), moderate (PAV from 8 to 12), high (PAV from 16 to 24), and very high (PAV from 27 to 36). The I_{UGZA} depends directly on both the PAV of each species and the total volume of pollen-producing vegetation (mature individuals) and is inversely proportional to the total surface area of the park. The surface area occupied by each species was estimated from the maximum horizontal crown projection area (in m^2) for an adult individual, obtaining this information from published research into the standard size attained by species during reproductive maturity in a specific climate zone. To calculate the crown volume of vegetation, tree height was estimated as a cylinder, shrubs as hemispheres, and hedges as parallelepipeds (height × surface). The value to be obtained would thus lie between $I_{UGZA} = 0$ for spaces with no allergenicity and $I_{UGZA} = 1$ for spaces with maximum allergenicity. The threshold value (TV) of a park determining allergy symptoms has been observed when $I_{UGZA} = 0.3$. Several Mediterranean urban parks, starting from Garcia Lorca Park in Granada, Spain [13], the Mediterranean cities of Spain and Italy [74], three types of urban gardens in Poland [75], several metropolitan areas in Bratislava (Slovakia) [76], and the Macaronesian islands (Funchal City, Madeira) [77], have been investigated through this index.

I_{ISA} index, a graded system proposed by Jochner-Oette in 2018 [51], is similar to the previous one. Still, it considers the crown height and surface area individually measured for each plant (trees and shrubs), not based on a mean height or diameter attained at reproductive maturity, as in Cariñanos [73]. This index is obtained through a specific formula [51]. In Bratislava (Slovakia) [76], some areas have been investigated, such as designing a running index over time.

CARE-s index, a graded system, has been defined by Magyar as 'the potential of a plant taxon to provoke allergy based on immunogenicity, pollen production, and morphology/pollination type' [3]. The AC_p (the raw value of a plant's allergenic potential) was proposed using Thommen's postulates and two geographical factors (population size and the pollen season length). Geographically variable factors, such as differences among countries (ie, pollen concentration or population size), have been excluded from the parameters used in this system. This index is a product of three parameters: Im (Immunogenicity, based on the strength of evidence to cause allergy symptoms in patients, mainly found in the Allergome database [53] and references based on evidence); Mo (Morphology, evaluated as stamen morphology, pollen morphology, pollination strategy, and palynology from the literature); and Po (Pollen production, obtained from a horticultural collection of tree taxa common in urban street lines in the Pannonian biogeographical region). All parameters are not calculated but are instead estimated in three classes. Thus, potential allergenicity is defined as 'the potential of a plant taxon to provoke allergy based on immunogenicity, pollen production, and morphology'. The CARE-s index is expressed in five classes of allergenic potential (ap) and a sixth class, 'unknown': non-allergenic (0), low (1), medium (2), high (3), and very high (4). The index is also available online, enabling users to make more straightforward calculations with their local plant taxa [77].

A regional guide for the allergenic potential of tree pollen is a method developed by De Weger in 2024 [78], based on six published classification guides, pollen sampling (using Hirst-type seven-day volumetric spore traps), and tests conducted on 467 patients at the hospital. The criteria for allergenic potential have been based on the literature, the amount of airborne pollen measured, and the sensibilisation levels found in the patients. The allergenicity of taxa in the Netherlands was classified into five classes (low or not available, weak, moderate, strong, and very strong) based on scientific evidence of symptom manifestation. This list considers the effects on the local population of some species considered low allergenic, which in other parts of the world result in highly allergenic reactions (eg, *Chamaecyparis lawsoniana, Taxodium distichum, Thuja*), probably due to climatic factors (some coniferous species cannot pollinate in places with a cold climate). To compare the classes of allergenic potential, see **Table 2**.

Other evaluations of the allergenic potential of plants have been investigated in the literature. For instance, the case of Beijing (China) has been studied through a survey and experts' interviews [79], which identified 99 pollen-allergenic plant species. Pollens were concentrated in March and April (trees) and from July to September (herbs). The case of the Mexico City Metropolitan Area (dry season 2012–2013), investigated using a Hirst-type trap sampler [67], shows that the most representative pollen types found at the three sites were, regardless of urbanisation levels: *Fraxinus*, Cupressaceae/Taxodiaceae, *Casuarina*, *Alnus*, Myrtaceae, and *Pinus*. Total pollen concentration was most significant in the moderately urbanised area, although earlier blooming occurred in the highly urbanised zone. In the medium–high urbanised site, pollen concentration was the lowest because there were few green areas. At several sites (more or less urbanised), the pollen peak emission occurred near midday or in the afternoon and evening, correlating with air temperature and relative humidity. A qualitative study of the relationship between monitored pollen and vegetation in some areas (Cordoba, Spain, and Ascoli Piceno, Italy) at a regional scale was proposed by Staffolani et al. [80]. In South Africa, the prevalence of airborne allergen sensitisation in a polluted area has been studied using skin prick testing and botanical studies [81]. The highest allergy prevalence was attributed to Poaceae (*Cynodon dactylon, Lolium perenne, Zea mays*), *Olea* (olive tree), and *Platanus* (plane tree). Other allergies were caused by weed mix: Artemisia,

Allergenicity level [72]	**Classes and value of potential allergenicity (VPA)** [73, 74]	**Classes of allergenic potential** [51]	**CARE-s index** [3]	**Grade of allergenic potential** [78]
Not allergenic or unknown	0	0	Unknown	Low or not available
			0 (nonallergenic)	
Low	1 (1≤ VPA≤ 6)	1	1 (low)	Weak
Medium (or moderate)	2 (8≤ VPA≤ 12)	2	2 (medium)	Moderate
High	3 (16≤ VPA≤ 24)	3	3 (high)	Strong
Very high	4 (27≤ VPA≤ 36)	4	4 (very high)	Very strong

Table 2.
Classification of allergenic potential and references (VPA = value of potential allergenicity) [3, 49, 72, 74, 78].

Chenopodium, Salsola, Plantago, and *Ambrosia,* underlining the strong impact of allergens from exotic plants. The effect was amplified by the simultaneous spread of airborne fungal spores (*Alternaria, Cladosporium*).

3.4 Possible applications of allergenic potential

The ap has been applied to assess the possibility and strength of plants in an urban park to provoke sensitisation or allergy in the population and to try to classify the urban green areas on an index with a scientific basis. The ap of green areas has been linked to a threshold value (TV = 0.3 in the case of IUGZA), giving the appearance of symptoms of allergy in several experimental studies on populations in different areas of the world and across different age groups. Several city parks in Mediterranean cities have been studied from this point of view. In assessing ap, limits and comparability of indexes are also published by Suanno [82]. In general, they were not compared or standardised over the same dataset. The expression of allergenicity using an index should be applied to green spaces with similar characteristics. In a study in the Botanical Garden of Bologna, Italy, the indexes I_{UGZA} and I_{ISA} (also named SAI) have been compared, collecting vegetation data through systematic sampling and arboreal census in the same dataset. Thus, it was possible to compare them. The allergenic risk of the park was moderate to high, according to IISA, and very low, according to I_{UGZA}. The first index does not consider the total volume of the crowns, so it was considered less reliable than the second, $I_{UGZA,}$ in evaluating the allergenic potential of a specific enclosed green space [82]. However, it must be considered that the current assessments of the ap of a specific local green area are based on the flora composition, the allergenicity of the plants in the green area, the height and surface occupied by the tree crown, but, based on the cited literature, not on the ap of pollen coming from other parts yet, which can also originate from long distances, carried by the prevailing winds. Thus, the real expression of allergy symptoms can also be influenced by 'alien' airborne pollens, depending on climate change [69], and only real-time airborne allergen monitoring can provide this information. Furthermore, the local evaluation of ap shows several differences in the values assigned to the same taxa. The diffusion may differ from place to place, so the amount of airborne pollen and its impact on people varies significantly. *Olea europaea* or *Chamaecyparis lawsoniana* have a completely different evaluation from Eastern Europe (Grade 1, low allergenic) to the Mediterranean area (Grade 4, very high allergenic). Despite this, it is important to calculate the ap of a park as a prediction of allergenicity and use it in green area planning to make cities healthier, smarter, and more liveable for people. In the future, possible applications of a.p. and plant pollen monitoring, including the pollen portion from long distances, are automated real-time monitoring of airborne allergens, forecasting and modelling of airborne allergens, and smartphone applications to mitigate the health impacts of airborne allergens [69].

4. Pollen allergy and CR

Cross-reactivity refers to an immunological phenomenon whereby an immune response to a given antigen causes reactivity towards other antigens structurally

similar to the inducing antigen [13, 83]. A protein can be considered capable of CR with other allergens if it shares at least 35% similarity with them. The greater the homology, the greater the risk of CR. The common view is that diet can promote the onset of pollen allergy. The opposite is true; in fact, some individuals with respiratory allergies also have adverse reactions to certain foods. The culprits are pan allergens, that is, allergens that are present in both plant pollen and some fruits and vegetables (but also some fish, such as shellfish) and that can give cross-allergies (thus due to the summation of environmental pollen exposure and food intake). There are about 10 pan allergens, but the most frequent are profilin, PR-10, and LTP. Profilin is found in most cells of all eukaryotic organisms. PR-10 (pathogenesis-related protein) is a group of pan allergens widely distributed in the plant kingdom. The family's progenitor is *Betula*, and its major allergen is Bet v 1. CR is most frequent among individuals allergic to birch and fruits belonging to the Rosaceae family, such as apple, apricot, pear, and cherry (homology > 50%) (**Table 3**). PR-10 are proteins characterised by marked sensitivity to both heat and the action of digestive juices. Therefore, PR-10, particularly abundant in fruit flesh, disappears with cooking. Lipid transfer proteins (LTPs) are proteins that are resistant to the action of digestive enzymes and heat, so cooking often does not resolve them, except for some vegetables such as asparagus, cabbage, and fennel, which, when boiled, lose LTPs by releasing them into the cooking water. The characteristic clinical syndrome of allergic individuals with CR to the above-mentioned foods is oral allergy syndrome. Immediate symptoms are local itching, palate and tongue burning, and swelling of the lips and oral mucosa. A sense of constriction in the pharynx and difficulty swallowing may be associated in severe cases. The phenomenon of CR is not an exclusive manifestation of pollinosis. Other respiratory allergens can trigger reactions to foods. The most characteristic example is the CR between dust mite (*Dermatophagoides pteronyssinus*) and shrimp; since a minor mite allergen, the Der p 10, belongs to the group of tropomyosins (pan allergens) found within the crustacean family in this case, reactions also occur with cooked food.

Pollen (scientific name of plants)	**Vegetal food (common name)**
Poaceae (sin. Gramineae)	Melon, watermelon, orange, kiwi, tomato, wheat, peach, apricot, cherry, plum, peanuts, cereals
Artemisia sp. (Asteraceae)	Melon, banana
Asteraceae (sin. Compositae)	Chamomile, celery, carrot, melon, watermelon, apple, banana, pumpkin
Parietaria (Urticaceae)	Mulberry, basil, peas
Olea europaea (Oleaceae)	Olive
Betula (Betulaceae)	Apple, peach, apricot, walnuts, hazelnuts, cherry, pear, banana, carrot, potato, fennel, celery, peanuts, almonds
Corylus avellana (Betulaceae)	Hazelnuts
Ambrosia (Asteraceae)	Banana, watermelon, melon, chamomile, pumpkin, celery

Table 3.
Examples of CR in Southern Europe.

5. Biodiversity and allergenic potential

Biodiversity is the basis for a healthy environment. Nature in cities has several benefits (ecosystem services), particularly regarding the urban climate: One of the most frequently mentioned benefits of urban parks is the reduction of the heat island effect. Some of the important reasons for enjoying a park include nice weather, comfortable wind flow, better temperature, and insulation compared to less natural areas of the city [84]. Vegetation filters air dust, removes pollution, provides natural sounds and smells, and, through evaporation and transpiration, reduces air moisture [75]. It also captures soil water, reducing the impacts of extreme weather events. Improving the contact between humans and nature is very important, especially in urban areas [85]. In cities, the urban jungle is the collection of trees, shrubs, and other plants that coexist with people (**Figure 5**). Despite this, unfortunately, plants can also cause disservices to human health. The falling of diseased or old trees or branches, the emission of biogenic volatile organic compounds into the air, the danger of toxic and poisonous plants, and the production of allergenic pollen [75] are some examples.

Several research studies have been conducted worldwide to identify the source of pollinosis or asthma caused by plants. In Japan (Tokyo city), taxonomic classification indicates multiple pollen sources, including natural forests, planted forests, roadsides, parklands, and horticultural activities. The most allergenic plant is Japanese cedar (*Cryptomeria japonica)* and other Cupressaceae species, peaking in mid-February to March [7]. This is one of the most allergenic plant families in different parts of the world and may originate from natural forests or anthropic plantations in parks and gardens. A plant may be allergenic in some areas but not highly allergenic in other parts of the world. Ginkgo (*Ginkgo biloba*), a very ancient



Figure 5.
A location in a historic courtyard, showing a high level of biodiversity and several phenological aspects (photo by F. Marinangeli).

and beautiful tree often cultivated in gardens in Japan, is considered one of the most allergenic pollen sources there because it is very widespread. In other parts of the globe, where Ginkgo is sporadically cultivated in parks, such as in Italy [72], Spain [86], the Netherlands [78], and Hungary [3], it is considered a low-to-moderate allergenic plant. Additionally, the olive tree (Olea europaea), one of the most impactful allergenic plants in the Mediterranean area [73], the elective range of the species, has a lower allergenic potential in Eastern Europe [3].

Tree selection decisions (choosing the right family, genera, species, variety, or planting female individuals of dioecious species in parks, see [61]) can effectively reduce airborne pollen [6]. Urban green space planners should consider planting more non-allergenic trees and improving public pollen information and warning systems [87]. The criterion of high biodiversity in greenery systems should always be used. This means a high number of different species and few individuals of each species, high biodiversity (number of species), female individuals of dioecious species (with zero allergenic potential), and less impact of allergenic pollen on citizens. In green space planning, many professional skills are required in collaboration. Optimising existing knowledge sets and encouraging the integration of interdisciplinarity can facilitate the functions of biodiversity needed for sustainable urban landscapes [88].

5.1 The most allergenic plants

Several scientific studies show some plant lists based on qualitative or quantitative evaluations of allergenic potential. In Italy, a 100-plant list (trees and shrubs) was produced in 2015 [72]. This list was updated by Cariñanos and Marinangeli in 2021 [74], where the specific allergenicity of 150 urban trees and shrubs was assessed. In cases where a different value from those already assigned by the previous authors was obtained, it was agreed to apply the most conservative criterion, that is, to maintain the value most supported by scientific evidence. The airborne pollen in Granada (concentration and time) was studied using a biological particulate matter sampler [51, 73]. A database was generated in which groups of trees were assigned a value rated in five classes (nil, low, moderate, high, and very high). Other studies have especially investigated the most commonly used ornamental plants or trees. In particular, a recent study [78] consulted six published classification guides that classified the allergenicity of tree pollen for different regions. It adopted a five-class classification used in the Netherlands, with the following values: low or not available, weak, moderate, strong, and very strong. Additionally, a comprehensive work published in the literature [3] adopted a five-class system based on similar parameters to those used by Cariñanos [73, 74]. It is impossible to express all the plant lists here. Still, it is possible to collect data obtained through a cross-control of several reference sources, grouping plants with allergenic pollen into three main risk classes to provide useful information to doctors and patients (**Table 4**). The plants have been checked in the lists, and the allergenic potential (ap) value has been reported in the third column. In the IUIS allergen database, all types of allergens have been investigated. Wherever possible, subspecies levels have been detailed to the greatest extent found in the literature, since some ornamentals are single-sex clones or sterile plants, which may be relevant when establishing their allergenic capacity.

Plant source of allergenic pollen	Mtype	Allergenic potential class	IUIS
Acer negundo	Tree	Very high/high/medium	NF
Alnus × spaethii	Tree	Very high	NF
Alnus glutinosa	Tree	Very high/high	Yes
Alnus incana	Tree	Very high/high	NF
Ambrosia artemisiifolia	Herb	Very high	Yes
Ambrosia trifida	Herb	Very high	Yes
Betula alba	Tree	Very high	NF
Betula ermanii	Tree	Very high	NF
Betula papyrifera	Tree	Very high	NF
Betula pendula	Tree	Very high	Yes
Betula pubescens	Tree	Very high	NF
Betula utilis	Tree	Very high	NF
Broussonetia papyrifera, (male)	Tree	Very high/low	Yes
Carpinus betulus	Tree	Very high/medium	Yes
Castanea sativa	Tree	Very high/high/medium/null	Yes
Casuarina equisetifolia	Tree	Very high/high/medium	NF
Chamaecyparis lawsoniana	Tree	Very high/low/null	NF
Corylus avellana	Tree	Very high/high/low	Yes
Cryptomeria japonica	Tree	Very high	Yes
Cupressocyparis leylandii	Tree	Very high/medium/null	NF
Cupressus arizonica	Tree	Very high	Yes
Cupressus macrocarpa	Tree	Very high	NF
Cupressus sempervirens	Tree	Very high/medium	Yes
Dyospiros kaki	Tree	Very high/low	NF
Fagus sylvatica	Tree	Very high/high/medium	Yes
Fraxinus excelsior	Tree	Very high/high/medium	Yes
Hesperocyparis macrocarpa	Tree	Very high	NF
Juglans nigra	Tree	Very high/high	Yes
Juniperus communis	Shrub	Very high/high/medium/low	NF
Juniperus phoenicea	Shrub	Very high	NF
Juniperus virginiana, (male)	Shrub	Very high	Yes
Ligustrum vulgare	Shrub	Very high/high/medium/low	Yes
Metasequoia glyptostroboides	Tree	Very high/null	NF
Morus nigra	Tree	Very high/low	Yes
Olea europea	Tree	Very high/high/medium	Yes
Ostrya carpinifolia	Tree	Very high/high/medium	Yes
Parietaria	Herb	Very high/high/medium	Yes
Platanus acerifolia	Tree	Very high/high	Yes
Platanus orientalis	Tree	Very high	Yes

Plant source of allergenic pollen	**Mtype**	**Allergenic potential class**	**IUIS**
Platanus x *hispanica*	Tree	Very high/high	Yes
Platycladus orientalis	Shrub	Very high/meduim	NF
Podocarpus neriifolius, (male)	Tree	Very high	NF
Populus deltoideus	Tree	Very high	NF
Taxodium distichum	Tree	Very high/high/medium/null	NF
Taxus baccata, (male)	Shrub	Very high/high/medium/null	NF
Tetraclinis articulata	Shrub	Very high	NF
Thuja plicata	Tree	Very high/low	NF
Ailanthus altissima, (male)	Tree	High/medium	NF
Alnus cordata	Tree	High	NF
Araucaria spp	Tree	High	NF
Carya spp	Tree	High	Yes
Cedrus atlantica	Tree	High/medium/null	NF
Chamaecyparis nootkatensis	Tree	High	NF
Chamaerops humilis	Tree	High/medium	NF
Corylus colurna	Shrub	High	NF
Fraxinus ornus	Tree	High/medium	NF
Ginkgo biloba, (male)	Tree	High/medium/low/null	NF
Juglans regia	Tree	High	Yes
Ligustrum sinensis	Shrub	High	NF
Ligustrum lucidum	Shrub	High	NF
Liquidambar styraciflua	Tree	High/medium/null	NF
Morus alba	Tree	High/medium/low	Yes
Nothofagus antarctica	Tree	High	NF
Pinus sylvestris	Tree	High	NF
Populus alba 'Pyramidalis'	Tree	High/medium	NF
Populus nigra 'Italica'	Tree	High/medium	Yes
Populus spp, (male)	Tree	High/medium/low	NF
Quercus ilex	Tree	High/medium	Yes
Quercus petraea	Tree	High/medium	NF
Quercus robur	Tree	High/medium	NF
Salix alba	Tree	High/low	NF
Salix purpurea	Tree	High	NF
Ulmus minor	Tree	High/medium	NF
Ulmus pumila	Tree	High/medium	NF
Acacia dealbata	Tree	Medium/low	NF
Acer griseum	Tree	Medium/low	NF
Acer monspessulanum	Tree	Medium/low	NF
Acer pensylvanicum	Tree	Medium/low	NF

Plant source of allergenic pollen	Mtype	Allergenic potential class	IUIS
Acer platanoides	Tree	Medium/low	NF
Acer pseudoplatanus	Tree	Medium/low	NF
Acer rubrum	Tree	Medium/low	NF
Acer saccharinum	Tree	Medium	NF
Aesculus hippocastanum	Tree	Medium/low	Yes
Aesculus x carnea	Tree	Medium	NF
Agrostis stolonifera	Herb	Medium	NF
Alopecurus pratensis	Herb	Medium	NF
Amaranthus caudatus	Shrub	Medium	NF
Amaranthus retroflexus	Shrub	Medium	Yes
Anthoxanthum odoratum	Herb	Medium	Yes
Artemisia vulgaris	Herb	Medium	Yes
Atriplex hortensis	Herb	Medium	NF
Atriplex tatarica	Herb	Medium	NF
Callistemon spp	Shrub	Medium	NF
Calocedrus decurrens	Tree	Medium	NF
Cannabaceae	Herb	Medium	Yes
Cedrus deodara	Tree	Medium	NF
Cedrus libani	Tree	Medium	NF
Celtis australis	Tree	Medium	NF
Celtis occidentalis	Tree	Medium	NF
Cephalotaxus drupaceae	Shrub	Medium	NF
Cercidiphyllum japonicum	Tree	Medium	NF
Chenopodium album	Herb	Medium	Yes
Cynodon dactylon	Herb	Medium	Yes
Dactylis glomerata	Herb	Medium	Yes
Eucalyptus chamaldulensis	Tree	Medium/low	NF
Eucalyptus globulus	Tree	Medium	NF
Eucommia ulmoides	Tree	Medium	NF
Eupatorium capillifolium	Herb	Medium	NF
Festuca rubra	Herb	Medium	NF
Fraxinus americana	Tree	Medium	NF
Fraxinus angustifolia	Tree	Medium	NF
Fraxinus pennsylvanica	Tree	Medium	NF
Holcus lanatus	Herb	Medium	Yes
Humulus japonicus	Herb	Medium	Yes
Humulus lupulus	Herb	Medium	NF
Iva xanthiifolia	Herb	Medium	NF
Larix decidua	Tree	Medium/null	NF

Plant source of allergenic pollen	Mtype	Allergenic potential class	IUIS
Lolium perenne	Herb	Medium	Yes
Melaleuca cajuputi	Tree	Medium	NF
Mercurialis annua	Herb	Medium	Yes
Parietaria judaica	Herb	Medium	Yes
Partenium hysterophorus	Herb	Medium	Yes
Phleum pratense	Herb	Medium	Yes
Phoenix canariensis	Tree	Medium/low	NF
Phoenix dactylifera	Tree	Medium	Yes
Picea abies	Tree	Medium/low/null	NF
Picea omorika	Tree	Medium/low	NF
Picea pungens	Tree	Medium	NF
Pinus halepensis	Tree	Medium	NF
Pinus nigra	Tree	Medium	NF
Pinus pinaster	Tree	Medium	NF
Pinus pinea	Tree	Medium	Yes
Pistacia atlantica	Tree	Medium	NF
Pistacia vera	Tree	Medium	Yes
Plantago lanceolata	Herb	Medium	Yes
Poa spp	Herb	Medium	Yes
Podocarpus macrophyllus	Tree	Medium	NF
Polygonaceae	Herb	Medium	NF
Populus tremula	Tree	Medium	NF
Populus x canadensis	Tree	Medium/low	NF
Prosopis cineraria	Tree	Medium	NF
Prosopis juliflora	Tree	Medium	Yes
Pterocarya fraxinifolia	Tree	Medium/null	NF
Quercus cerris	Tree	Medium	NF
Quercus frainetto	Tree	Medium	NF
Quercus imbricaria	Tree	Medium	NF
Quercus palustris	Tree	Medium	NF
Rumex crispus	Herb	Medium	NF
Salix caprea	Tree	Medium	NF
Sambucus nigra	Shrub	Medium/low/null	NF
Schinus terebinthifolius	Tree	Medium	NF
Secale cereale	Herb	Medium	Yes
Sequoia sempervirens	Tree	Medium	NF
Sequoiadendron giganteum	Tree	Medium	NF
Solidago canadensis	Herb	Medium	NF
Solidago virgaurea	Herb	Medium	NF

Plant source of allergenic pollen	Mtype	Allergenic potential class	IUIS
Styphnolobium japonicum	Tree	Medium	NF
Syringa vulgaris	Shrub	Medium	Yes
Tamarix ramosissima	Tree	Medium/null	NF
Thuja occidentalis	Tree	Medium	NF
Tilia cordata	Tree	Medium	NF
Tilia henryana	Tree	Medium	NF
Tilia insularis	Tree	Medium	NF
Tilia mongolica	Tree	Medium	NF
Tilia neglecta	Tree	Medium	NF
Tilia platyphyllos 'Rubra' or 'Corallina'	Tree	Medium	NF
Tilia tomentosa	Tree	Medium	NF
Tilia x euchlora	Tree	Medium	NF
Tilia x europaea	Tree	Medium	NF
Trachycarpus fortunei	Tree	Medium	NF
Typha spp	Herb	Medium	NF
Ulmus americana	Tree	Medium	NF
Ulmus glabra	Tree	Medium	NF
Ulmus laevis	Tree	Medium	NF
Urtica dioica, (male)	Herb	Medium	NF
Vitis vinifera	Liana	Medium	Yes
Wisteria sinensis	Shrub	Medium	NF
Zea mays	Herb	Medium	Yes
Zelkova serrata	Tree	Medium/null	NF

Plants' source of allergenic pollen: family, genus, species, variety, or hybrid (scientific name).
Mtype (Morphotype): tree, shrub, herb, liana.
Allergenic potential class: Very high (4); High (3); Medium (2); Low (1); Null (0).
IUIS; Allergen found in database WHO-IUIS (Yes if present; NF if not found): All possible types of allergens have been investigated (food, contact, pollen, airborne, injection).

Table 4.
The main plant source of allergenic pollen and their allergenic potential for humans [3, 51, 72–74, 78]. Red colour describes plants with very high or high value of allergenic potential, while orange colour indicates plants with medium allergenic potential.

5.2 Green areas and their impact on respiratory health

The morphology of green space and human health are related [89], so it is essential to design green areas to enhance health outcomes. Plant species used for ornamental purposes in urban landscapes (parks, gardens, tree alignments, or open green spaces in a broad sense) are the most common cause of pollen allergies among the local population [49]. Health-promoting green area planning should be integrated into epidemiological research, which shows many allergy symptoms related to pollination periods, the number of individuals of a species, biodiversity, wind, and other climate factors. Therefore, it is essential in green planning and

plantations to consider the plant list to exclude (species with a high or very high allergenic potential), the plant list to include only a few individuals (species with a moderate allergenic potential), and the plants without restrictions (species with a low allergenic potential). When designing green areas, balsamic plants, such as conifers with low allergenic potential, that have a positive effect on respiratory health should also be taken into consideration.

5.3 Selection of relevant plant species in the context of urban environments

The selection of plants, from the point of view of allergenic potential, should focus on some fundamental points for an urban green design that respects human health.

5.3.1 The choice of species in urban greening

The choice of species should take into account multiple factors: the sexuality of the plant and of the individual to be planted. There are monoecious plants with hermaphroditic flowers or dioecious plants (eg, *Ginkgo*), where the sexes are separate on different individuals, or the male and female flowers are distinct on the same individual. Since pollen is only emitted by male flowers, female plants can be chosen to avoid the emission of airborne allergens. In species with hermaphroditic flowers, that is, with male and female parts on the same flower, or conifers with male and female cones on the same individual, it is necessary to take into account the allergenic potential of the species (or variety) published in some works, which are constantly updated [3, 49, 72, 74, 78]. In this chapter, the lists of the most commonly used species are published, which should instead be limited due to their high allergenic potential (**Table 4**). In this case, only a small number of such individuals should be foreseen in urban green areas.

5.3.2 Biodiversity

The aspect of biodiversity is fundamental to obtaining benefits both for the urban ecosystem environment and for humans. In fact, a high biodiversity index, determined by the number of different species in a green system, the diversity of biological forms (shrubs, herbs, trees, bulbous plants, etc.), chorological types (the main origin and best distribution area of the species), and the flowering and fruiting periods of the species, provides food to urban fauna (lepidoptera, hymenoptera, other insects, earthworms, birds, bats, and so on) and avoids monoculture systems where the same species is repeated in an artificial pattern. A highly biodiverse plant system (which we could define as 'bio-diverse greenery') imitates, reproduces, and restores the potential natural environment of the place. In this sense, as is known from scientific conferences (personal reference of Prof. Carlo Blasi, Italy), it is useful to consult maps, where available, of the potential vegetation of the place and of the vegetation dynamics. This involves selecting, first, the shrubs of the dynamic succession that will lead to the formation of the forest, ensuring optimal rooting and a natural evolution of the green system. From an allergenic point of view, it is both possible and advisable to avoid planting species with very high allergenic potential, particularly if they are non-native, and to select species with medium–low allergenic potential [87]. Planting very few

individuals among the allergenic species and more individuals of harmless species can help ensure the future healthiness of greenery for the urban population, which includes vulnerable groups such as fragile individuals, athletes, children, the elderly, and even pets, who may be more exposed to allergenic risks.

5.4 Selection of relevant plant species in reforestation efforts

In forestry interventions, in semi-natural or natural environments, the population density is much lower; therefore, the impact of allergenic pollens on the human population is also much lower at an epidemiological level. However, if the interventions concern semi-inhabited areas or areas close to cities (eg, green belts or other nature-based solutions), it is necessary to take into account the direction of the prevailing winds and implement a choice based on biodiversity and low allergenic potential, as expressed in the previous paragraph. In this case, the choice of native species that are well-adapted to the local geopedological and climatic environment will determine better rooting of the species, with better vigour and capacity to colonise the environment. In some historical periods, some pioneer forestry species, such as Cupressaceae, have been overused. Today, in light of discoveries regarding their very high allergenicity, determined by a long pollen season (eg, *Cupressus*, January–April, in the Northern Hemisphere), they should be avoided as much as possible. In their replacement, taking into account the positive aspects of the balsamic substances emitted and useful for air purification, other conifers (*Cedrus, Pinus, Abies, Picea*) can be used, which have medium–low allergenicity but, above all, a reduced pollen season (15–30 days, depending on the climate and location) [72, 74, 87].

5.5 Implications of invasive species and globalisation of the flora

The diffusion of invasive alien plant species (IAPS) across the globe indirectly impacts human health, causing reduced native plant diversity and increased exposure to air pollution [90]. In some cases, the spread of IAPS can have significant and direct implications for allergology. The considerable airborne pollen diffusion of *Ambrosia* (ragweed), one of the main allergenic genera in the world, in Asia, Australia, Africa [91], or Europe [92] from the Adriatic East Coast, is a typical example. Additionally, the spread of certain species from the highly allergenic Asteraceae family (such as ornamental daisies) significantly impacts respiratory health in urban areas. *Senecio inaequidens* (**Figure 6**) also known as South African ragwort, for example, is transported by animals, wind, and motorised rubber-wheeled vehicles, making it widespread along main roads, railways, pastures, and gardens in South Africa (its native country), other parts of Africa, and several regions of the world, such as the Canary Islands, Europe [93], and Korea [94]. The pollen of this species is toxic in honey, and the plant is dangerous in fodder, being lethal to animals (eg, horses and rabbits) because it contains pyrrolizidine alkaloids. Its pollen can also be allergenic due to the high allergenic potential of the family. The potential ecological risk includes its ability to expand its range and invade various habitat types, from coastal regions to mountainous areas. Managing and controlling invasive species in urban green areas, roadsides, and railways is equally essential.



Figure 6.
Senecio inaequidens*, an invasive plant whose pollen can cause toxicity in honey (photo by F. Marinangeli).*

5.6 Implications of climate change

Over the past century, the air temperature has increased due to the impact of anthropogenic climate change, and an alteration in the air mixture has occurred [Kim, 2024]. Consequently, human exposure to organic and inorganic compounds, irritants to respiratory health, has increased [66, 95]. The impacts of climate change on pollen seasonality have been the topic of many studies. Climate change has been observed to affect the seasonality, production, atmospheric concentration, and geographic distribution of airborne pollen [69, 96, 97]. Pollen granules are part of the particulate matter PM_{10}: The warmer air and increased carbon dioxide have produced a more extended pollen period [98]. The start date of pollination, the date of maximum pollination, the end date, the pollen concentration, and the duration of the pollen season are influenced by climate change [69]. Some groups of the main allergen taxa have been studied: The Poaceae (grass) family and *Quercus* (oak) over the 26 years (1995–2020) have shown an advance in the start date of pollination; *Betula* has not exhibited the same reaction [99], probably due to the autecology of the genus, which is typical of temperate northern zones. The increasing pollen season duration in Northern Europe has been estimated at 0.9 days per year on average, and in 17 locations in the Northern Hemisphere, trees grown at elevated CO_2 concentrations produced substantially more pollen [100]. Another study of the impacts of climate change on PE in the United States by the end of the century found that temperature and precipitation alter daily PE maxima by 35% to 40%, and the change in phenology and temperature-driven pollen production increases the annual total PE by 16–40%. The increasing atmospheric CO_2 may increase pollen production, which, in conjunction with climate, increases end-of-century emissions by up to 200% [101]. Climate change can modify the epidemiology of viral infections, and coexposure to airborne pollen has enhanced human susceptibility to severe acute respiratory syndrome coronavirus infections, as verified in 130 monitoring stations in 31 countries across the globe [102]. The results of this study

show that airborne pollen, sometimes in synergy with humidity and temperature, explained, on average, 44% of the infection rate variability. Outside of lockdown, an increase in pollen abundance by 100 pollen/m^3 resulted in a 4% average increase in infection rates.

Urban heat island intensity can disturb flowering periods and pollen concentrations, mainly in highly urbanised areas, as shown in a study in Mexico City [67], due to increased air temperature.

5.7 Biodiversity, air pollution, and pollinosis

Pollen granules, exposed to more polluted air, express greater allergenicity in humans from all world regions [98]. Climate, land-use change, and air pollution are expected to promote the spread of some invasive species, increase airborne pollen concentrations (eg, Ambrosia or ragweed), extend the pollen season, encourage long-distance transport of pollen or subpollen particles containing allergens [92], and contribute to increasing pollen allergenicity. Epidemiological studies suggest a potential link between the rising global prevalence of allergic diseases and increased air pollution [91]. Several pollutants can combine with climatic changes to enhance the expression of allergenic proteins in various pollen grains [103]. Pollen sensitisation is increased by exposure to contaminants for 24 to 48 hours. The pollutants make the exine surface more fragile, triggering a mucosal reaction and exposing it to pollen allergens. Pollutants also act as adjuvants to pollen allergens, leading to a greater production of IgE [1]. Educational aspects are also important: it is possible to study respiratory allergic diseases through digital technologies (eg, online platforms) to collect patient data (such as daily allergy symptoms) and improve diagnostic precision [104].

6. Plants as food and allergy for humans

Recently, there has been a growing interest in plant-based, ecologically more sustainable food education. However, food proteins from plants can cause severe allergies in humans. Plant-based products expose consumers to new sources of allergens through *de novo* sensitisation or cross-reactions with homologous allergens [105]. Some emerging allergens must be considered for control, management, and labelling to inform consumers. In the food industry, the new use of plant protein isolates or hydrolysates (especially from the Fabaceae family or pulses) increases the evidence of allergic, neo-allergic, and cross-allergic reactions, as described in western countries [106]. Therefore, emerging allergens must be considered for control, management, and labelling to inform consumers. In the food industry, the new use of isolated or hydrolysed plant proteins (especially those of the Fabaceae or legume family) increases the evidence of allergic, neo-allergic, and cross-allergic reactions, as described in western countries [106]. Allergen databases are essential for doctors and researchers to disseminate knowledge, as reported in [53]. All food allergens are shown. In the main group of foods, many fresh fruits (*Actinidia, Fragaria, Ananas, Prunus, Ziziphus,* and others) or vegetables (*Brassica, Cucurbita, Solanum,* and others), several cereals (wheat, rye, maize), legumes (*Cicer, Glycine, Lens, Pisum, Vigna,* and others), nuts, dried fruits, or seeds (*Arachis, Carya, Castanea, Corylus, Juglans, Macadamia, Pinus, Pistacia, Prunus dulcis, Sesamum,*

Ricinus, and others), spices, tubers, and roots (*Manihot, Panax ginseng, Solanum*) are potentially allergenic. Some examples of allergenic proteins in plant foods are the seed storage proteins (SSPs), which are essential in plants for development and defence and are present in nuts, seeds, and legumes; SSPs can be responsible for severe systemic reactions. In *Macadamia* nuts, a specific legumin (Mac I 2) has been isolated, and in pumpkin seeds (Cucurbita seeds), the Cuc ma 4. Also, the 2S Albumins SSPs can produce allergic reactions in humans. They have been isolated from *Cucurbita* seeds and flaxseeds (*Linum*). The most crucial food allergens in the Mediterranean are the LTPs, isolated from narrow-leaf lupine (*Lupinus*). The allergen Pru du 1061 has been isolated from almonds (*Prunus dulcis*) [58]. The uploaded list of allergenic food plants in [52], simplified into eight leading groups of foods, is available online.

To complete the topic, a few cases of anaphylaxis caused by vegetal foods are mentioned. An analysis of 100,000 human cases shows that the frequency of anaphylaxis is about 0.5–2%, especially in children and adolescents [107]. Reactions to peanuts and tree nuts were studied in the USA by Furlong in 2001 [108]. Out of 706 subjects in restaurants or ice cream and pastry shops, 156 episodes (29 first-time reactions) were recorded: Most reactions were caused by peanuts (67%), nuts (24%), a combination thereof, or were unknown (9%). Symptoms started within an average of 5 minutes after exposure and were severe in 27% of reactions. The food was not visually identifiable in 50% of these cases (eg, in sauces, condiments, spring rolls, etc.). In 23 cases, exposures were reported due to contamination during cooking or serving.

7. Some plants giving benefits to human respiratory health

Some plants are known in traditional medicine and healthy urban greening as applicable to respiratory health. In literature, several interesting examples of them have been tested, some of which are presented here. A group of tree plants with balsamic benefits is that of Coniferae (conifers), due to the presence, on the buds, leaves, and bark, of resins, monoterpenes (such as pinene), and essential oils that are diffused into the forest atmosphere. However, considering the allergenic potential of some of them, also used in urban parks, it is necessary to distinguish the period in which conifers pollinate from that in which they bring benefits to respiratory health, inviting park users to differentiate their behaviour in the different seasons of the year. The least impacting conifers for respiratory health are *Pinus and Cedrus,* compared to *Cupressus, Thuja, and Chamaecyparis,* which have a high allergenic potential. Also, *Eucalyptus* is a balsamic plant, often used in temperate-warm climates as a windbreak on marine and ocean edges. The leaves are steam-distilled to extract eucalyptus oil (eucalyptol or cineole), with therapeutic, perfumery, flavouring, and antimicrobial properties. As regards herbaceous and shrubby plants, we cite *Borago officinalis* (ubiquitous), extract against asthma [109]; seed oil, anti-leukotriene generation in mild asthma patients [110]; *Campanula takesimana* (Korean endemic plant), callus extract against asthma, tonsillitis, and sore throat [111]; *Cyclamen*, extract against rhinosinusitis [112]; *Daphne*, extract against atopic dermatitis and asthma [113]; *Gentiana olivieri*, extract with anti-inflammatory and immunomodulatory effects [114]; *Gentiana rigescens* (Dian long Dian in southern Yunnan, China), phenolic extract with anti-inflammatory and anti-allergy effects

[115]; *Hedera helix*, *Althaea officinalis, Drosera rotundifolia, Grindelia, Hedera helix, Pelargonium sidoides, Sambucus nigra, and Thymus vulgaris* extracts, effects on post-viral acute cough [116]; *Hedera helix* (ubiquitous, ivy), leaves dry extract: children with mild uncontrolled asthma despite regular inhaled corticosteroid therapy might benefit from an additional treatment with ivy leaves dry extract [117]; and *Thymus* (Moroccan *thymus*), essential oils with anti-inflammatory and anti-cyanobacterial effects [118]. The presence of secondary metabolites with favourable properties in treating respiratory diseases is evidenced in scientific literature [101, 117, 119–121], and many more examples could be found.

8. Conclusions

Pollen enables the reproduction of plants and photosynthetic autotrophic organisms, which are essential for life on the planet. Plants, whether integrated into urban green spaces or forestry around the perimeters of cities and inhabited centres, serve as a source of food and nutritional supplements for humans. However, they sometimes pose risks of allergies while often being beneficial for the respiratory system. The dispersion of pollen into the atmosphere, combined with air pollution, can significantly impact the human respiratory system. This allergenic potential varies according to several factors and has been thoroughly evaluated in the scientific community. Disseminating knowledge on this subject is urgent and must be as widespread as possible to reach all experts who engage in this field: doctors, allergists, researchers, botanists, green designers, patients, and ordinary citizens. For this reason, evaluating the allergenic potential of plants is crucial to planning healthy green areas, reducing the risk of exposure to allergens, and benefiting citizens. The degree of allergenic potential is already known for hundreds of plant taxa, primarily cultivated trees and shrubs [122, 123]. However, minor and spontaneous species, which are not cultivated in urban parks, remain understudied [124]. Furthermore, significant advancements can arise from new technologies that support automatic, computerised readings of pollen recorded by pollen samplers, enabling real-time pollen bulletins. Seasonal weather variations caused by global climate change influence the duration of pollen seasons, plant growth, and pollen allergenicity [125, 126]. Consequently, the design strategies for green spaces and forestation facilities near cities and towns must account for these increasingly prominent aspects of allergology [127, 128–131].

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Conflict of interest

The authors declare no conflict of interest.

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