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Review Article

Expanding perennial grass bioenergy crops and influence on allergenic burden: A short review

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Abstract

In recent years, second-generation perennial energy grasses have gained attention for their potential role in reducing greenhouse gas emissions. However, the possible health risks associated with their large-scale cultivation remain insufficiently addressed. This paper presents a narrative literature review of the potential allergenic effects of the main perennial grass energy crops (*Phalaris arundinacea*, *Phragmites australis*, *Miscanthus* × *giganteus*, *Arundo donax*), with *Zea mays* used as a reference first-generation energy crop. A structured search was conducted in major electronic databases using predefined keywords related to bioenergy crops, pollen dispersal, and allergenicity. The search identified a wide body of literature on crop biology and bioenergy potential, but only a limited number of studies addressed allergenic outcomes directly. The evidence suggests that, except for *P. arundinacea*, most second-generation grasses are late-flowering species. If cultivated on a larger scale near urban centers, these crops could alter the seasonal pattern of allergenic pollen exposure by shifting the allergic burden toward the late growing season (August-October). While the expected overall impact on the annual pollen load appears modest-potentially reducing the June peak typical for Europe while slightly increasing exposure later in the season-these changes warrant consideration in land-use and public health planning.

Keywords: aeroallergen load; common reed; giant reed; maize; miscanthus; reed canary grass

Introduction

Climate change is considered the greatest global threat to sustainable development (Hou, 2021). Increased use of renewable energy sources is expected to help mitigate climate change and improve energy

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security (Taylor *et al*., 2019). Due to climate change, natural vegetation and cultivated crops will be at an increased risk of droughts and extreme weather events (Dželetović and Simić, 2024). The cultivation of energy crops is considered a promising solution for the future, as it is a neutral, clean and environmentally renewable energy source (Janković *et al*., 2023). Second-generation perennial grass energy crops have been the focus of research in recent years, as they are expected to contribute significantly to achieving greenhouse gas emission reduction targets. Compared to food production systems and typical annual crops, the cultivation of rhizomatous perennial grasses offers a sustainable alternative. It reduces competition for land used for food production while mitigating the potentially negative impacts on food security, greenhouse gas emissions and biodiversity loss (Pulighe *et al*., 2019; Clifton-Brown *et al*., 2023). The targeted cultivation of fast-growing energy crops can ensure that the share of renewable energy sources increases and contributes to the sustainable development of regions (Kotrla *et al*, 2017). As part of the energy transition, a significant increase in the area under cultivation of second-generation energy crops is expected (Cvetković *et al*., 2014). Such plants have a significantly lower input requirement, produce more energy and emit fewer greenhouse gases per hectare than the first-generation annual food crops (e.g. *Zea mays*) used to date (Schrama *et al*., 2016).

Only about 10% of all plant species are wind-pollinated (Friedman *et al*., 2009), i.e. their pollen is transported over short to long distances (a few meters to over 100 km) (Smith *et al*., 2005). In the literature, there are a variety of definitions for pollen transport over short, medium and long distances, without differentiating between species. However, knowledge about the type of land use, its potential pollen emission, and the importance of local sources remains limited (Jung *et al*., 2022). For example, the pollen concentration decreases at higher altitudes (Damialis *et al*., 2017). The release of pollen occurs when the flower structures have reached a sufficient degree of maturity and are favored by meteorological dispersal mechanisms. Release is generally favored by higher air temperatures, lower relative humidity and increased wind activity. Samples collected in urban environments differ significantly from those collected in rural areas. In urban areas, increased air pollution such as soot, dust and other particulate matter can combine with pollen grains, increasing their allergenic potential and posing an additional risk to sensitized individuals (SEPA, 2025).

With almost 12,000 species, the grasses (Poaceae) are one of the most diverse plant families in the world (Christenhusz and Byng, 2016). In addition to natural habitats, which generally have a very high diversity, grasses are also important in agriculture and include the three most cultivated crops: maize (*Zea mays* L.), rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) (Koehler *et al*., 2014; Shavanov, 2021). Despite morphological similarities, the pollen of different grass species sometimes have very different allergenic properties (Bullimore *et al*., 2012). Grass pollen is one of the most important triggers of IgE (Immunoglobulin E) mediated allergic reactions worldwide. A European study confirmed the widespread prevalence of this allergy and fsoshowed that more than 30% of allergy sufferers reacted positively to grass pollen in the skin prick test (Burbach *et al*., 2009). The pollen season in Europe is long, from May to July, although it varies depending on altitude and geographical location (Dirr *et al*., 2023).

The focus of allergology research is primarily on the most widespread species in certain regions, while various ornamental grasses or local peculiarities are often not studied in detail (Dirr *et al*., 2023). Local phenomena can lead to a longer duration of allergenic exposure to grass pollen due to variations in the flowering period. It is important to carefully document and study the grass pollen season due to its complexity, as grass pollen is one of the most important aeroallergens with a sensitization rate of up to 30% in Europe (García-Mozo, 2017). Due to the influence of regional climatic conditions, both the intensity and the detailed course of the grass pollen season vary, which makes it difficult to make generalized statements. However, parameters such as the start and end of the season and the main pollination time show a uniform trend across Europe. In Northern, Eastern and Central Europe, the grass pollen season starts at the beginning of May and lasts until the end of July (Dirr *et al*., 2023). In the Mediterranean regions, where the season starts and ends a month earlier, there is a clear shift in the timing. Altitude also plays a role in the growing season: grasses at higher altitudes flower 2-3 weeks later than grasses in the lowlands (Dirr *et al.*, 2023). D'Amato *et al.* (2007) point out that the highest concentrations of grass pollen in Europe are typically observed in June, 1-2 months after the start of the season.

Potential health problems that could arise from expanding the cultivation of second-generation energy crops to larger areas have not yet been sufficiently considered. While their bioenergy potential is well documented, much less is known about their potential contribution to allergenic pollen load, especially in peri-urban landscapes. Our study aims to answer the following question: Can the flowering and pollen dispersal of second-generation perennial energy grasses affect allergenic exposure in a way that could affect the sustainability of their mass cultivation and their integration into land-use policy and planning?

This review aims to critically summarize the existing knowledge on the flowering phenology, pollen release, and allergenic potential of the main perennial energy grasses (*Phalaris arundinacea*, *Phragmites australis*, *Miscanthus* × *giganteus*, *Arundo donax*), using *Zea mays* as a first-generation reference crop. In this way, we aim to evaluate whether their large-scale dissemination could lead to a shift in seasonal allergy burden and highlight potential implications for public health, land-use planning, and the long-term sustainability of these crops. Accordingly, our aim was also to summarize general trends, provide a conceptual narrative overview of the most important findings, and make suggestions for future research in this field.

This paper provides a narrative review (Snyder, 2019) of the potential allergenic effects of second-generation perennial energy grasses in the context of their large-scale cultivation for bioenergy production. The study is based on a structured literature search in major databases (Web of Science, Scopus, JSTOR, ScienceDirect, ProQuest) using predefined keywords (bioenergy crops, pollen dispersal, aeroallergens, *Miscanthus*, *Arundo, Phalaris*, *Zea mays*, etc.), prioritizing relevant peer-reviewed articles in English. The aim was to critically summarize the available evidence, identify research gaps, and outline future directions.

Description of the most important perennial grass bioenergy crops and influence on allergenic burden

Zea mays L. (Maize)

The example of a first-generation energy crop that we use as a reference in this paper is maize (Figure 1A). Originally from America, it is one of the most widespread cereals and one of the most important crops in Europe (Koehler *et al.*, 2014; Shavanov, 2021). In 2023, maize was grown on around 208 million hectares worldwide, in Serbia, on 923 thousand hectares (FAO, 2025). In addition to its use as food for humans, maize silage is also used as animal feed or for bioethanol production (Shiferaw *et al.*, 2011). The addition of bioethanol to fossil fuels could lead to a further increase in maize cultivation in Europe in the future. Thanks to its high yields, high starch content and good digestibility, silage maize is the most widely grown crop for biogas production (Mayer *et al.*, 2014a).

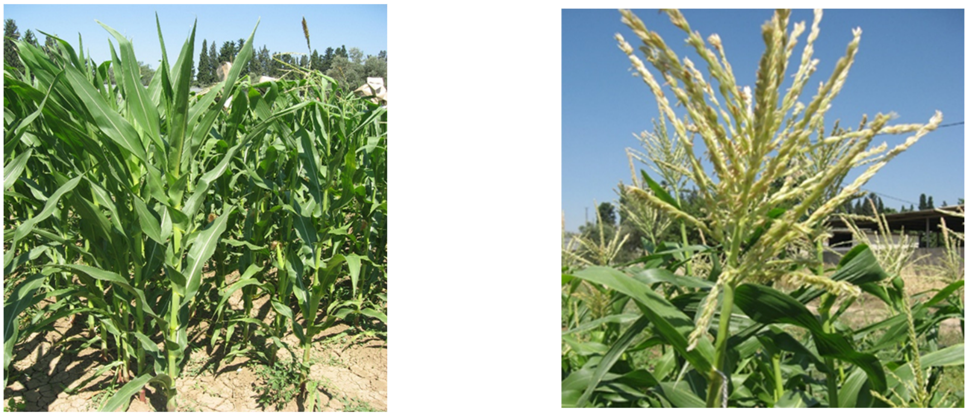
(A) (B)

Figure 1. Maize (*Zea mays* L.): Crop (A), Flowering (B) [original pictures]

Maize has a C4 photosynthetic metabolism that is an adaptation for more water use efficiency under certain conditions, although it is not effective under severe water stress (Xu *et al.*, 2020; Sánchez *et al.*, 2021; Arias *et al.*, 2023). It is considered a late-flowering plant. A characteristic feature of maize is the separation of terminal male flowers and clustered female flowers in the leaf axils, from which only a very long pistil protrudes from the cob at the juvenile stage. The tip of the stalk ends in a tassel, a panicle of male flowers. When the tassel matures and the weather is sufficiently warm and dry, the anthers open and release the pollen. Maize pollen is anemophilic (windborne), and due to its high settling speed, most of the pollen falls within a few meters of the tassel.

Most cultivated cereals either do not release airbone pollen (e.g. wheat, *Triticum aestivum* L.) or produce pollen that is too large and heavy to be transported over long distances (e.g. maize, *Zea mays* L.). Only a very small proportion of cereal pollen (e.g. rye, *Secale cereale* L.) is transported over distances of more than 500 meters (Damialis and Konstantinou, 2011). In comparison, pollen from pastures and meadows is much smaller and lighter and can therefore be transported further (Jung *et al.*, 2022).

Depending on the hybrid and the time of sowing, maize can flower over a very long period (Figure 1B). In combination with the increasing cultivation rate, this could significantly extend the pollen season of grass. According to Nestorović *et al.* (2015), the allergenic properties of maize pollen are very pronounced. However, maize produces relatively large and heavy pollen grains, which are characterized by a higher sedimentation rate. Therefore, at average wind speeds, significant pollen concentrations in the ambient air can only be expected within a radius of 20-40 meters around the plant. As a wind-pollinated member of the grass family, maize is a significant source of airborne pollen. Seasonal pollen output per plant varies between 5 and 50 million grains, depending on genetic characteristics and growing conditions. At a typical plant density of 7 to 12 plants m^{-2}, the cumulative pollen emission from a 1 ha field during the flowering period is estimated at 1011 to 1013 grains (Hofmann *et al.*, 2014).

In addition to the large amounts of pollen produced, the physical characteristics of the maize pollen also have a significant influence on its dispersal patterns. Maize pollen is relatively large and heavy and has a diameter of 80 to 125 μm (Aylor, 2002). Accordingly, it is unlikely that maize pollen will be transported over long distances and result in significant exposure outside of cultivated areas. Pollen was found at distances of several hundred meters from the source, underlining the possibility of long-distance dispersal (Arritt *et al.*, 2007). These findings have led researchers to re-evaluate previously underestimated factors, including turbulent airflow, heat-related updrafts and stronger winds, which are common during summer maize flowering. Such environmental conditions-characterized by warm, dry, and windy weather significantly favor the release and further dispersal of maize pollen (Viner *et al.*, 2010). However, people who are allergic to grass pollen should expect to be exposed to allergens in the vicinity of large maize growing areas after the main grass pollen season (Oldenburg *et al.*, 2011; Hofmann *et al.*, 2014).

Miscanthus × giganteus Greef et Deu. (Miscanthus)

M. × *giganteus* is a natural hybrid resulting from the crossing of Amur silvergrass (*Miscanthus sacchariflorus* (Maxim.) Franch.), a diploid species, and Chinese silvergrass (*Miscanthus sinensis* Anderss.), a tetraploid species (Nishiwaki *et al.*, 2011). Due to its triploid nature, *M.* × *giganteus* is sterile and cannot produce fertile seeds. Miscanthus (Figure 2A), which originates from Asia, has been cultivated in Europe and North America since the late 1980s. Miscanthus was grown on around 20,000 hectares in the European Union, mainly in the United Kingdom (10,000 ha), on 4,000 hectares each in France and Germany, and on 500 ha each in Switzerland and Poland. Nevertheless, the area under cultivation is declining (Lewandowski, 2016), primarily due to high set-up costs, a delayed return on investment, underdeveloped biomass markets, agronomic and technical challenges, and insufficient political and financial support. It is characterized by high biomass yields, resistance to drought and cold (Mann *et al.*, 2013; Fonteyne *et al.*, 2018), adaptability to nutrient-poor soils and elevated levels of potentially toxic elements, as well as adaptability to different climatic conditions (Dubis *et al*., 2020; Davis *et al*., 2021; Voća *et al*., 2021; Grzegórska *et al*., 2023).

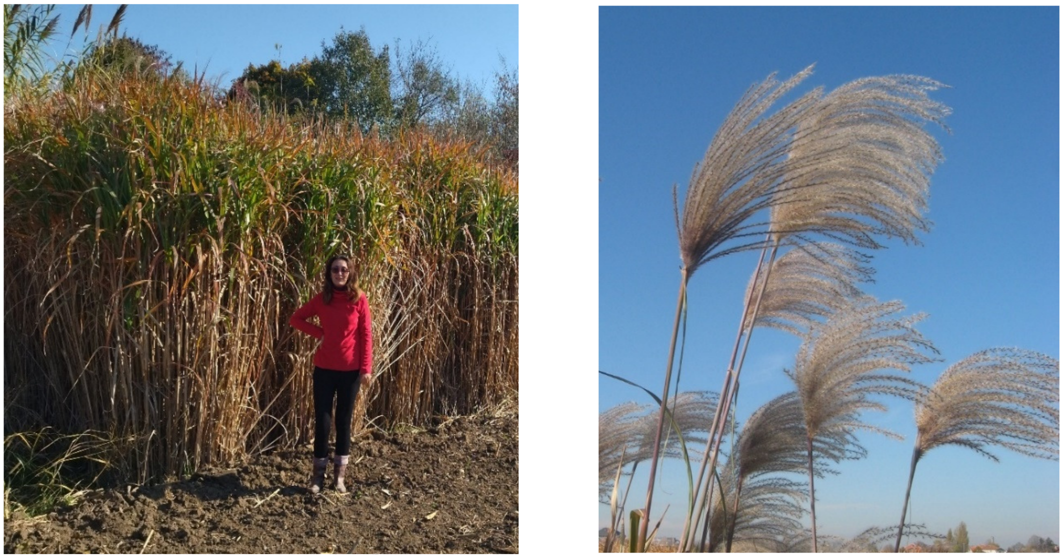
(A) (B)

Figure 2. Miscanthus (*Miscanthus* × *giganteus* Greef et Deu): Crop (A), Flowering (B) [original pictures]

M. × *giganteus* has a C4 photosynthetic metabolism, grows rapidly and reaches a height of 2-3 m. Due to its low fertilizer and pesticide requirements, it is ideal for pellet production and energy generation (Perić *et al*., 2018). Miscanthus is considered the most effective alternative to maize for biogas production through anaerobic digestion (Mayer *et al*., 2014b; Kiesel and Lewandowski, 2016; Prčík *et al*., 2022). In addition, miscanthus biomass can be converted into biomethane, bioethanol and a variety of energy rich fuels and gasses through various biochemical and thermochemical processes - such as pyrolysis, enzymatic saccharification, and fermentation (Janković *et al*., 2023).

Panicles 20-35 cm long form at the top of the miscanthus plants (Figure 2b). These panicles appear mainly on plants that are exposed to stress, especially due to low nutrient content and drought in the soil (Dželetović *et al*., 2012). Miscanthus is characterized by well-developed ligules and dense, hanging inflorescences of spikelets. The flowering period is typically in September and October (Dželetović *et al*., 2012; Dong *et al*., 2021) and thus significantly later than the flowering period of many grass species in natural habitats (D'Amato *et al*., 2007).

Miscanthus is a sterile hybrid that rarely flowers in temperate climates. The timing of flowering is an important characteristic that influences both biomass yield and certain quality traits such as moisture content at harvest (Jensen *et al*., 2011). Flowering and potential pollen production are strongly dependent on photoperiod and temperature. The induction of floral meristems requires photoperiod between 12.1h and 14.2h and accumulated temperature of 553-1157 °C above a base temperature of 10 °C (Jensen *et al*., 2013). In the Mediterranean and southern parts of the Balkans, flowering can occur in late summer or early autumn when conditions are favorable (short days in combination with high temperatures). In contrast, *M.* × *giganteus* almost never flowers in the northern regions of Europe due to an unsuitable photoperiod and the early onset of low temperatures (Zub and Brancourt-Hulmel, 2010). The pollen of *M.* × *giganteus* exhibits considerable size variation, ranging from 25.5 to 47.6 µm, indicating a cytological imbalance resulting from its allotriploid nature (Słomka and Kuta, 2012). According to Dirr *et al*. (2023), due to the suitability of *M.* × *giganteus* as a biomass grass, it is possible that the pollen concentration also increases in rural areas, which should be further monitored from an aerobiological point of view. In urban areas where several species of this genus are grown as ornamental plants, local grass pollen exposure may be significantly increased due to the prolonged pollen season, which is detrimental to people with grass pollen allergies. The expansion of *M.* × *giganteus* cultivation as biomass grass may lead to higher pollen concentrations in rural areas, underlining the need for continuous aerobiological monitoring (Dirr *et al.*, 2023).

Arundo donax L. (Giant reed)

A. donax (Figure 3A) is a perennial grass species that grows naturally over a wide area from the Mediterranean to India and is often found in wetlands. It utilizes a C3 photosynthetic pathway, but its photosynthetic rate and productivity are similar to those of C4 plants (Faralli *et al.*, 2021; Sánchez *et al.*, 2021; Arias *et al.*, 2023). Compared to miscanthus, it has a lower efficiency in utilization of nitrogen, phosphorus and potassium, which is probably due to its lower yields and C3 photosynthetic pathway (o Di Nasso *et al.*, 2011).

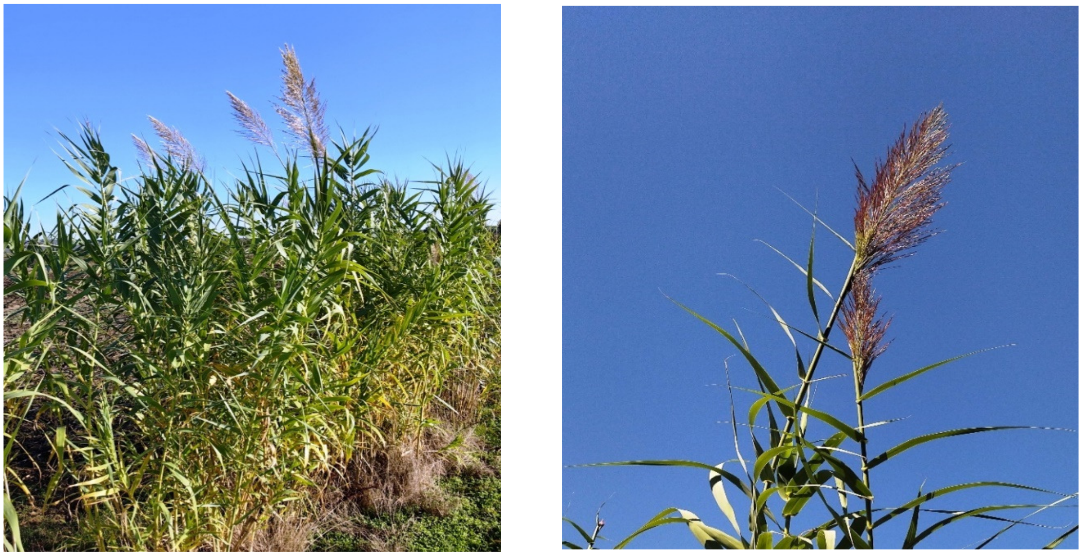
(A) (B)

Figure 3. Giant reed (*Arundo donax* L.): Crop (A), Flowering (B) [original pictures]

From the end of June to the end of September, long panicle like inflorescences with unisexual spikelets emerge from the uppermost stem joint (Figure 3B). The flowers are arranged in 30-100 cm long, branched panicles, with numerous unisexual spikelets appearing at the tips of the lateral branches. A study of *A. donax* clones collected in southern Italy revealed that flowering and inflorescence formation were observed in late summer and early autumn, which, according to Cosentino *et al.* (2006), suggest that prolonged dry periods may serve as triggers for flower induction. In addition, the authors reported that older plants (i.e. those older than 2-3 years) showed a higher tendency to form inflorescences (Cosentino *et al.*, 2006). About 1,000 flowers are formed, but they do not produce fertile seeds. Johnson *et al.* (2006) analyzed over 36,000 flowers and found only five that were fertile. Like *M.* × *giganteus*, *A. donax* also flowers much later than most grasses in nature, which significantly extends the period during which people with grass pollen allergies are exposed to the pollen. In winter, the plant begins to age, the stems turn yellow and lose most of their leaves and flowers.

A. donax is recognized as a potential allergen, although it is not fully documented in allergological literature. Cases of contact allergy have been reported, particularly in musicians using reeds of this plant, and cross-reactivity with other grasses such as *Phragmites* has also been observed, suggesting the possibility of respiratory allergic reactions in sensitized individuals (Petrus *et al.*, 2009). The association with hay fever like symptoms emphasizes the allergenic potential of *A. donax*, especially in the context of its increasing use and presence in the environment (Poitevin, 2017). In contrast, Hardion *et al.* (2015) report in their re-search that *A. donax* has a significantly reduced pollen viability, with a germination rate of 0% and an overall viability of only 6.2%, indicating its functional sterility. For this reason, this species is considered to have minimal allergenic potential.

Phragmites australis (Cav.) Trin. ex Steud. (Common reed)

The common reed (Figure 4A) is one of the most widespread flowering plant species in the world and is found on all continents except Antarctica (Huhta, 2009). It is widespread in abandoned fields, along riverbanks, in swamps, ponds and wetlands, forming tall (2-6 m) and dense habitats (Važić *et al.*, 2015). It is robust, helophytic and very productive grass with an extensive system of rhizomes and stolons involved in its vegetative propagation. The wide global distribution and cosmopolitan character of *P. australis* are due to its specific ecophysiological strategies, its large ecological amplitude due to high phenotypic plasticity, and its significant evolutionary potential (Kettenring *et al.*, 2015; Kettenring *et al.*, 2016; Eller *et al.*, 2017).


(A) (B)

Figure 4. Common reed (*Phragmites australis* (Cav.) Trin. ex Steud.): Crop (A), Flowering (B) [original pictures]

This plant is only grown in Japan as a grass crop for silage components in cattle feed mixtures (Asano *et al.*, 2015). The cultivation technique of reed mainly involves the utilization of existing natural stands (reed beds) (Važić *et al.*, 2015). Common reed is often used in the treatment of municipal and industrial wastewater as part of the wetland method, where it plays an important role (Nikolić *et al.*, 2007; Rezania *et al.*, 2019). It is very resistant to organic pollution and has an excellent ability to absorb various toxic substances from wastewater (Morari *et al.*, 2015; Huang *et al.*, 2017). The plant has rapid above and belowground growth, with growth rates of up to 4 cm/day reported (Važić *et al.*, 2015). It quickly forms a monospecific biocover and displaces other competing plant species from the ecosystem.

In addition to the morphological characteristics mentioned above, the common reed is characterized by very late flowering, which lasts from July to September. The photoperiod plays a decisive role in regulating phenological characteristics such as the time of flowering and the length of the vegetative growth period. Longer day lengths generally promote increased plant growth and developmental processes, while shorter day lengths can limit successful reproduction, especially in regions at higher latitudes (Hong *et al.*, 2021). The panicle is large, consists of numerous small flowers and measures 20-50 cm in length (Figure 4B).

According to Nestorović *et al.* (2015), the allergenic properties of common reed pollen are very pronounced. A study conducted in one of the largest reed belts in Europe, around Lake Neusiedl in Austria, shows that reeds have a significant influence on the timing of grass pollen allergy exposure (Bastl *et al.*, 2020). During the flowering period of the reed, pollen concentrations of more than 20 pollen grains m^{-3} of air were measured exclusively around Lake Neusiedl, which is higher than at all other measurement locations in the country. The amount of pollen released by the reeds considerably extends the clinically relevant exposure time. The impact of such local specificity shows that knowledge of the local vegetation is important for pollen predictions and this should also be considered for other areas close to reed belt regions (Bastl *et al.*, 2020). Although non-systematic observations suggest that pollen from common reed can trigger asthma, allergic rhinitis, allergic conjunctivitis and skin symptoms in sensitized individuals, the relevant scientific data is still limited. A study conducted in Spain found that 90% (27 out of 30) of patients with respiratory symptoms during the grass pollen season were sensitized to reed pollen (López-Matas *et al.*, 2016). Of the 31 participants initially recruited (one patient was later excluded), all suffered from rhinitis, 20 from conjunctivitis, and six reported asthma symptoms and skin reactions (López-Matas *et al.*, 2016).

Phalaris arudinacea L. (Reed canary grass)

The reed canary grass (Figure 5A) is a perennial, fast-growing grass with a photosynthetic C3 metabolism (Usťak *et al.*, 2019). It is native to Eurasia and temperate regions of North America (Laurent *et al.*, 2015) and thrives in a wide range of agroclimatic conditions, making it suitable for cultivation on poor quality soils unsuitable for other plants (Perdereau *et al.*, 2017; Dželetović *et al.*, 2023), as well as on abandoned industrial sites (Lord, 2015) and ash fields (Dželetović *et al.*, 2023). *P. arudinacea* is characterized by very early growth in spring, high growth potential, rapid vegetative reproduction and high physiological tolerance to various agroecological conditions (Lord, 2015). The peak yield is reached in summer (Edwards *et al.*, 2006) and typically in the second vegetation period (Vymazal and Kropfelová, 2005). In recent years, the area under reed cultivation has shown an upward trend, especially in northern European countries (Usťak *et al.*, 2019). Fresh biomass is used as animal feed, while mature biomass is used as a source of cellulose (a raw material for various industries) or as biofuel.


(A) (B)

Figure 5. Reed canary grass (*Phalaris arudinacea* L.): Crop (A), Flowering (B) [original pictures]

P. arudinacea growth stops during flowering (Figure 5B), while senescence begins after seed maturation, although the leaves can remain green for several months after flowering (Christian *et al.*, 2006). In temperate regions of Europe, flowering usually takes place between May and July, although it varies depending on the location (Usťak *et al.*, 2012), and usually lasts several weeks (Christian *et al.*, 2006). The flowering process is strongly influenced by environmental factors, particularly temperature and day length. It requires a combination of short-day conditions for primary floral induction and long days (13-15 hours of light) for secondary induction. Optimal temperatures for flowering are around 30/20 °C (day/night), with higher temperatures accelerating ontogenetic development and enhancing photosynthesis, particularly during the early vegetative phase, contributing to earlier flowering (Lindig-Cisneros *et al.*, 2001).

In northern European countries, the combination of long autumn days and low temperatures often leads to incomplete first induction, which can result in a lower seed yield the following year (Sahraama *et al.*, 2000). During the flowering period, *P. arudinacea* can cause discomfort in sensitive individuals and lead to respiratory and skin reactions, e.g. as seasonal allergic rhinitis and conjunctivitis (Luis *et al.*, 2017, Ramón *et al.*, 2017; Ramón *et al.*, 2019). Hypersensitivity reactions, including respiratory symptoms (asthma and rhino-conjunctivitis) and skin symptoms, can be triggered by *P. arundinacea* pollen in sensitized individuals (Ramón *et al.*, 2019).

Discussion

Agricultural producers play an important role in the occurrence and intensity of exposure of the population to pollen allergens, as the choice and structure of crops cultivated, how crops are managed, and the maintenance of agricultural land have a direct influence on the amount and duration of pollen input into the atmosphere. They therefore have a considerable impact on the risk of the occurrence and aggravation of allergic diseases in the population. This review provides the first comprehensive overview of the potential allergenic effects of second-generation perennial energy grasses in the context of their large-scale dissemination for bioenergy production. While these crops are recognized for their role in reducing greenhouse gas emissions and for their contribution to climate change mitigation, their impact on public health through exposure to allergens has been largely overlooked. By comparing the phenology and allergenic potential of the major perennial energy grasses with that of *Zea mays*, this work shows that the widespread cultivation of these grasses near urban centers could shift seasonal pollen exposure until late summer and early autumn. Although the overall increase in allergen exposure may be small, understanding this temporal shift is critical for public health planning, allergy prevention strategies, and risk assessment when implementing bioenergy measures. Thus, this report closes an important knowledge gap between climate change mitigation strategies and human health impacts and supports a more holistic evaluation of bioenergy crop deployment in Europe. In this context, it is important to note that first-generation biofuels were mainly produced from sugar-based materials (such as sugar cane - *Saccharum officinarum* and sugar beet - *Beta vulgaris*) or starch (such as maize - *Zea mays* and sorghum - *Sorghum bicolor*). This led to an increase in agricultural product prices, which in turn raised food prices (Karp and Richer, 2011).

Zea mays pollen can cause allergic reactions such as hay fever (seasonal allergic rhinitis), asthma and conjunctivitis in sensitized individuals. Seasonal exposure to maize pollen has been shown to trigger symptoms in patients with pollen allergy, and positive skin prick test (SPT) results confirm its importance as an aeroallergen. Due to the relatively large maize pollen grains, allergic symptoms are primarily limited to the upper respiratory tract, with higher exposure of the population in rural areas near maize fields than in urban areas (Oldenburg *et al.*, 2011). However, the extent to which exposure to maize pollen contributes to sensitization and the development of allergic diseases is not yet fully understood. A study in Germany, involving workers who were occupationally exposed to maize pollen did not confirm a correlation between the duration of exposure and the frequency of sensitization (Oldenburg *et al*., 2011). In this study, eight participants reported symptoms of rhinitis, conjunctivitis, urticaria and dyspnea, with symptoms occurring 1 to 7 months after the onset of exposure. All symptomatic individuals had detectable specific IgE antibodies directed against maize pollen (Oldenburg *et al*., 2011). Further clinical reports indicate that occupational exposure to maize pollen is a significant risk factor for sensitization. The case of a 55 year-old man with a long history of recurrent seasonal rhino conjunctivitis and asthma who tested negative to a wide range of allergens other than maize pollen was described (Gonzalo-Garijo *et al*., 2004). Accordingly, clinical reports indicate that occupational exposure may pose a significant risk, which is important to consider in risk assessment and in planning preventive measures to protect the health of workers and the population in areas of intensive maize production.

Second-generation biofuels are designed to help overcome these challenges by providing a sustainable fuel supply at an affordable price while also offering greater environmental benefits. These systems are far superior to first-generation biofuels as they contribute to a much greater extent to the reduction of greenhouse gas emissions, provide a much higher net energy yield and have better resource utilization as they significantly reduce soil erosion and nitrogen leaching (de Vries *et al*., 2014). Therefore, current research aims to find suitable, long-term sustainable land use practices that mitigate the effects of climate change (Dželetović and Simić, 2024). Perennial energy grasses are well suited to the changing landscape of European agriculture and thrive under different environmental conditions, even on marginal land (Maksimović *et al*., 2018; Scordia and Cosentino, 2019). The cultivation of second-generation perennial energy crops contributes to the multifunctionality of agriculture and rural development (Daraban *et al*., 2015).

Rural areas are predominantly covered by farmland and forest. Peri-urban landscapes are defined as "urban-agricultural", recognizing the crucial role and potential of agriculture (Gatarić *et al*., 2024). Land use policy and planning for these landscapes is adapted to local/regional requirements. The expected consequences of changes in the structure (representation) of individual agricultural crops in a peri-urban landscape usually boil down to the fulfilment of social, economic and/or environmental needs. It is known that the type of land use determines habitat composition, biodiversity and ecosystem processes (Foley *et al*., 2005).

Allergic diseases have increased significantly in both frequency and prevalence in recent decades. This increase can be attributed to factors such as changes in lifestyle, air pollution, an increase in pollen allergens and higher pollen concentrations in certain regions (Dirr *et al*., 2023). The increase in pollen concentration in the atmosphere is not due to rising temperatures, but to increased CO2 emissions caused human activities (Ziello *et al*., 2012). To provide grass pollen allergy sufferers with the best possible information on which species contribute to allergen exposure at a given time, phenological fieldwork is a promising approach. However, this method requires a considerable amount of time and precise knowledge of the regional flora (Kmenta *et al*., 2016). Phenological observations are an essential part of routine aerobiological research to understand regional characteristics, such as late flowering grasses that contribute to the extension of the grass pollen season (Dirr *et al*., 2023). Likewise, given the extensive cross-reactivity mediated by the major grass allergens (Groups 1 and 5), sensitization is usually detected by standard testing for grass extracts and constituents, and treatment should follow the Allergic Rhinitis and its Impact on Asthma (ARIA) and European Academy of Allergy and Clinical Immunology (EAACI) guidelines, including consideration of allergen immunotherapy for grasses (AIT) when indicated. We note that there is limited, species-specific clinical data for these taxa and recommend targeted aerobiological surveillance and regional clinical trials to refine risk assessments and provide public health guidance. Systematic aerobiological monitoring of these plants in conjunction with clinical studies on sensitization and symptom incidence is needed to increase the reliability of future assessments. There is a need to include policy relevance and emphasize the importance of integrating allergenic risk assessment into sustainable crop production and energy policy planning. In natural ecosystems and industrial environments, complete avoidance of allergens is not possible. Therefore, regular phenological observations are crucial for aerobiologists to better understand the vegetation and local conditions. Only in this way can we provide allergy sufferers with the most accurate information possible and help them to manage the pollen season with minimal impact (Dirr *et al.*, 2023).

The grass pollen season can be divided into several phases, each characterized by different plant species that contribute to the allergenic burden (Kmenta *et al.*, 2016). The concentration of grass pollen is higher in rural areas (Šikoparija *et al.*, 2006). The importance of the individual species varies depending on geographical and climatic conditions (Bastl *et al.*, 2021). Pollen concentration is recorded as the number of pollen grains m^{-3} and categorized as absent, low, moderate, high or very high (Table 1). In addition, the density of the different pollen types (trees, grasses and weeds) and their allergenic burden differ. Compared to trees and weeds, smaller amounts of grass pollen cause a much higher allergenic burden (Table 1).

Table 1. Pollen density ranges (grains/m^3) and categories of different pollen types: grasses, weeds and trees (according to Weber (1998))

Pollen rating scale	Grasses	Weeds	Trees	Likelihood of allergy sufferers who are allergic to these pollens may be experiencing symptoms of hay fever or asthma
Absent	0	0	0	No symptoms
Low	1 - 5	1 - 10	1 - 15	Only individuals extremely sensitive to these pollens
Moderate	6 - 20	11 - 50	16 - 90	Many individuals are sensitive to these pollens
High	21 - 200	51 - 500	91 – 1,500	Most individuals with any sensitivity to these pollens
Very high	> 200	> 500	> 1,500	Almost all individuals with any sensitivity at all to these pollens

Air temperature, precipitation (Rojo *et al.*, 2021), humidity, wind speed and direction (Schwartz, 2013), land use and land management (Menzel, 2019) have a strong influence on the amount of pollen released and pollen transport in the air. The concentration and composition of grass pollen is strongly influenced by the spatial distribution of the sources (Rojo *et al.*, 2020) Source distribution, in turn, is strongly influenced by land use (Haberle *et al.*, 2014) and changes in land use (Emberlin, 1994).

Due to their relatively late flowering time, the plant species described here could prolong the period of allergen exposure compared to others. Holzmüller and Jose (2012) consider *P. arundinacea* and *P. australis* to be the most aggressive invasive species among ornamental grasses. However, they also include *Miscanthus spp*. in this group. According to these authors, the rapid spread of these species can contribute to an increased pollen concentration in the area. The allergen burden from pollen of *P. arundinacea* (Luis *et al.*, 2017, Ramón *et al.*, 2017; Ramón *et al.*, 2019) and *P. australis* (Nestorović *et al.*, 2015) could be somewhat higher but is not critical. These species are characteristic of humid areas in rural and peri-urban areas where human exposure is lower.

Compared to current agricultural use, which consists mainly of arable land, meadows and grasslands, the large-scale cultivation of perennial grasses as second-generation energy crops could shift allergen exposure to the end of the growing season (August-October; Table 2) due to their later flowering time. This shift would likely reduce allergenic impact and mitigate the peak in June, when grass pollen concentrations are highest in Europe (Dirr *et al.*, 2023), with only a slight increase in exposure during late season when pollen concentrations naturally decrease and dissipate. In addition, the ability of these plants to suppress competing weed species from the second year of cultivation is of great importance. These weeds usually produce large amounts of pollen, so their suppression could help to reduce the overall allergenic burden.

Table 2. Summary of flowering times of second-generation perennial grass energy crops and estimated allergy burden for the South-Eastern European region

Energy crops	Crop longevity (years)	Flowering time (average)	The expected allergic burden	Estimated impact on production sustainability (relative to *Zea mays*)
Zea mays L. (first generation and reference crop)	1	6-10 weeks after sowing (depending on the hybrids used): June - July	Medium impact	-
Miscanthus × *giganteus* Greef et Deu.	15 - 20	End of September - October	Low impact	No impact
Arundo donax L.	12 - 15	End of June - September	Medium impact	Low
Phragmites australis (Cav.) Trin. ex Steudel	10 - 15	End of July - September	High impact	High
Phalaris arundinacea L.	8 - 10	May - July	High impact	High

Accordingly, from a clinical and public health perspective, the pollen of these plants can therefore contribute to allergic diseases such as hay fever and asthma, especially in rural populations and agricultural workers exposed during the flowering period. A structured and quantitative risk assessment that includes estimates of pollen density, duration of the flowering period, and overlap with other allergenic species would provide a more accurate basis for assessing health effects. Future studies should include systematic pollen monitoring and clinical investigations in different regions. The inclusion of allergenic risk assessment in the sustainability assessment of bioenergy production could help to ensure that the promotion of second-generation energy crops does not inadvertently increase the burden of allergic diseases.

Conclusions

Compared to the reference energy crop of the first generation (maize), only *P. arundinacea* flowers earlier and have a major influence on the expected allergy load. The other energy crops analyzed flower later (July-October) and, except for *P. australis*, have a relatively low impact on the expected allergy load. In this sense, the potential impact on the sustainability of growing *M. giganteus* and *A. donax* on larger areas can be considered minimal. Land use policy and planning for the cultivation of these two perennial energy grasses in peri-urban landscapes can be considered appropriate, sustainable and with low impact on potential allergy burden.

Authors' Contributions

Conceptualization: ŽSD; Resources: ŽSD, SMB, NSM and ASS; Writing-original draft: ŽSD, SMB, NSM and ASS; Writing-review and editing: ŽSD, NSM, ASS and VTM; Visualization: ŽSD, SMB and NSM; Supervision: ASS, VTM and NSM; Project administration: ŽSD, ASS and VTM.

All authors have read and agreed to the published version of the manuscript

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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