



Association of airborne particulate matter with pollen, fungal spores, and allergic symptoms in an arid urbanized area

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Abstract Studies focused on the seasonal distribution of pollen and spores in semiarid cities are scarce. At these sites, climate change potentiates the emission and transport of fine (PM₁₀) to ultrafine particles (PM_{2.5}), easily attached to pollen surfaces, causing allergen's release. This study examines the potential correlation of seasonal variations of pollen, fungal spores, PM₁₀, and meteorological parameters with allergic reactions of 150 people living in a Sonoran desert city. We collected PM₁₀, airborne pollen, and spores during a year. We also studied topsoil and road dust samples as potential PM-emission sources. We obtained dust-mineralogy, chemistry, and particle size attached to pollen by X-ray diffraction and scanning electron microscope. Results show that seasonal high

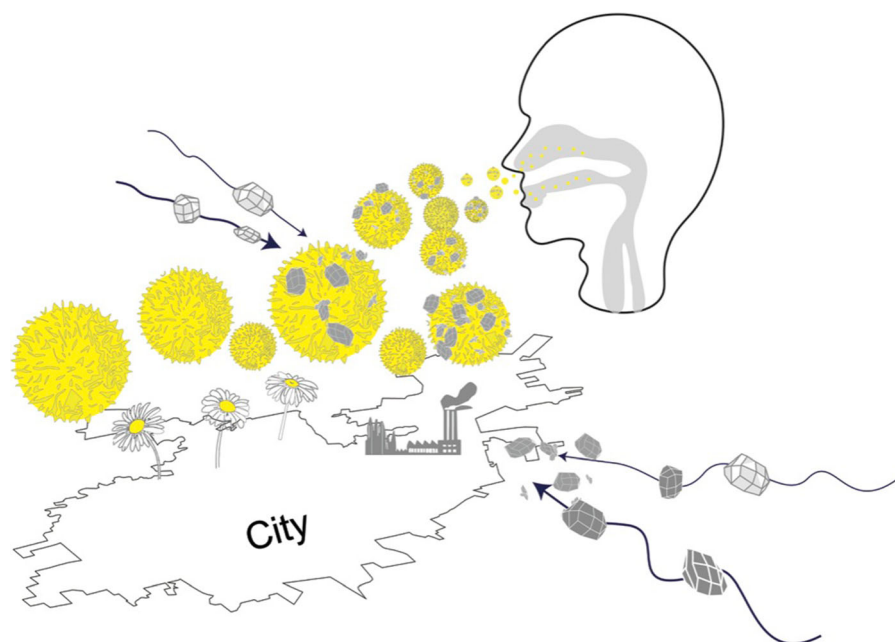
PM-loading in the urban atmosphere coincides with aeroallergens promoting micro- to nanoparticles' attachment to pollen's surface. A collapsed membrane was observed in several samples after individual grains show the following maximum wall coverage: Poaceae 28%, Asteraceae 40%, Chenopodiaceae-Amaranthaceae 29%, Fabaceae 18%. Most of the particles covering pollen's surface have a geogenic origin mixed with metals linked to traffic (bromide, chlorine, and antimony). Mineralogical, granulometric analysis, and main wind-direction show that two local soil-types are the main contributors to PM. A high frequency of positive sensitization to pollen with high particle loading was detected. These results suggest that climate-driven dust emissions may alter pollen and spore surfaces' physicochemical characteristics with the further consequences in their allergenic potential.

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Graphic abstract



Keywords Allergy · Pollen · Particulate matter · Fungal spores · Climate · Desert dust

Introduction

The contribution to global dust emissions from the deserts of southwestern North America has been historically underestimated (Urban et al. 2018). The hydrologic and geomorphic evolution of the Sonoran desert in Northwestern Mexico, and Mojave desert in Arizona, USA, produce landscapes of basin-alluvial settings representing small dust-source areas. This area has been affected by several climate changes in the last years due to global warming (Gay-García et al. 2015; IPCC 2018). Navarro-Estupiñan et al. (2018) reported an enhancement of mean temperatures of around 2 °C for the last 30 years. This increase in temperatures has produced several impacts in urban areas located within the desert ecosystems. An example is Hermosillo city, in Sonora, México, which records an increment of hot waves, heat urban island (Mercado and Marincic 2017), and dust emissions for the last ten years (Moreno-Rodríguez et al. 2015; CCA 2014). Dust emissions in the area are not fully

understood and commonly linked to (1) extreme meteorological events and (2) the erosion of the surrounding geological landscape affecting the city's flooding patterns. Flooded areas accumulate sediments and fine particulate matter by surface runoff, and such material is further suspended to the urban atmosphere (Moreno-Rodríguez et al. 2015). Airborne dust in urban areas could have different sources: (1) erosion of fine-grained soils from surrounding geological areas, (2) vehicle exhaust pollutants, (3) erosion of paved roads following surface runoff, and (4) construction and industry. The crustal sources contribute an average of ~ 40% to 60% of PM_{10} and ~ 5% to 20% of $PM_{2.5}$ in urban areas where Air Quality Standards have been exceeded (Watson & Chow 2000). This geological contribution to ambient measurements is often overestimated from fugitive dust sources (Watson & Chow 2000), but only particles with a small aerodynamic diameter ($< 10 \mu m$ or PM_{10}) have long atmospheric residence time, becoming long-term suspended (Harrison, 2004). Particulate matter (PM) is a mixture of solid and liquid particles found in the air from diverse natural and anthropogenic sources (WHO 2013). This group includes the primary biogenic aerosols, such as pollen (Calvo et al. 2013). PM is among the most

harmful atmospheric pollutants in highly populated areas (Perrone et al. 2018), and projections foresee outdoor PM is likely to cause even more severe health effects in the future unless more stringent policies are adopted (EEA 2016).

Particulate emissions from paved roads are complex mixtures derived from different sources (Karaniou et al. 2014). The particles deposited on the road surface originate from motor vehicles and include mixtures of metals from the brake, tires wear, and exhaust emissions. Such settled dust and its suspension by vehicle turbulence or wind affect air quality (Candeias et al. 2020). Several toxic pollutants embedded in road dust, such as metals and polycyclic aromatic hydrocarbons, PAHs (Rogge et al. 1993), have been associated with an increased risk of adverse effects on human health (Lee and Dong 2011). A recently published study (Karagulian et al. 2015) shows traffic (25%), combustion and agriculture (22%), domestic fuel burning (20%), natural dust and salt (18%), and industrial activities (15%) as the primary sources of particulate matter contributing to cities' air pollution around Europe. However, there are significant differences between various regions of the world.

Along with particulate matter, dust suspended over urban areas also contains several biological particles such as viruses, bacteria, pollen, and fungal spores (Sofiev and Bergmann 2013). The last is associated with allergic and air pollution-related morbidity and mortality. Allergenic pollen and spore particles affect around 30% of the world's population (Terán et al. 2009). Anemophilous pollens (wind-pollinated) dominate the pollen rain of any area, representing major seasonal carriers of allergens (Shahali et al. 2009). Overall, pollen carried by the wind can travel over very long distances and interact with numerous biological and chemical agents present in the atmosphere.

Several studies also proved that pollutants attached to the pollen grains' surface could modify these antigen-carrying agents' morphology and alter their allergenic potential (Okuyama et al. 2007). Such processes may cause higher pollen allergenicity deteriorating human health, suggesting that air pollution impacts the prevalence and symptom severity of pollen allergies (Bédard et al. 2020; Armentia et al. 2002). Particles attached to pollen grains will likely act as adjuvants to modify the microenvironment in

which allergens are released from pollen and facilitate the access of allergens to antigen-presenting cells, enhancing inflammatory processes (Traidl-Hoffmann et al. 2009). Furthermore, air pollutants damage the membrane and cell wall of pollen grains, which, in turn, maximizes the release of pollen materials. A consequence of the release of allergen molecules into aerosol is that the molecules are free to interact with other types of airborne particles, such as diesel exhaust particles, associated with air pollution. (Chehregani et al. 2004). The degree of these reactions may be dependent on the physical characteristics of the PM, and the toxicity of its chemical composition (Berger et al. 2020; Zhang et al. 2019; Ribeiro et al. 2015) as well the urban air could worsen the allergy symptoms of the urban citizen (Bos-Chano et al. 2011).

Pollen identification in Mexico's urban areas is restricted to Mexico City and its suburbs (Calderón-Ezquerro et al. 2018; Calderón-Ezquerro et al. 2015). Some studies in northern Mexico include Monterrey (Rocha-Estrada et al. 2009, 2013), Baja California (De la Fuente et al. 2013; Ahumada-Valdez et al. 2006; Quintero et al. 2006), and Sonora (Ortega-Rosas et al. 2019). Nevertheless, all those studies only publish pollen concentration on air during different periods, few studies show the fungal spores concentration (Ortega-Rosas et al. 2019; Moreno-Sarmiento et al. 2016; Rocha-Estrada et al. 2013) and, to our knowledge, there is no published research in Mexico related to particles attached to pollen wall.

In urban areas, people are continuously exposed to this kind of airborne and particulate matter. However, most studies focus either on the characterization of aerobiological (e.g., Calderón-Ezquerro et al. 2018) or inorganic particulate matter (e.g., Meza-Figueroa et al. 2018, 2016), and few published works address the effect of both (Bagheri et al. 2020; Ribeiro et al. 2015; Sénéchal et al. 2015; Duque et al. 2013). Therefore, characterizing the time distribution and physicochemical features of particulate matter and aeroallergens is essential for developing appropriate mitigation strategies to protect human health in developing countries. This study describes (1) daily pollen and spore concentrations during 2018 from Hermosillo, northwestern Mexico; (2) particulate matter concentrations during the year and potential pollution sources, (3) characterization of particulate matter attached to the surface of airborne pollen grains, and (4) incidence of allergy in the population.

Materials and Methods

Study region, geological, and environmental settings

Hermosillo (29°05.02'N, 110°57.56'W) locates in the central Sonora region, within the Southern Basin and Range province (Henry and Aranda-Gómez 1992), between the Gulf of California and the Sierra Madre Occidental (Fig. 1a). This area's geomorphology presents valleys, hills, and mountains aligned NNW-SSE, where peaks of up to almost 700 m high can occur. Hermosillo's geology (Fig. 1b) is generally composed of Paleocene igneous-metamorphic crystalline basement, with granites and granodiorites of continental arc-related cropping out in the mountains located on the eastern edge of the city (Rodríguez-Castañeda 1981). Calco-silicate hornfels and marbles host these units. Paleozoic marine rocks occur at a few kilometers east of the city, where cement plant companies exploit the rocks. Basement lithological units were faulted and exhumed during a distensive event in the Miocene (Calmus et al. 2015), to be later covered by poorly consolidated detrital deposits and volcanic rocks, which crop out in hills to the west, derived to the end of the volcanic arc and the development of the Gulf of California opening (Vidal-Solano et al. 2005). This last cortical extension process is responsible for strong denudation in the region, toward the west, from 12 May to today. The geographic area is part of the intermontane Basin and Range Province in the western USA and Northwestern Mexico, forming the North American deserts (Chihuahua, Mojave, and Sonora), which are the most significant dust sources for the southwest of USA (Carmona et al. 2015; Rivera-Rivera et al. 2010; Reynolds et al. 2007).

The study area is located in the Sonora desert, harboring high biodiversity (Molina-Freaner and Van Devender 2000). Our aerobiological monitoring station is located in the northern part of the city, at the Administration building's roof at the Sonora State University (Fig. 1), near a high-traffic road during rush hours, and residential areas around it. The climate in Hermosillo is a transition of two types (García 2004): very dry and very warm BW(h'), and very dry and semi-warm (BW_h). The mean annual temperature equals 25.1 °C. December is the coldest month (mean monthly temperature 16.8 °C), and July is the warmest

month (mean monthly temperature 32.6 °C). The mean annual precipitation is 393 mm, with a summer rains regime due to the North American monsoon system (Gobierno Municipal de Hermosillo 2003). Five soil types occur in the area: calcisols, cambisols, phaeozems, regosols, and vertisols (INEGI(), 2014)). Figure 1c shows that local topsoils have 25–50% clay-silt, with the phaeozems and cambisols soils containing the highest amount of lime-clay with an approximate amount of 50% when compared to the other soils in the area. Together, both soil types are the most abundant in the area. The wind rose shows an annual main northeastward direction with a 4 to 6 m s⁻¹ wind speed, and a second dominant westward direction (Fig. 1d, e). Accordingly, there is a possible natural contribution from phaeozems-cambisols soil reservoirs to particulate matter in the urban atmosphere. Vegetation and land-use change types within the Municipality of Hermosillo are desert scrub (74.75%), agriculture (14.64%), forest (0.06%), grassland (3.03%), and others (7.52%) (INEGI 2014). Sonoran desert scrub communities are the principal source of pollen in Hermosillo's atmosphere (Ortega-Rosas et al. 2019). Dominant taxa are legume trees *Parkinsonia*, *Olneya*, *Acacia*, *Prosopis*, cacti (Cactaceae), and many different grasses (Poaceae). Hermosillo is mostly in flat terrain flanked by a mountain range to the north and east. This mountain range determines the westward wind direction and, consequently, the behavior of airborne particles. However, there are two dominant winds, northeastward from the Sonora coast (SW) and westward from the Sierra Madre Occidental (W). Dominant winds from SW have an average annual speed of 1.2 m s⁻¹, with mean annual calms of 83%.

Sampling of airborne pollen and spore

We applied a standard sampling method proposed by the Red Española de Aerobiología (Spanish Aerobiology Network, REA) (Galan et al. 2007) and used by the Red Mexicana de Aerobiología (REMA, Mexican Aerobiology Network). We sampled atmospheric pollen and spores daily from January to December of 2018 using a Hirst (1952) type volumetric spore-trap (Burkard; <https://www.burkard.co.uk>). This Hirst spore-trap was located ~ 20 m above ground level on an exposed flat roof at the Sonora State University

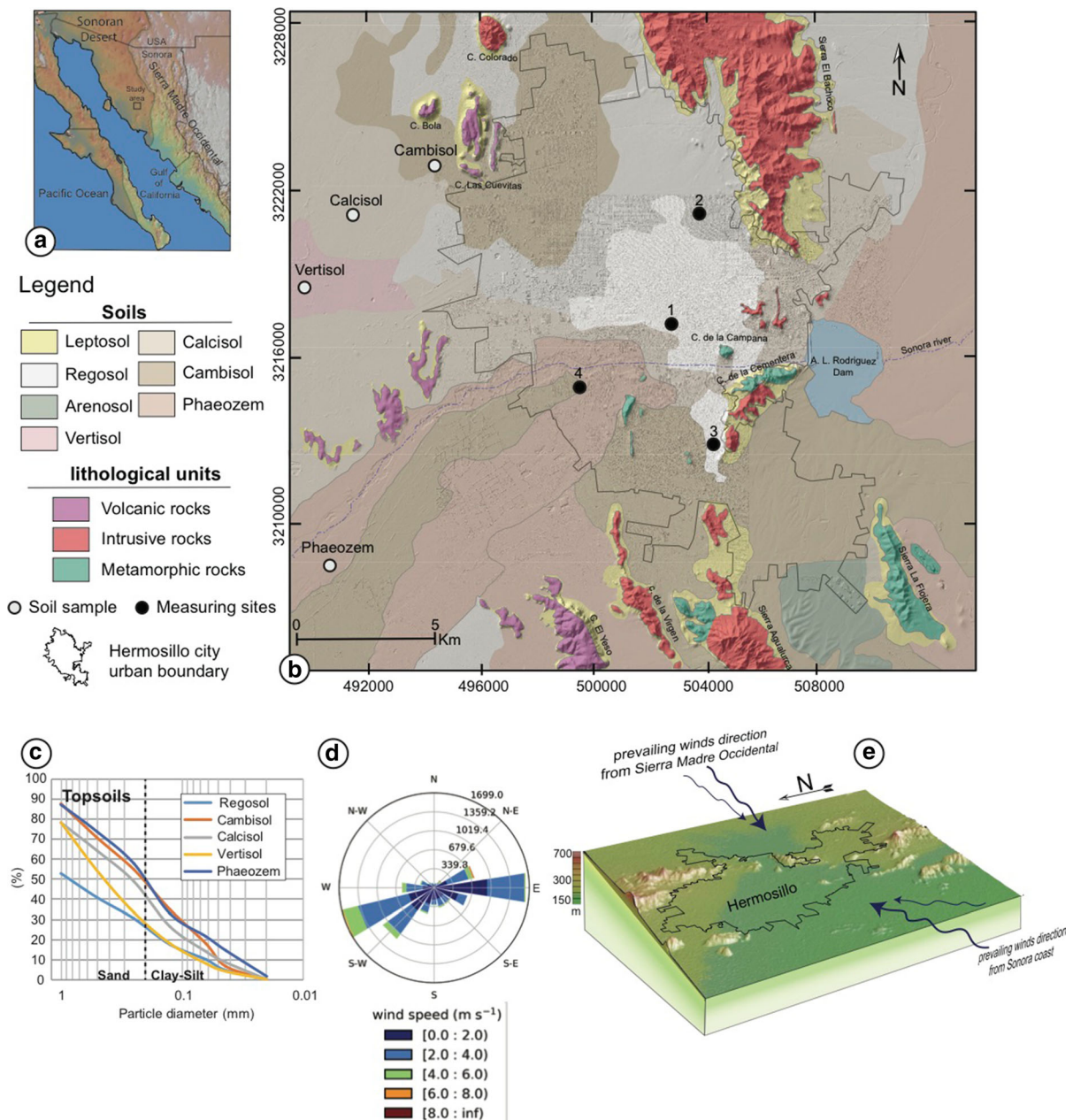


Fig. 1 Location of the study area. **a** Map of the topography of NW Mexico; **b** Simplified lithological and soil map of Hermosillo region and distribution of sampling locations; (1) Meteorological station RUOA; (2) Pollen and spore sampler; (3)

and 4) PM₁₀ measuring sites; (C) Grain-size distribution of topsoils; (D) Wind rose for 2018; (E) DEM of Hermosillo region showing highest speed wind direction

(Fig. 1b). We adjusted the Hirst spore-trap to aspirate 10 L air min⁻¹ and trap pollen and spores on a Melinex tape coated with an adhesive (silicone fluid). We counted pollen and spores trapped on daily Melinex tape segments using an optical microscope with four

longitudinal sweeps per slide and 400 × magnification. Therefore, we obtained daily concentrations of pollen and spores expressed as grains m⁻³ air (Galán et al. 2007).

Particulate matter (PM) and meteorological data

We measured PM₁₀ levels at four sites within the urbanized area, according to Fig. 1b: (1) RUOA atmospheric station, (2) Sonora State University or UES, (3) PEMCA station in the southern side of the city (Villa de Seris), and (4) PEMCA station in the western side of the city (Villa Bonita). We used saturation frm-OMNItm Ambient Air samplers (BGI, USA) with a 5 L min⁻¹ miniPM inlet for PM₁₀ sample collection. We kept a constant volumetric flow of 5 L min⁻¹ at the equipment inlet using calibrated temperature, flow sensors, and pressure. We collected suspended particles smaller than 10 µm on quartz fiber filters for subsequent gravimetric analysis. Pre- and post-conditioning and weighing of filters were performed under standardized laboratory conditions. We used the initial and final weight of the filter and volume of air suctioned (24 h) for the estimation of PM₁₀ in µg m⁻³. We also obtained meteorological data from the monitoring station located at a nearby airport. Saturation frm-OMNItm Ambient Air samplers have been successfully used in environmental studies by Chen et al. (2011) and Sharma et al. (2012).

The RUOA (Red Universitaria de Observatorios Atmosféricos) is a research platform that generates information about climate change, air pollution (e.g., particulate and greenhouse gases), and water resources. The network has 15 regional atmospheric stations located in different regions, cities, and protected natural areas, around Mexico. In Hermosillo city, the station locates at the ERNO (Estación Regional del Noroeste) observatory (Fig. 1b). The FH62C14 Continuous Ambient Particulate Monitor by ThermoFisher Scientific corporation, installed in RUOA-ERNO station, measures the mass concentration of suspended particulate matter ambient air and provides real-time measurements. PM₁₀, expressed in µg m⁻³, was sampled in stable temperature, pressure, and relative humidity condition (automatic compensation), with 0.6 L min⁻¹ constant volumetric flow rate. Instrument returns 24 h PM₁₀ measurement, with a concentration range 0 to 1000 µg m⁻³, the detection limit of < 1 µg m⁻³ in 24 h time resolution, and accuracy of ± 5%. Meteorological data, like temperature, pressure, relative humidity, wind speed, and direction, were obtained from a sensor situated in the RUOA-ERNO station. We performed a statistical

analysis with a Python programming language version 3.7.

Mineralogy of local soils and road dust

Mineralogy of soils and road dust was identified with an X-ray powder diffraction (XRPD) by a Bruker D8 Advance diffractometer with a Cu-radiation source. Equipment was operated at 40 kV/35 mA at room temperature and with a 2theta scan range from 6° to 77°. We identified the mineralogy with a Diffrac-plus EVA software and the International Centre for Diffraction Data (ICDD) database.

Scanning Electron Microscope analyses of pollen and attached PM

We measured the morphology and particles' size in pollen surfaces with a ThermoFisher Scientific Phenom Pro Scanning Electron Microscope SEM. We mounted samples in carbon tape, and EDS analyses were obtained under 10 kV accelerating voltage. EDS analyzed semi-quantitative chemical composition for individual particles attached to the pollen surface. Image processing and analysis using Image J software (Abramoff et al. 2012) estimated the particle percentages covering the pollen wall.

Allergenic data from the Secretariat of Health

Particular cases of patients attended in Hermosillo, Sonora, related to pollen and spore allergies during 2018 were provided by “General Hospital Zone 2 Hermosillo” of the Mexican Institute of Social Security (IMSS). Data were provided directly by a specialist in allergy who records the cases of allergies inside the city and performs several tests of sensitization to pollen and fungal spores on Hermosillo's population. Allergic sensitization to pollen and spores is usually documented by stimulating specific immunoglobulin E (IgE) concentrations, either with skin tests or with quantification specific serum IgE. Monthly data during 2018 of patients having positive allergic sensitization to each kind of pollen and spores were provided. We compared monthly values of

pollen and spore concentrations with the monthly cases of allergic sensitization people.

Results

Airborne pollen and spore concentration within the city during 2018

We identified 34 pollen taxa and 15 different fungal spores (Table 1) during 2018 in Hermosillo (Fig. 2). The most crucial pollen taxon is Poaceae, accounting for 40% of the total annual pollen count, followed by Nyctaginaceae (15%), *Ambrosia* spp. (10%), Chenopodiaceae-Amaranthaceae (10%), Urticaceae (8%), Fabaceae, and Cupressaceae (4%, not shown in Fig. 2). These pollen taxa differ in their degree of allergenicity. For fungal spores (Table 1), the essential taxon is *Cladosporium*, with around 51% of total annual spore count, followed by Diatrypaceae (14%), *Alternaria* (12%), the Smuts complex (10%), Basidiospore (11%), and Ascospora (Ascomycetes, 7%).

The Annual Pollen Integral (API_n) is defined as the amount of recorded airborne pollen during a year (Sofiev and Bergmann 2013; Galán et al. 2017). API_n for Hermosillo was 7899 pollen day m⁻³, whereas the Annual Spore Integral (ASI_n) was 58,940 spore day m⁻³. Major allergenic pollen taxa had different concentration trends during 2018 (Table 2, Fig. 2). Poaceae was present through the year, but concentration levels increased only during two seasons: in spring (March) and summer-fall (September to November), raising daily counts ~ 80–100 pollen day m⁻³. *Ambrosia* pollen first flowering occurs from February to March, with a daily concentration of 100–120 pollen day m⁻³. Urticaceae pollen was present through the year, but concentration levels increase only from June–September when daily concentration levels reached 50 pollen day m⁻³. Nyctaginaceae, which is also present during all year, was more abundant from August–November, reaching daily concentration levels of 50 pollen day m⁻³ (Fig. 2). Chenopodiaceae-Amaranthaceae pollen is also prevalent in this desert city, being present mostly during 2018 with higher concentration values during March (100 pollen day m⁻³) and August–November, reaching 20 pollen day m⁻³. Finally, Fabaceae pollen appeared at several periods of the year but became more critical during spring–summer (from March–

July) with daily concentrations ~ 20 pollen day m⁻³. Fabaceae also reached high concentrations (10 pollen day m⁻³) in February (Fig. 2).

Fungal spore taxa had a more homogeneous seasonal variation in concentration during 2018 than pollen taxa (Fig. 2). The most crucial fungal spore is *Cladosporium*, which was present during the year with increased concentrations from June to October (800 to 1,200 spores day m⁻³) and February–March (Fig. 2). *Alternaria* was the second major fungal spore taxa with high concentrations all year, but concentrations peaking from June to October, reaching daily concentrations of around 150 spores day m⁻³. Ascospore was also present all year, with higher concentrations from June to October and daily concentrations around 100 spores day m⁻³. Smuts were also present all the year with a small increase during summer-fall, reaching daily concentrations of 100 to 150 spore day m⁻³. Basidiospores were important only during one period from August to November, but their concentrations were relatively low (15 to 30 spore day m⁻³). Diatrypaceae spores present a peak at June and July with high concentrations (800 spores day m⁻³), but they were absent during the rest of the year (Fig. 2).

The presence of pollen and spores at the atmosphere in Hermosillo was discontinuous through 2018. Seasonal patterns of their concentration vary considerably among taxa (Fig. 3). For pollen, we documented two peaks: one from March–April, with concentrations around 1200 pollen day m⁻³, and from September–November, with higher concentrations ranging from 1000 to 1500 pollen day m⁻³ (Fig. 3).

The fungal spore's seasonal behavior attained a single critical period (from June to October) of very high concentrations ranging from 8000 to 12,000 spore day m⁻³. These fungal spore concentrations far exceed those of pollen concentration (Fig. 3). In winter-spring (from December to April), fungal spore concentration levels remained low (Fig. 3).

Allergic reaction of the Hermosillo population to airborne pollen and spores

Several performance tests were applied to 151 persons during 2018 at Hermosillo related to sensitization of different spores, and pollen types (Table 3) reveal a high frequency of positive sensitization of people to those aeroallergens (Fig. 3). Of 151 people who attend

Table 1 Different species of pollen and fungal spores allergenic-tested on Hermosillo population

Pollen	Pollen type	Fungal spores	Spores type
<i>Amaranthus palmeri</i>	Cheno-Ams	<i>Aspergillus fumigatus</i>	Aspergillus
<i>Ambrosia elditor</i>	Ambrosia	<i>Aspergillus niger</i>	Aspergillus
<i>Populus alba</i>	Salicaceae	<i>Alternaria</i>	Alternaria
<i>Populus sargentii</i>	Salicaceae	<i>Candida albicans</i>	Smuts
<i>Artemisa ludovicina</i>	Asteraceae	<i>Fusarium</i>	Ascomycetes
<i>Cynodon dactylon</i>	Poaceae	<i>Penicillium</i>	Ascomycetes
<i>Lolium perenne</i>	Poaceae	<i>Apsidia</i>	Zygomycetes
<i>Fraxinus latifolia</i>	Rosaceae	<i>Mucor</i>	Zygomycetes
<i>Helianthus annuus</i>	Asteraceae		
<i>Hoculus alapensis</i>	Poaceae		
<i>Zea mays</i>	Poaceae		
<i>Prosopis</i>	Prosopis		
<i>Phleum pretenses</i>	Poaceae		
<i>Phleum crispus</i>	Poaceae		
<i>Rumex mexicanus</i>	Polygonaceae		
<i>Schinus molle</i>	Anacardaceae		
<i>Plantago major</i>	Plantaginaceae		
<i>Plantago lanceolata</i>	Plantaginaceae		
<i>Ambrosia trifida</i>	Ambrosia		
<i>Ambrosia</i>	Ambrosia		
<i>Artemisa</i>	Artemisa		
<i>Artemisa vulgaris</i>	Artemisa		
<i>Artemisa annua</i>	Artemisa		
<i>Salsola kali</i>	Cheno-Ams		
<i>Salsola pestifer</i>	Cheno-Ams		
<i>Ligustrum vulgare</i>	Oleaceae		
<i>Quercus albus</i>	Quercus		
<i>Quercus rubra</i>	Quercus		
<i>Plantanus recemsa</i>	Platanaceae		
<i>Chenopodium lbum</i>	Cheno-Ams		
<i>Salix nigra</i>	Salicaceae		
<i>Pinus palustris</i>	Pinus		
<i>Juniperus ashei</i>	Juniperus		
<i>Juniperus communis</i>	Juniperus		
<i>Eucaliptus</i>	Eucaliptus		
<i>Olea europaea</i>	Oleaceae		
<i>Alnus</i>	Alnus		

the Public Health System (IMSS) hospital to be treated for allergic diseases, 62% were female and 38% were male. The seasonal distribution of allergenic-reactions by the city's population reveals two critical periods: during spring (March to April) and summer-fall (September–October). Several cases of aeroallergen reactions were registered during winter (December

and February, Fig. 3). Summarizing, the local population reacts more to five different pollen types: Poaceae (44 cases), Asteraceae (34 cases), Chenopodiaceae-Amaranthaceae (29 cases), *Ambrosia* (26 cases), and Fabaceae (18 cases), whereas for spores, most important types were: Zygomycetes (35 cases), *Alternaria* (31 cases), Ascomycetes (30 cases),

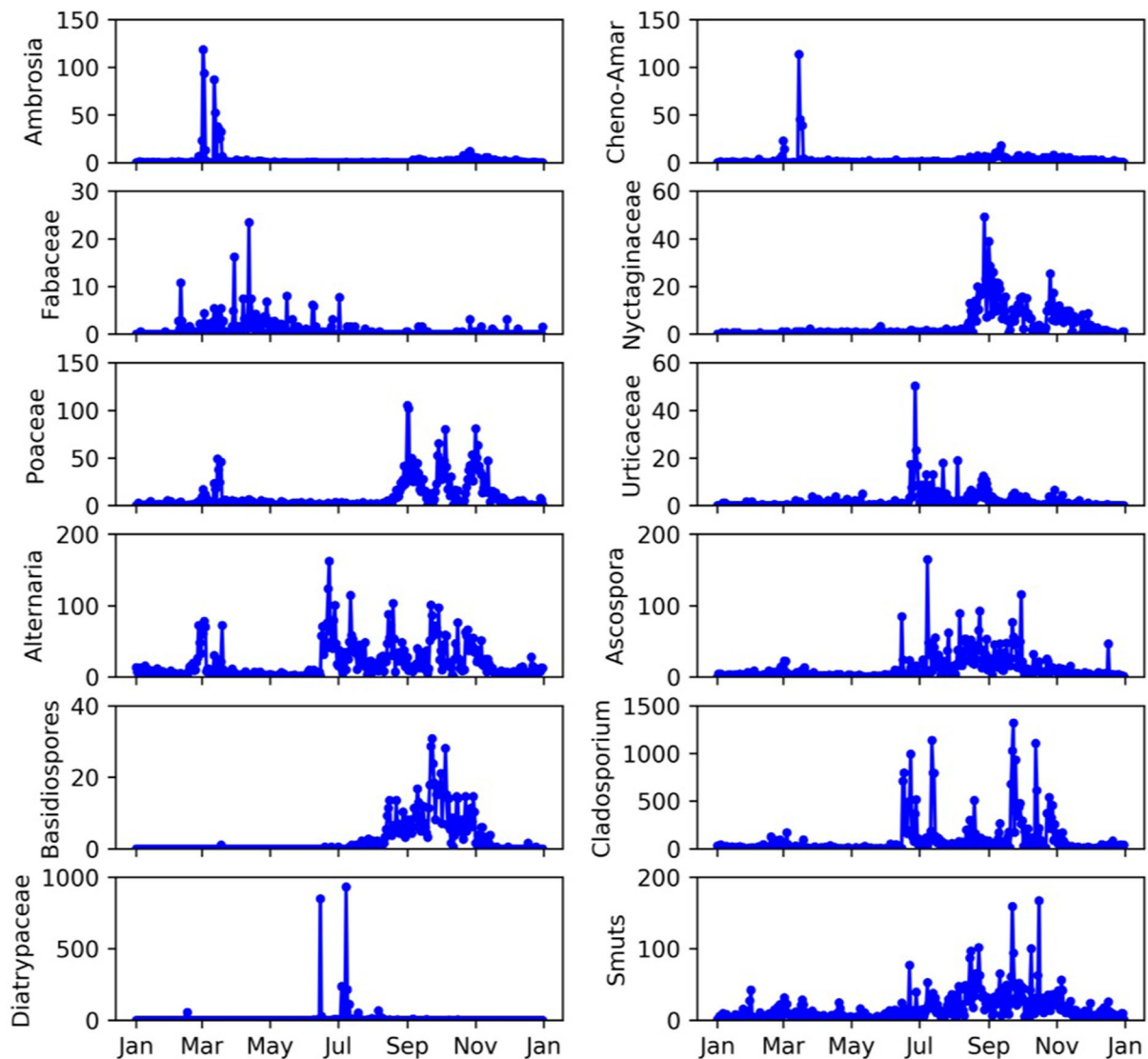


Fig. 2 Most important aeroallergenic pollen and fungal spores at Hermosillo city during 2018, expressed as total daily pollen grains.m⁻³

Cladosporium (28 cases), and Smuts (27 cases). The test data reveal then that Poaceae and Asteraceae pollen represents 50% of the Hermosillo population's total positive sensitization reaction, whereas fungal spores of Zygomycetes and *Alternaria* account for 55% of total positive sensitization of the population. Supplementary Material (S3) provides a more detailed description of the sensitization test.

Particulate matter concentration, mineral dust, and anthropic pollutants in airborne pollen and spores.

We measured PM₁₀ concentrations and temporal distribution in four sampling stations for one year (Fig. 4b). The highest value occurs in December (146 µg m⁻³) with additional peaks in mid-January, March, and April. High PM₁₀ values in the early months are related to lower humidity, whereas peaks in October–December occur with low temperature and low humidity (Fig. 4a). The maximum permissible

Table 2 Aeroallergens diversity and concentrations (expressed as total pollen grains.m⁻³) recorded during 2018 at Hermosillo city

Pollen	Concentration pollen/ m ³ air	% of annual sum	Fungal spores	Concentration spores/ m ³ air	% of annual sum
<i>Acacia</i>	12	0.16	<i>Alternaria</i>	6973	11.83
Agavaceae	39	0.49	<i>Arthrimum</i>	221	0.37
<i>Alnus</i>	15	0.18	Ascospora	4062	6.89
Chenopodiaceae- Amaranthaceae	798	10.11	Basidiospores	2438	4.14
<i>Ambrosia</i>	789	9.98	<i>Bipolaris</i>	738	1.25
<i>Artemisia</i>	16	0.21	<i>Boerlagella</i>	74	0.13
Asteraceae	60	0.77	<i>Cladosporium</i>	29,960	50.83
Burseraceae	104	1.32	Diatrypaceae	7942	13.48
Cactaceae	19	0.25	Myxomicetes	463	0.79
Caesalpinioideae	33	0.42	<i>Periconia</i>	102	0.17
<i>Celtis</i>	3	0.04	Pithomyces	56	0.10
Cruciferae	30	0.38	Smuts	5767	9.78
Cupressaceae	280	3.54	<i>Spegazzinia</i>	15	0.02
Euphorbiaceae	30	0.38	<i>Sporormiella</i>	37	0.06
Fabaceae	29	0.36	<i>Torula</i>	91	0.15
Iridiaceae	5	0.06			
Liliaceae	3	0.03			
Lobeliaceae	138	1.74			
Mimosaceae	1	0.01			
Myrtaceae	28	0.36			
Nyctaginaceae	1166	14.76			
<i>Parkinsonia</i>	122	1.54			
<i>Pinus</i>	21	0.26			
Poaceae	3093	39.16			
Potamogetonaceae	2	0.03			
<i>Prosopis</i>	77	0.97			
<i>Quercus</i>	125	1.58			
Rubiaceae	37	0.47			
Scrophulariaceae					
Solanaceae	26				
117	0.33				
1.48					
<i>Tidestromia</i>	26	0.34			
Ulmaceae	14	0.18			
Urticaceae	597	7.56			
Zygophyllaceae	43	0.55			
Total annual	7899	100%		58,940	100%

level (MPL) for PM₁₀, according to Mexican legislation, is 40 µg m⁻³ (annual). The mean value for PM₁₀ collected in 2018 is 46.03 µg m⁻³, slightly exceeding

the MPL. The maximum value is 518.65 µg m⁻³, and the minimum value is 1.53 µg m⁻³, with a standard deviation of 7.94 (Table 4). The implication of such

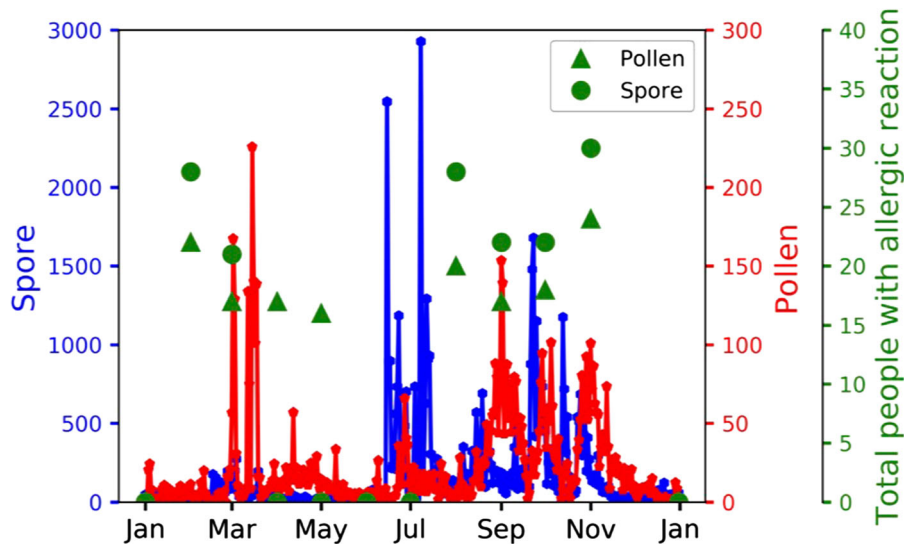


Fig. 3 Annual distribution of pollen and fungal spores in the study site, including total people with allergic reaction

Table 3 Total cases of sensitization patients to most important allergenic pollen and fungal spores at Hermosillo city

Pollen/Fungal spores	Total cases	Percentages (%)
Poaceae	44	29.1
Asteraceae	34	22.5
Chenopodiaceae-Amaranthaceae	29	19.2
Ambrosia	26	17.2
Fabaceae	18	11.9
Zygomycetes	35	23.2
Alternaria	31	20.5
Ascomycetes	30	19.9
Cladosporium	28	18.5
Smuts	27	17.8

PM₁₀ annual concentrations is a loading of fine particles in the urban atmosphere during almost the entire year (Fig. 4b). Monthly variation in PM₁₀ (Table 4) shows that January ($63.7 \mu\text{g m}^{-3}$) > December ($61.6 \mu\text{g m}^{-3}$) > April ($60 \mu\text{g m}^{-3}$) > March ($51.1 \mu\text{g m}^{-3}$) > November ($48.9 \mu\text{g m}^{-3}$). All these values are exceeding the MPL for México. Pollen is, therefore, continuously exposed to such inorganic particles that are subsequently adhered to its surface.

The most crucial pollen taxa with allergenic potential, such as Poaceae, Chenopodiaceae-Amaranthaceae, Asteraceae, and Fabaceae, record several micro- to nanoparticles attached to his pollen wall (Fig. 5). One pollen grain can contain variable percentages of fine particles attached to his wall

surface. Maximum surface coverage % is reported as following: Poaceae (28), Asteraceae (40%), Chenopodiaceae-Amaranthaceae (29%), and Fabaceae (18%). Some pollen types, such as Poaceae, show a collapsed membrane after excessive particle loading (see Fig. 5), whereas other pollen types with external equinate morphology such as Asteraceae can attach more fine particles. Other pollen grains such as Fabaceae (*Parkinsonia*) have external reticulate morphology attaching more ultrafine particles (see Fig. 5). We provide a more detailed description of the measured particle size in Supplementary Material (S1 and S2).

Based on the two peaks in total airborne pollen and spore concentrations during the year (spring and summer-fall), and taking into account the data

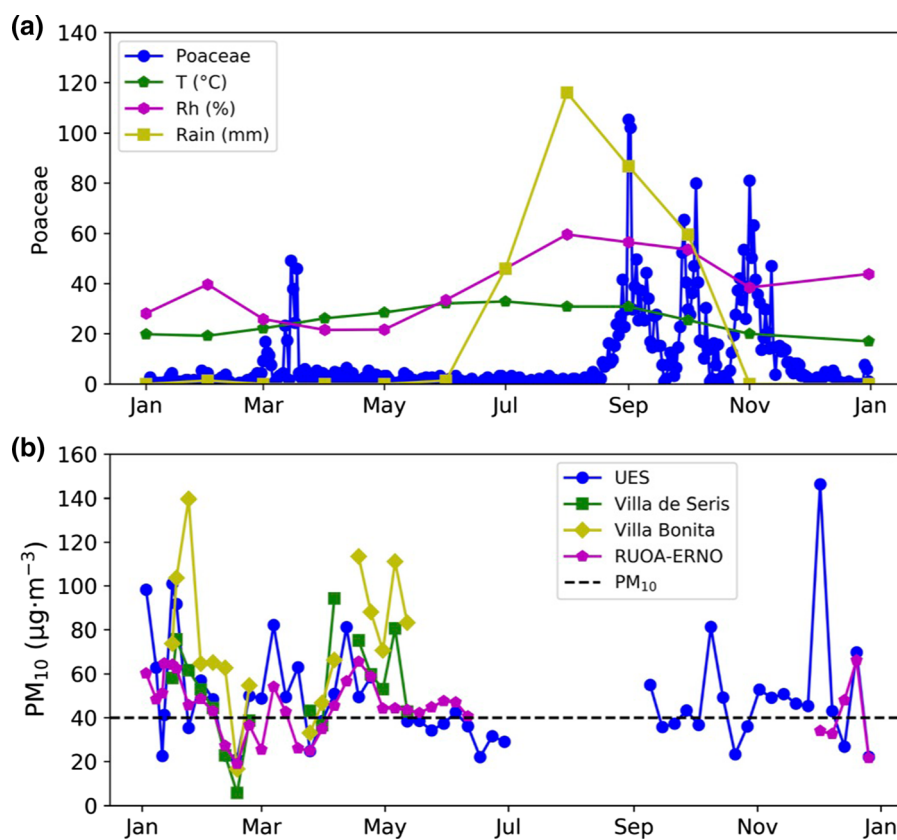


Fig. 4 **a** Poaceae pollen distribution (concentration expressed as total daily pollen grains.m⁻³) and comparison with relative humidity (%), temperature (°C), and precipitation (mm). **b** PM₁₀

monthly distribution in four monitoring stations. The dotted black line indicates the maximum permissible values of PM₁₀ according to Mexican standards

provided by IMSS about the sensitization test to pollen and spores on population, we chose samples from airborne particles of those periods to characterize his composition at the SEM. EDS spectra for attached particles to Poaceae pollen collected during spring are shown in Fig. 6. Crystalline inorganic particles in sizes smaller than 3 μm were detected. Most particles contain Al, Si, O, and major elements such as K, Ca, Na, and Mg, which are of possible geogenic origin (aluminosilicates). XRD did not identify mineralogy in the pollen surface because of the small amount of the collected sample. Bromide (Br), chlorine (Cl), and antimony (Sb) were detected, possibly as chemical pollutants linked to traffic sources (Fig. 6). Supplementary Material S1 shows agglomerates of particles smaller than 1 μm. Such chemical pollutants are relevant because it might facilitate the release of pollen allergens, with the modification of the allergenic potential (Sedghy et al. 2018). Most studied

patients in this study show sensitization to inhaled allergens such as Poaceae. The inorganic particulate loading in the Poaceae surface varies from 3.94% to 28.12%, and many of the detected particles are ultrafine and likely related to a mixing origin (anthropic and geogenic).

Discussion

Concentrations of airborne particles at Hermosillo city have an inter- and intra-annual variation. A previous study during 2016 for Hermosillo shows an APIn of 16,243 pollen day m⁻³ (Ortega-Rosas et al. 2019), whereas for this study, the 2018-year has a lower APIn with 7,899 pollen day m⁻³. This recorded value is within the range reported for arid zones where ASIn values range from 3,500 to 34,000 pollen day m⁻³ (Rocha-Estrada et al. 2013). While for spores, the

Table 4 Statistical monthly variation of spore, pollen, PM₁₀, and meteorological parameters, such as temperature and relative humidity

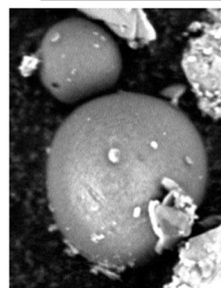
	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec
<i>Spore (counting)</i>												
Min	12.9	8.1	12.4	4.8	3.7	7	27.6	67.8	55.9	23.1	11.3	18.9
Max	66.4	197.1	274.3	42.6	46.4	2542.4	2926.9	690.9	1679.5	1175.2	295.6	122.1
Mean	32.1	58.1	61.4	17.1	12.6	337.6	370	221.6	395	311.2	72.8	43.5
SD	13.9	53.1	64.9	9.1	8.4	525.3	572	138.3	417.1	253.8	64.3	22.5
SE	2.4	10	11.6	1.6	1.5	95.9	102.7	24.8	76.1	45.5	11.7	4
<i>Pollen (counting)</i>												
Min	0	0	2.1	6.4	1.1	0.5	1.6	1.6	2.1	2.1	7.5	0
Max	24.3	21.1	225.7	56.9	33.4	65.8	24.3	88	153.3	101.5	101	15.1
Mean	5.7	5.7	44.8	16.7	7.3	12.3	10.6	26.3	52.5	37.9	33.6	5.2
SD	5.3	6.1	61.2	9.2	6.1	14.9	6	23.7	35.1	26.7	24.6	4
SE	1	1.1	11	1.6	1.1	2.7	1.1	4.2	6.4	4.8	4.5	0.7
<i>PM₁₀ (μg m⁻³)</i>												
Min	22.5	21.1	24.8	49.4	34.2	22	–	–	35.7	23.3	45.4	22.1
Max	101	50	82.2	81.2	38.6	42.5	–	–	55	81.3	52.8	146.3
Mean	63.7	35.5	51.1	60	37.1	32.2	–	–	42.8	45.3	48.9	61.6
SD	28.3	13.6	18.1	12.7	1.7	6.8	–	–	7.5	19.7	2.7	45.5
SE	10.7	7.9	8	7.3	1	3.4	–	–	4.3	9.8	1.3	22.7
<i>Temperature (°C)</i>												
Min	12.8	13.3	17.7	23.1	20.6	25.9	28.1	26.5	26.1	20.2	15.8	9.7
Max	24.9	23.5	27.6	30.5	31.8	34.9	37.3	35	33.3	28.9	23.2	20.8
Mean	19.7	19.1	22.1	26	28.6	32.1	32.8	30.6	30.7	24.9	19.7	16.8
SD	2.4	3.1	3.3	1.9	2.7	1.9	2.4	2.1	1.7	2.6	2.1	2.8
SE	0.4	0.5	0.5	0.3	0.5	0.3	0.4	0.3	0.3	0.4	0.3	0.5
<i>Relative humidity (%)</i>												
Min	13.45	21.2	13.95	8.6	9.8	8.5	25.6	41.8	38.8	30.5	8.7	17.6
Max	52.6	78	43.1	41.6	41.3	72.4	69.4	76.6	77.8	91.7	66.1	66.7
Mean	28.1	39.6	25.5	21.9	21.1	33.8	46.5	60.1	56.7	52	39.8	42.8
SD	8.6	15.5	8.2	8	7.9	12.5	11.8	8.1	9.2	13.3	13	12.8
SE	1.5	2.9	1.4	1.4	1.4	2.2	2.1	1.4	1.6	2.3	2.3	2.3

SD Standard deviation, SE Standard error

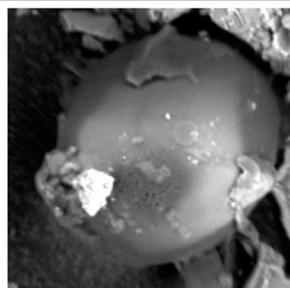
Annual Spore Integral (ASIn) was 58,940 spore day m⁻³, which was much bigger than APIn. Nevertheless, this value was much lower than that reported for 2016 (222,365 spore day m⁻³) (Ortega-Rosas et al. 2019). The inter-annual variation in pollen quantity indicates variations in the abundance of sources, and these variations have been used to assess changes in environmental conditions (Damialis et al. 2007). The annual pollen index can provide a biased measure of pollen's reproductive yield, which is influenced by

factors such as atmospheric transport, pollen deposition, and climatic factors that affect emission processes (Ranta et al. 2008). Environmental conditions in North America promote plants' precondition and their subsequent bloom because of the high temperatures and occurrence of dry seasons (Calderón-Ezquerro et al. 2015; Ranta et al. 2008). In Hermosillo, rainfall and temperature seem to be essential factors in the pollen production. For example, 2018 recorded annual precipitation of 311 mm, with maximum

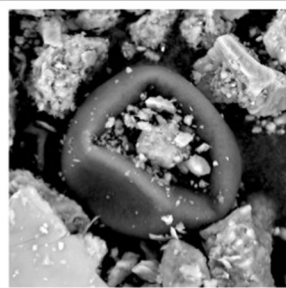
Poaceae



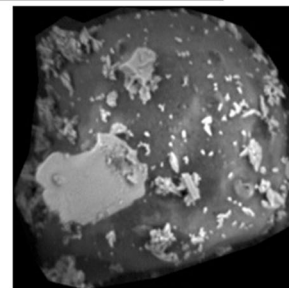
5 microns
Area 3.94%



5 microns
Area 8.77%

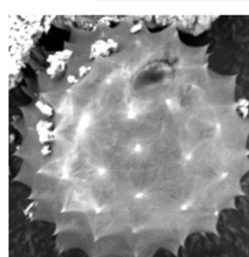


5 microns
Area 20.80%

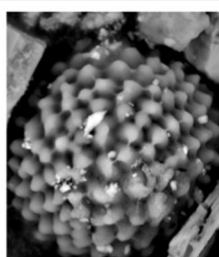


5 microns
Area 28.12%

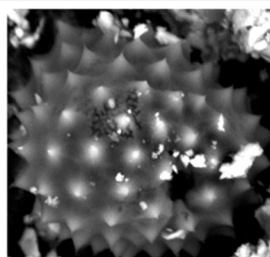
Asteraceae



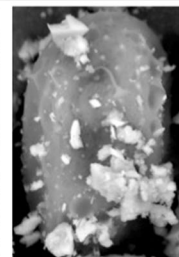
5 microns
Area 2.94%



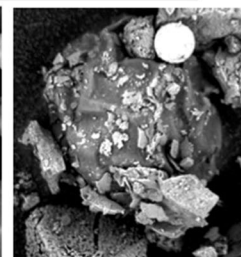
5 microns
Area 4.27%



5 microns
Area 4.50%

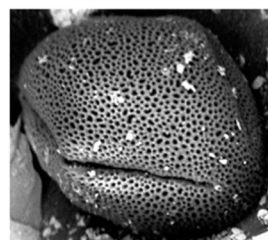


5 microns
Area 37.12%

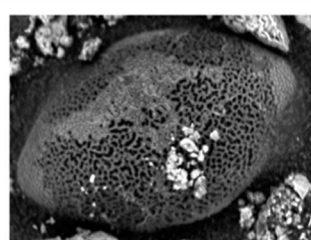


5 microns
Area 39.91%

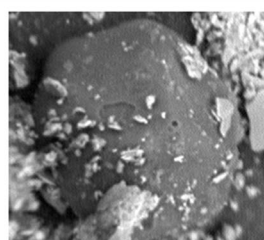
Fabaceae



5 microns
Area 2.37%



5 microns
Area 3.95%

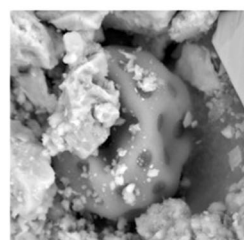


5 microns
Area 18.29%



5 microns
Area 61.75%

chenopodiaceae_amaranthaceae



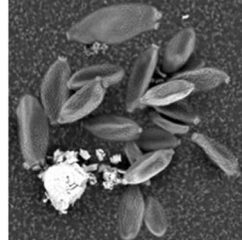
5 microns
Area 29.11%

Alternaria



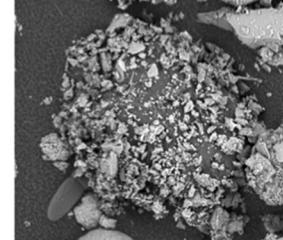
5 microns
Area 5.19%

Cladosporium



5 microns
Area ND

unidentified



5 microns
Area 64.43%

Fig. 5 Particulate matter attached to collected pollen and spores wall. The covered area is expressed in % related to the total observed pollen surface

temperatures lower than those reported in 2016 (Navarro-Estupiñan et al. 2018). These environmental conditions could explain lower pollen counting for 2018 (this work) compared to the 16,243 pollen day m^{-3} recorded in 2016 (Ortega-Rosas et al. 2019).

Considering that the most crucial pollen taxa in the air of Hermosillo were related to herbaceous plants (more than 70%), this kind of plant, such as Poaceae (most important taxa), is present throughout the year. Some aerobiological studies have reported increased Poaceae after the rainy season (Ortega-Rosas et al. 2019; Calderón-Ezquerro et al. 2015). Calderón-Ezquerro et al. (2015) report the highest Poaceae concentrations in Mexico City in December (dry season), accompanied by increased temperature and decreased precipitation. This result is in agreement with those reported by Torres-Valdos (2006) and with our data. Specially, we record an increase in Poaceae from September to November, just after the rainy season, due to Hermosillo's monsoon. In Mexico City, APIn ranges at higher levels from 25,062 to 113,253

pollen day m^{-3} (Calderón-Ezquerro et al. 2015), which is expected because of the lower water limitation of temperate regions.

In contrast, desert region plants are limited by precipitation events, and then pollen production is less important than those occurring in temperate regions (Ziska et al. 2008). Meteorological variables such as high temperature, low humidity, and high wind speeds also promote pollen release from anthers (Grewling et al. 2019). Nevertheless, for flowers and then pollen production, precipitation is needed. In desert regions such as Hermosillo, most pollen production occurs during summer, but its releasing depends on higher temperatures and low relative humidity; this is why after the rainy season of monsoon at Hermosillo, we record the highest concentrations of airborne pollen in the air.

The most critical pollen with allergenic potential is related to herbaceous plants such as Poaceae, *Ambrosia*, Chenopodiaceae-Amaranthaceae, the dominant species inside this kind of desert city (Molina-Freaner and Van Devender 2000). Between these, Poaceae (grasses) pollen is an essential airborne particle at Hermosillo, with 40% of the APIn, as well the allergic sensitization test on population arise that 29% of people tested ($n = 151$), presents a positive

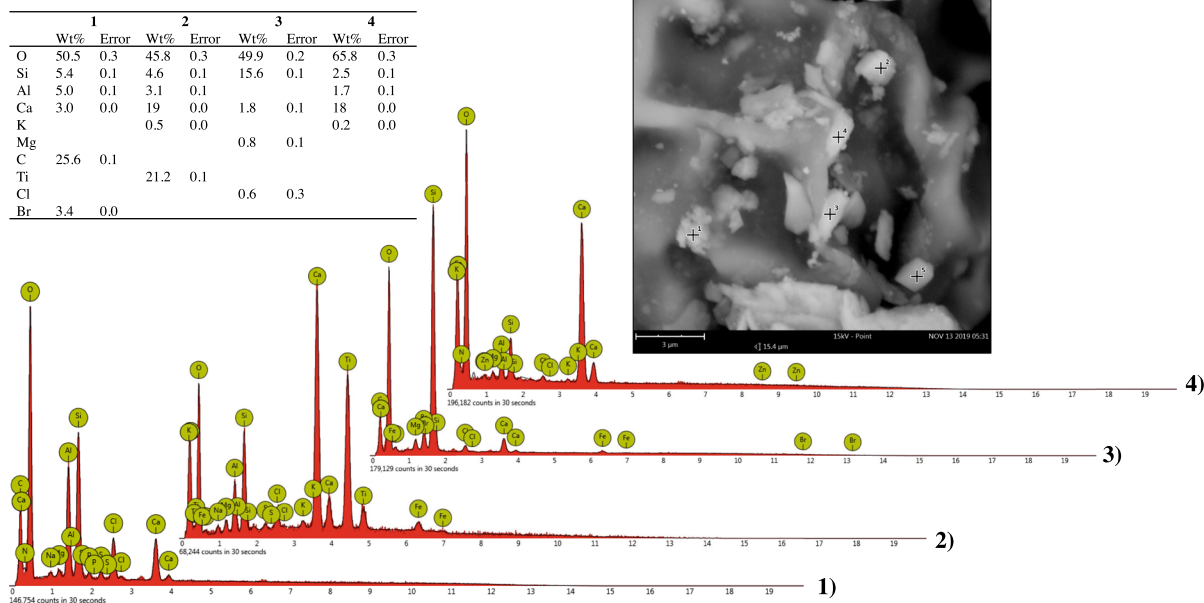


Fig. 6 EDS spectra for attached particles to Poaceae pollen collected during spring

reaction to this kind of pollen (Table 3). Poaceae pollen is currently regarded as “the leading airborne biological pollutant and the chief cause of pollen allergy worldwide” (García-Mozo 2017). We record that the highest peak of Poaceae pollen concentrations in September is causing severe effects on population health (Figs. 3 and 4). A recent study developed by Children’s Hospital (López-Romero et al. 2017) regarding the allergens sensitization of children’s (2–18 years old) in Hermosillo denotes a high frequency of patients suffering allergies related to pollen. One hundred and twenty-five patients were treated with asthma (68.8%) and allergic rhinitis (14.4%). Patients resulting positively in the allergic-cutaneous test are more sensitive to grasses (40.7%), trees (18.4%), and herbs (16.4%) (López-Romero et al. 2017).

Other pollen taxa such as *Ambrosia* (Ragweed) pollen are considered to be a highly potent aeroallergen worldwide (Grewling et al. 2019) by example, and it has been estimated that about 26% of the US population is sensitized to this kind of pollen (Arbes et al. 2005). For Hermosillo, *Ambrosia* pollen account for 10% of total APIn, and allergenic sensitization test performed indicates that 17% of the population tested is sensitive to this kind of pollen, correlating well with previous sensitization test realized on children in this city (López-Romero et al. 2017). The highest peak recorded in *Ambrosia* (Asteraceae) pollen during 2018 was during March, causing a high reaction on allergenic populations (Fig. 3). For arboreal pollen, only Fabaceae type, which includes: *Parkinsonia*, *Caesalpinioide*, *Prosopis* (see Table 2), has significant concentration during the year (5% of total APIn). The sensitization test on population arises that 12% of people tested present a positive reaction to this pollen type. The highest peak in concentrations recorded for this pollen type was in April, corresponding to the tree’s flowering season. Fabaceae pollen is reported to be one of the most important allergenic pollen from trees in Mexico (Rosas-Alvarado et al. 2011).

On the other side, the most critical fungal spores recorded in 2018 were *Cladosporium* with 50% of ASIn. This kind of spore has an elevate allergenic potential as reported worldwide (Grewling et al. 2019; Patel et al. 2018). The sensitization test for Hermosillo reveals that 19% of people ($n = 151$) show reactions (Table 3), the peak of concentration in the air for this kind of fungal spore was during October, reaching

1400 spore day m^{-3} . Another important fungal spore recorded is *Alternaria*, with 12% of ASIn. This kind of spore causes severe damage to allergic people in Europe (Grewling et al. 2019). For Hermosillo city, the sensitization test response for this kind of fungal spore was higher than *Cladosporium* since 21% of people present reaction (Table 3). The highest peak registered for *Alternaria* occurs in July. It correlates with environmental conditions that stimulate its increment in air. *Alternaria* spores are “dry-air spores,” and its releasing occurs during high-temperature conditions, low humidity, and high wind speeds (Grewling et al. 2019). These conditions occur during July at Hermosillo.

The seasonal variation in this airborne pollen and fungal spore concentrations during 2018 at Hermosillo reveals as we stated before (Ortega-Rosas et al. 2019), two critical periods at the year with high potential of allergenic reactions in population and, consequently, a poor biological air quality. The concentration of Poaceae, *Ambrosia*, Chenopodiaceae-Amaranthaceae, and Fabaceae increases together during the first critical period in the year (March–April). Fungal spores with *Alternaria*, *Cladosporium*, and Basidiomycetes concentrations increase during the second critical period (July to November). The allergenic Hermosillo’s population responds quickly to these higher concentrations (Fig. 4). The positive sensitization test to these kinds of pollen and spores is centered in both seasons, whereas there is little positive reaction detected during summer. The allergic risk then immediately increases after precipitation events as temperature increases and the concentrations of pollen and spores increase, as supported by other studies (Stevenson et al. 2017; Calderón-Ezquerro et al. 2015).

We found that airborne pollen could attach particle matter found in the atmosphere as was published before (Bedard et al. 2020; Ribeiro et al. 2015; Armentia et al. 2002). In the particular case of this desert city, with high concentrations of dust in the air, herbaceous pollen types (Poaceae, Chenopodiaceae-Amaranthaceae, and Asteraceae) show a higher particle loading (28% to 40% PM per pollen grain) than the arboreal pollen types such as Fabaceae (19% PM per pollen grain). Moreover, reported Poaceae pollen has more allergenic potential (García-Mozo 2017). It is documented that pollen grains may develop a smaller size and a thinner exine in air pollution areas,

causing a collapse of the pollen membrane (Azzazy 2016). The continuous plant damage in urban areas might cause an overexpression of stress proteins in the grass pollen (Armentia et al. 2002). Since some of these proteins are significant allergens, it is suggested that the same pollen can be more allergenic in contaminated urban areas than in rural ones (Armentia et al. 2002). In this work, several Poaceae grains have a collapsed membrane and a high particle loading (Fig. 6).

Semi-quantitative analysis by SEM–EDS shows that particulate matter adhered to the pollen surface is mainly composed of Si, Ca, and Al, possibly linked to crustal sources, but Br and Cl are also detected, most likely attributed to traffic sources. Surface soils in the Hermosillo region show high percentages of clays and silts (up to 50%; Fig. 1c). The < 20 µm size fraction is dominated by an association of rock-forming minerals with quartz and feldspars (70–92%), as well as ino- and phyllo-silicates, Fe-Ti oxides, carbonates (Ca, Fe and Mg varieties), and secondary or hydrothermal minerals such as lopezite, pretulite and laumontite (Table 5). This mineralogical relationship suggests that the shallow, and the fine fraction of these sedimentary deposits, derived from the erosion of the volcanic, intrusive and metamorphic rocks that crop out in the region, (Fig. 1b). The mineralogical constitution of phaeozem soils shows crystals with similar densities (2.2–2.7 g/cm³), but with a wide range of hardness (2–7 MSH). Both characteristics show an increase depending on the concentration of minerals in the sample, dominating high contents of the harder minerals, such as different feldspars and quartz species. Calcisol has these same characteristics. However, it contains phyllosilicates (biotite and muscovite), as well as the Fe-oxide (magnetite) and scandium phosphate (pretulite). The association of minerals in vertisol shows crystals with a narrow range of density and hardness (2.5–2.8 g/cm³ and 5.5–7 MHS). Low concentrations of Fe–Ti oxide (ilmenite) and phyllosilicates such as muscovite and kaolinite contrast with these characteristics. Finally, in cambisol, crystals decrease in density according to the increase in hardness and quantity. The Fe minerals, which are oxides (hematite) and carbonates (siderite), and the presence of the carcinogenic mineral lopezite, are out of the pattern, possibly linked to traffic sources. Road dust samples in the Hermosillo city, the soils-like, have a high quartz and feldspar content (71.5%).

However, its mineral relation, between density, hardness, and quantity, is equal to that of cambisol, with a more critical content of muscovite, calcite, and the presence of manganese carbonates (rhodochrosite). Mineral coincidences between road dust and cambisol suggest that microparticles to nanoparticles transported by pollen and spores could come from the Hermosillo peripheries' fine surface soils.

Namjoyan et al. (2020) reported geogenic particles smaller than 2.5 µm attached to pollen grains collected after the dust storm in Ahvaz city, Iran. Despite the geologic or anthropic sources for fine particles, the high loading causes changes in the pollen structure. The additional influence of urban pollution may prompt a more severe immunological response (Bedard et al. 2020; Garcia-Mozo 2017). Due to the synergistic interactions between air pollutants and pollen grains (Schiavoni et al. 2017), the adverse effects of “multi-pollutant mixture” on human health should be considered (Grewling et al. 2019). Therefore, it can be considered that pollen morphology also favors the association with air pollutant particles, as previously stated (Grewling et al. 2019; Rahman et al. 2019; Ribeiro et al. 2015). Traffic-related particles that make up the agglomerates in the pollen surface are reported continuously as particles that affect health (Valavanidis et al. 2008; Calderon-Ezquerro et al. 2018; Chegani et al., 2004). Pollen in cities could also impact health in other ways as it adheres and retains both micro- and nanoparticles, and agglomerates (Kiotseridis et al. 2013). Kim et al. (2013) report that PM air pollution may enhance an allergic inflammatory response in sensitive patients. Inorganic particles attached to the pollen surface may absorb aeroallergens released by the pollen grain, leading to prolonged retention of the allergen (Zhou et al. 2011). Kalbande et al. (2008) reported, based on experimental research, that polluted pollen grains are more effective than non-polluted pollen grains in inducing allergic symptoms as well the pollen grains may be acting as carriers of pollutants from one area to another.

Moreover, this micro- and nanoparticles attached to pollen can alter the pollination and reproduction of plants; published studies show that these airborne particles generated by traffic on unpaved roads can alter soil chemistry and then ecosystems process that finally influence the physiology of individual plants and their reproduction (Waser et al. 2017). Dust also interferes with the culmination of the pollination and

Table 5 Mineralogy of local soils and road dust in the < 20 µm fraction. Abbreviations are: phaeozem (Ph), vertisol (Vr), calcisol (Cl), cambisol (Cm), Hardness Mohs scale (HMS)

%	Density g/cm ³	Hardness HMS	Formulae	Local soils				Road dust <i>n</i> = 5
				Ph	Vr	Cl	Cm	
<i>Silica minerals</i>								
Quartz	2.62	7	SiO ₂	44.4	6.3	12.0	12.5	28.2
Cristobalite	2.27	6.5	SiO ₂			15.8		
<i>Feldspars</i>								
Anorthite	2.73	6	CaAl ₂ Si ₂ O ₈		17.0			
Labradorite	2.69	7	(Ca,Na)(Si,Al) ₄ O ₈	14.5				
Albite	2.62	7	NaAlSi ₃ O ₈	17.5	31.3	21.3	43.5	43.3
Sanidine	2.52	6	(K,Na)(Si,Al) ₄ O ₈	11.3	10.5			
Microcline	2.56	6	KAlSi ₃ O ₈	4.9	16.1		13.7	
Orthoclase	2.56	6	KAlSi ₃ O ₈		9.0	23.8		
<i>Ino and phyllosilicates</i>								
Actinolite	3.04	5.5	Ca ₂ (Mg, Fe ²⁺) ₅ Si ₈ O ₂₂ (OH) ₂					4.6
Biotite	3.09	3	K(Mg,Fe) ₃ AlSi ₃ O ₁₀ (OH,F) ₂			4.7		
Muscovite	2.82	2.5	KAl ₂ (AlSi ₃ O ₁₀)(OH) ₂		5.8	4.7	7.7	15
Kaolinite	2.6	2	Al ₂ Si ₂ O ₅ (OH) ₄	1.2	1.9			
<i>Fe–Ti Oxides</i>								
Hematite	5.3	6.5	Fe ₂ O ₃				1.9	1.7
Magnetite	5.15	6	Fe ₃ O ₄			3.3		
Ilmenite	4.72	5.5	FeTiO ₃		2.1			
<i>Carbonates</i>								
Siderite	3.96	3.5	FeCO ₃				0.5	
Rhodocrosite	3.69	3	MnCO ₃					1.1
Magnesite	3	4	MgCO ₃			1.5		
Calcite	2.71	3	CaCO ₃	4.8			3.7	6.2
Pretulite	3.71	5	ScPO ₄			10.0		
Lopezite	2.69	2.5	K ₂ Cr ₂ O ₇				12.9	
Gypsum	2.3	2	CaSO ₄ .2H ₂ O	0.3				
Laumontite	2.29	4	Ca(Si ₄ Al ₂)O ₁₂ .4H ₂ O	1.1				
Sodalite	2.29	6	Na ₈ Al ₆ Si ₆ O ₂₄ Cl ₂			3.1	3.1	
Total				100	100	100.2	99.5	100.1

onset of the fertilization phases by inhibiting pollen adhesion or germination on the stigma, or mechanical changes in the stigma that reduce the intake of pollen. That research also indicates that pollen with more particles attached presented lower stigma pollen loads (Waser et al. 2017).

Conclusions

The impacts of pollen, fungal spores, and particle matter concentrations during a year at Hermosillo city lead to several impacts on the allergenic population's health. The action of high-temperature winds and lower precipitation promotes the release of pollen, fungal spores, and mineral dust in this desert city. We record that fine and ultrafine particles attached to those aeroallergens are higher during the dry season

(October–November), forming mixtures of agglomerates pollen/spores with PM₁₀, PM_{2.5} and causing an increase in the risk of health damage in population. Synergistic interactions between aeroallergens and human-made air pollutants could change their physiologic and allergenic properties and act as an adjuvant promoting allergic disease. The most crucial pollen and fungal spores with allergenic potential were Poaceae, *Ambrosia*, Asteraceae, Chenopodiaceae–Amaranthaceae, and *Alternaria*, *Cladosporium*, and Basidiospores, respectively. Micro- and nanoparticles attached to pollen grain and fungal spores were related to both geogenic and anthropogenic sources. The impact of allergenic pollen and fungal spores mixtures with micro- and nanoparticles on human health deserves further investigation.

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Data availability Available by request.

Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest.

Code availability Not applicable.

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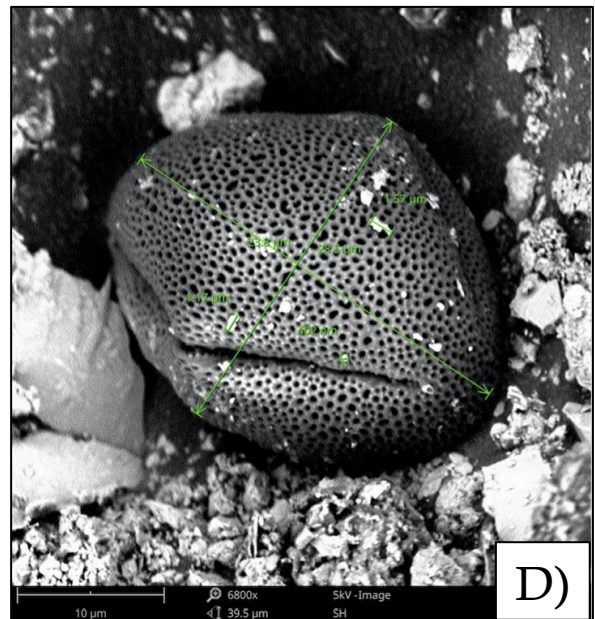
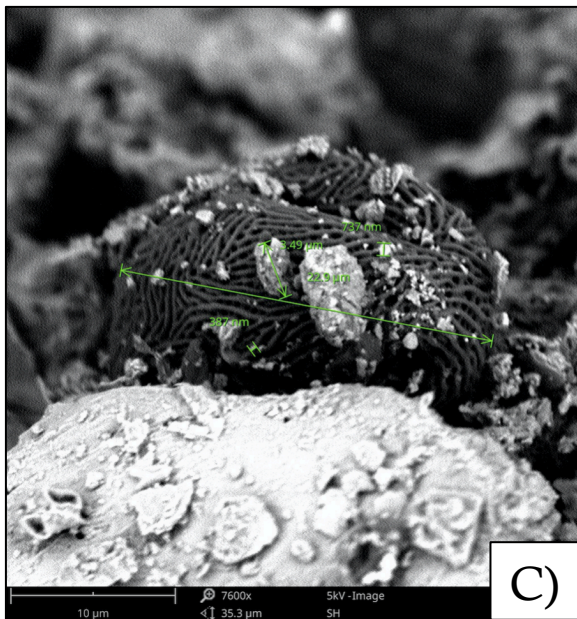
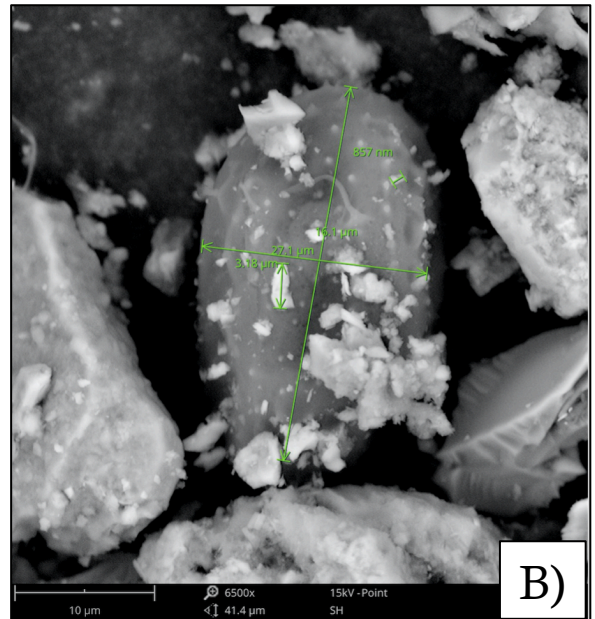
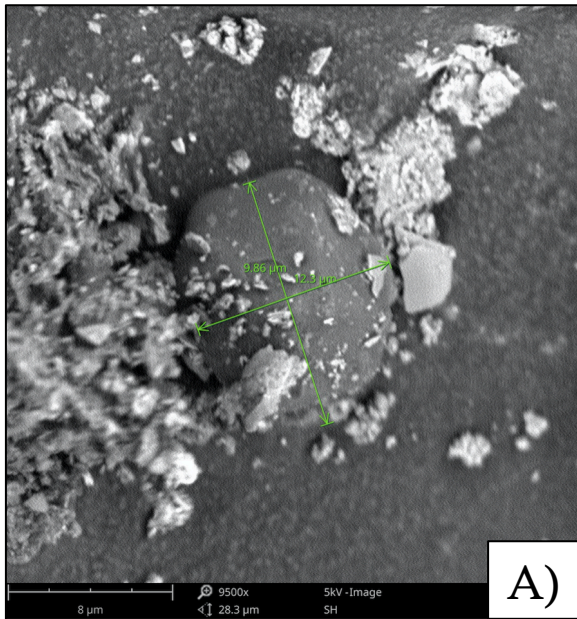
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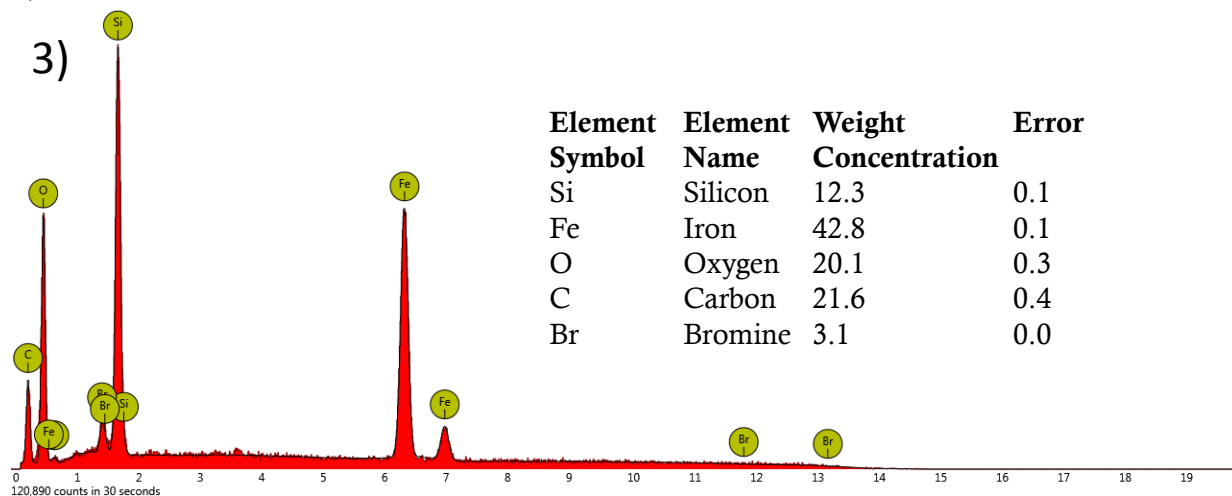
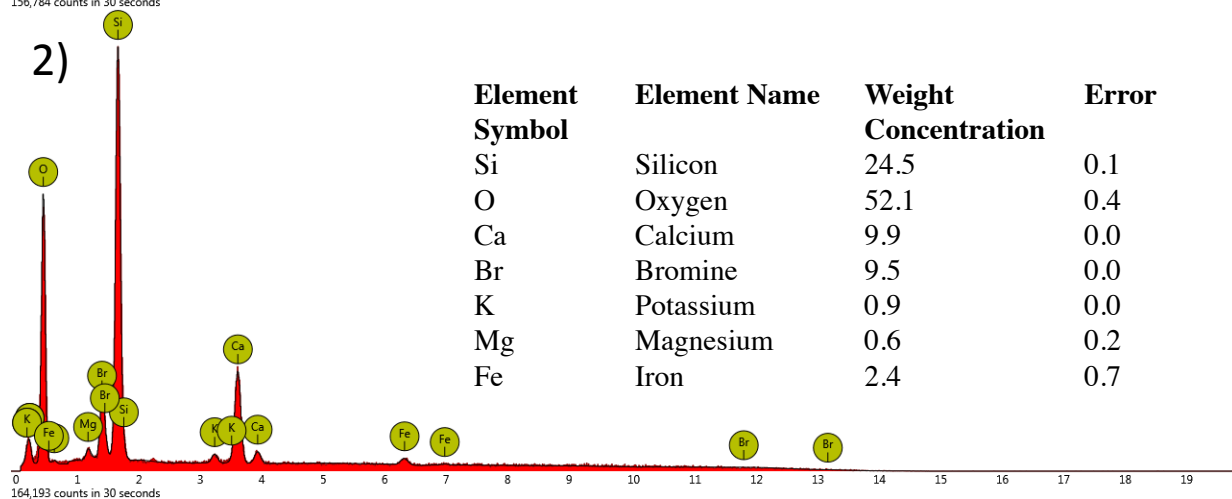
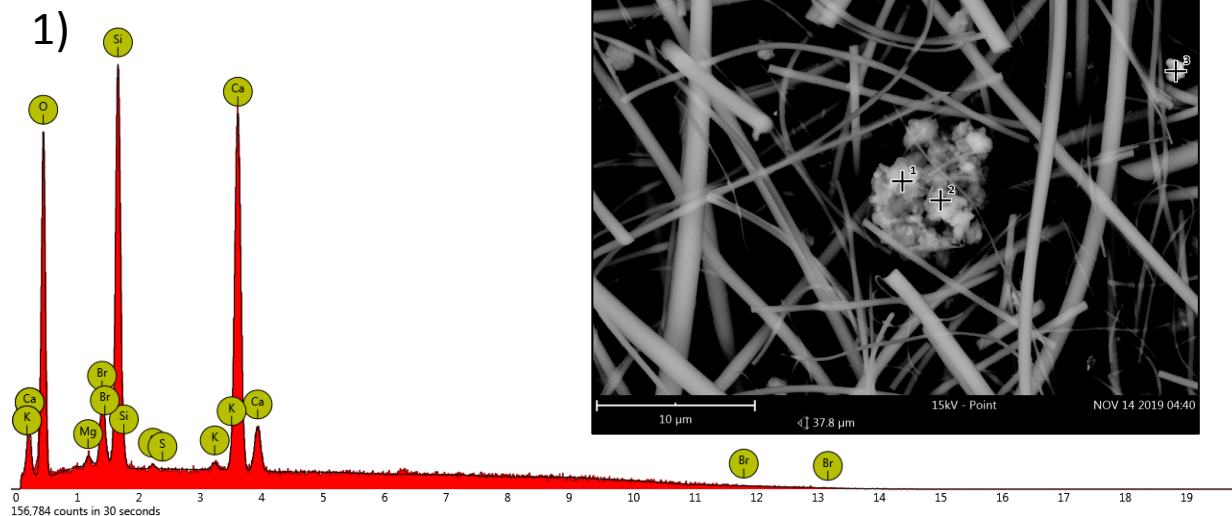
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Supplementary file S1
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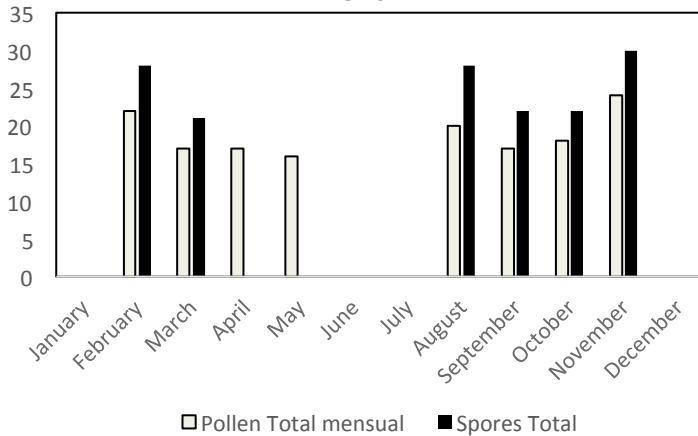
S1: SEM images of most important pollen taxa recorded in this work, showing the particle matter attached to pollen wall: A) Poaceae, B) Asteraceae, c) Rosaceae, D) Parkinsonia (Fabaceae)

Element Symbol	Element Name	Weight Concentration	Error
Ca	Calcium	23.5	0.0
Si	Silicon	14.4	0.1
O	Oxygen	54.2	0.2
Br	Bromine	6.9	0.0
Mg	Magnesium	0.4	0.5
K	Potassium	0.4	0.0
S	Sulfur	0.2	1.0

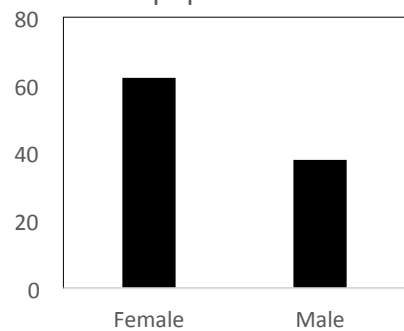


Supplementary file S3

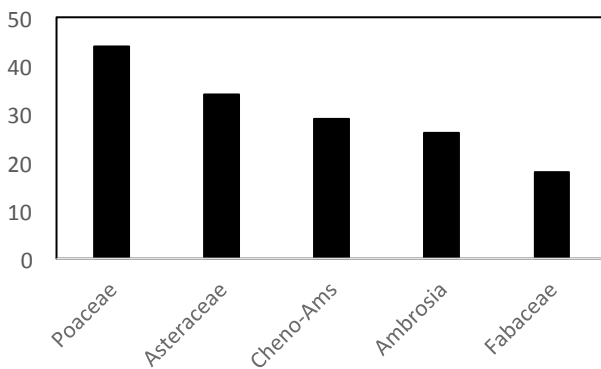
A Pollen and spores allergic-population by month



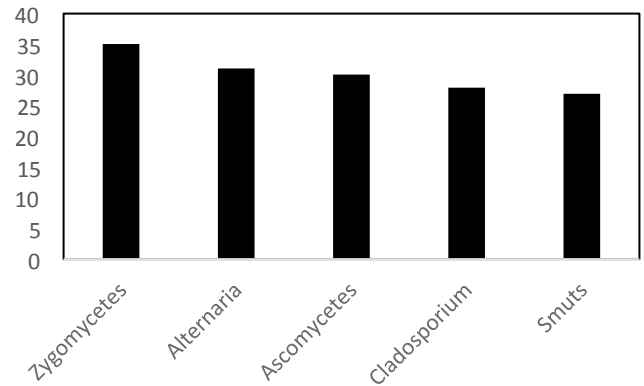
B Sex distribution of allergic population



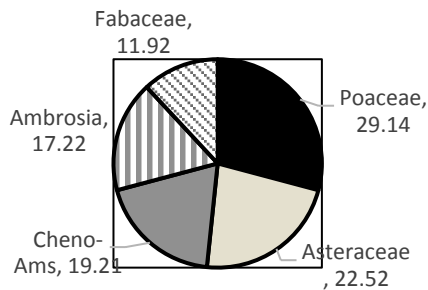
C Total allergic people by pollen type



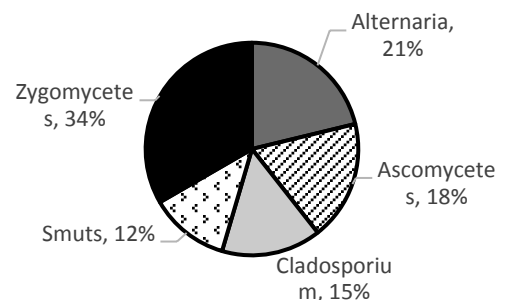
D Total allergic people by spore type



E Percentage of principal airborne allergenic pollen



F Percentage of principal airborne allergenic spores



S3: Sensitisation allergenic test-results reported by IMSS (Instituto Mexicano del Seguro Social) we analyzed the data from the 151 people-test results realized during 2018 at Hermosillo: A) monthly cases of positive pollen and fungal spores sensitisation test, B) Sex distribution of population tested C) Most important allergenic pollen and a number of positive sensitisation people, D) Most important allergenic fungal spores and a number of positive sensitisation people, E) Percentage of positive sensitisation by pollen types, F) Percentage of positive sensitisation by fungal spores types.