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# Internet search volume reflects pollen exposure and seasonal allergic burden in Germany

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## ABSTRACT

**Background:** Seasonal allergic rhinitis is an immunoglobulin E (IgE)-mediated disease triggered by airborne allergens such as birch or grass pollen. Despite its high prevalence, it remains underdiagnosed and undertreated, contributing to impaired quality of life and substantial socioeconomic burden. Climate-related changes are expected to increase pollen exposure, prolong the pollen season, and potentially exacerbate disease burden. Digital search data may provide insights into population-level interest in allergy-related information and health-seeking behavior. We therefore examined whether allergy-related search volume is associated with pollen exposure and environmental conditions across Germany.

**Methods:** For this retrospective longitudinal study, pollen allergy-related search volume (SV) in Germany was analyzed using Google Ads data (April 2020–March 2024) and Google Trends data (2004–2024), comprising 49, 275, 340 search queries. Search terms were categorized by theme and analyzed for temporal, seasonal, and regional patterns. Associations between SV, nationwide birch and grass pollen concentrations, and meteorological variables were evaluated using Spearman's rank correlation coefficient (r). Additional subgroup analyses were conducted to explore regional heterogeneity and urban differences in search behavior.

**Findings:** A total of 49, 275, 340 pollen allergy-related search queries were identified. Search activity demonstrated pronounced seasonal peaks in spring and early summer. Temporal/seasonal information, treatment-related information, and general information accounted for the largest proportion of searches. SV showed positive correlations with birch and grass pollen concentrations and sunshine duration, while associations with temperature were weaker and precipitation was predominantly negative or not significantly associated. Regional and urban differences in search behavior were observed.

**Interpretation:** Pollen allergy-related search behavior is strongly associated with seasonal pollen exposure and environmental conditions. These findings indicate that pollen allergies represent a substantial and climate-sensitive burden on public health. Web-based search data

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may complement traditional disease monitoring by capturing population-level interest in near real-time.

**Keywords:** Seasonal allergic rhinitis, Birch pollen, Internet search volume, Environmental factors, Pollen exposure

## INTRODUCTION

The increasing prevalence of allergic diseases worldwide represents a growing global health challenge.[1,2] More than 500 million people across the globe are affected by pollen-induced seasonal allergic rhinitis (SAR),[3] which is typically characterized by sneezing, rhinorrhea or nasal obstruction, nasal itching, or irritation of the eyes.[4] SAR is an immunoglobulin E (IgE)-mediated inflammatory disease triggered by airborne allergens such as birch *(Betula)* and grass *(Poaceae)* pollen.[4–7] Pollen allergies are often associated with asthma, sinusitis, and atopic dermatitis due to shared immunological mechanisms.[8]

Despite its high prevalence, SAR remains underdiagnosed and undertreated worldwide, which continues to be a major public health issue. Many affected individuals do not receive a formal diagnosis or adequate therapy, resulting in impaired quality of life, reduced daily functioning, and potentially avoidable disease burden.[4,9,10] In addition to its clinical impact, SAR has been associated with reduced productivity at school and work, sleep disturbance, and increased healthcare utilization.[11,12]

Environmental and climatic changes have been associated with shifts in pollen seasons, including changes in duration, intensity, and geographic distribution. Rising temperatures and increased $CO_2$ concentrations may contribute to prolonged pollen exposure and altered allergenicity, potentially increasing the burden of allergic diseases.[13–16] Climate projections suggest that rising temperatures and changing environmental conditions may alter the distribution of allergenic plants and the intensity of pollen seasons, potentially leading to regional differences in pollen exposure.[17] These dynamic environmental conditions complicate diagnosis and management and highlight the importance of improved population-level monitoring strategies. In this context, complementary surveillance approaches may help to better characterize temporal patterns, environmental influences, and potential unmet medical needs.

Internet search engines are increasingly used to search for health information, including information on symptoms and treatment options. Ninety percent of the population in Germany uses the internet and 57% of them have searched at least once for health information.[18,19] The analysis of web search data has been applied in epidemiological research to explore temporal or regional patterns in health-related information-seeking and has proven to be a valuable addition to traditional surveillance systems. Particularly for noncommunicable diseases, search queries can provide insights into public health concerns, symptom burden, and treatment-related information needs.[4,20–23] Given the limited availability of traditional and cost-effective health data (eg, prescription statistics), digital approaches may offer an additional perspective on pollen allergy activity, public interest, symptom perception, and unmet medical needs.[23–26]

The objective of this study was to analyze patterns of public interest and population search behavior related to pollen allergies in Germany and to examine their association with environmental and meteorological factors. Building on previous studies linking pollen exposure with internet search activity, we integrated Google Ads and Google Trends data with nationwide pollen and meteorological information across national, federal-state, and city levels in Germany and characterized the thematic content of allergy-related searches. This comprehensive, multi-source and multi-level approach represents the main added value of the present study. This

approach may help to improve the understanding of seasonal allergic burden in the population and to evaluate the potential relevance of digital search data for complementary disease surveillance.

## MATERIALS AND METHODS

### Data collection

For this retrospective longitudinal study, web search volume data were extracted from Google Ads Keyword Planner using the Google Ads application programming interface (API). Predefined German keywords related to seasonal allergic diseases (pollen allergy (*Pollenallergie*), hay fever (*Heuschnupfen*), allergic asthma (*allergisches Asthma*), allergic rhinitis (*allergische Rhinitis*), allergologist (*Allergologe*), pollen count (*Pollenflug*), prick test (*Pricktest*)) were used to extract monthly search volume (SV) data between April 2020 and March 2024. The total SV was intentionally constructed to capture the broad spectrum of pollen allergy-related information-seeking behavior, including searches related to symptoms, pollen exposure, treatment, diagnostics, healthcare providers, and the differentiation of allergy symptoms from other respiratory conditions. It was therefore not restricted to terms expected to respond immediately to monthly fluctuations in pollen concentrations.

Google Ads provides aggregated monthly estimates of search activity for specified regions and time periods. Individual user-level data are not accessible.

The analyses were conducted at the national level, across all 16 German federal states (including the city states Berlin, Bremen, and Hamburg), and for 24 urban cities, comprising 21 selected cities (Bielefeld, Cologne, Dortmund, Dresden, Erfurt, Frankfurt, Freiburg im Breisgau, Hanover, Kassel, Kiel, Leipzig, Lübeck, Magdeburg, Mainz, Mannheim, Munich, Münster, Nuremberg, Rostock, Saarbrücken and Stuttgart) plus the city states Berlin, Bremen, Hamburg. Only data from users located in Germany and queries submitted in the German language were considered.

Google Ads was used for scientific research, even though its primary purpose was advertising.[25,26] All data were publicly available and anonymized. Informed consent from Google users and approval from an authorized ethics committee were therefore not required. This study was conducted in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines.

### Categorization of search queries

Search queries were qualitatively classified into 22 predefined principal categories, including temporal/seasonal information (terms related to time), treatment (terms related to therapy/treatment), general information (general terms), pollen count/prediction/forecast (terms related to pollen level/forecast), symptoms (terms related to symptoms), doctor/health practitioner (terms referring to healthcare providers), grasses/rye (terms related to grass/rye pollen), birch/early bloomers (terms related to early-blooming trees like birch, alder, and hazel), stage of life (terms related to age groups like children or older adults), COVID/cold/flu (terms related to COVID-19 or respiratory illnesses), diagnostics (terms concerning diagnostic tests), consequential disease (terms concerning diseases associated with allergies), animals (terms related to allergies in animals), non-specific/others (terms that do not fit into other categories), rare allergens (terms related to uncommon allergen sources), other disease (terms not related to allergies), not clearly assignable to allergy (terms with unclear allergy relevance), regional information (terms specific to regions), precipitation (terms about rain or humidity), no pollen allergy (terms indicating absence of pollen allergy), information/platform (terms for health-related platforms) and alcohol (terms related to alcohol) (Fig. 1).

To ensure mutually exclusive categories and avoid double counting, each search query was assigned to 1 primary category. For queries containing multiple relevant concepts, the first relevant term was used as a predefined operational rule to determine the primary category. Secondary search intentions were not coded separately. This rule was applied consistently by the raters using the predefined codebook.

The categories "No pollen allergy", "Not clearly assignable to allergy", "Animals", and "Non-specific/others" were excluded from further analysis.

To ensure categorization reliability, a double cross-checking procedure was performed. A stratified random sample of N = 542 search queries was independently categorized by 2 raters. The observed percent agreement was 99.4% and Cohen's κ was 0.994, indicating very high interrater reliability.

## Google Trends

In parallel, Google Trends was used to determine the relative search volume (RSV) for the German term for pollen allergy (*Pollenallergie*). RSV is scaled from 0 to 100, with 100 representing the peak search interest within the selected time frame and region.

## External factors

The study investigated whether there is a correlation between SV and various environmental and meteorological variables. Pollen count data and meteorological data were used for this purpose.

Pollen data for Germany were obtained from the German Pollen Information Service Foundation, which operates a nationwide monitoring network. The analyses were based on birch (*Betula*) and grass *(Poaceae)* pollen measured at 26 monitoring stations using Hirst-type volumetric traps in accordance with national and European Union standards. The data represent average daily (24-h) pollen concentrations (in pollen grains/$m^3$ of air).[27] Data were available for multiple locations for the period 2008–2022, including Berlin, Bochum, Bonn, Borstel (Sülfeld), Chemnitz, Delmenhorst, Dresden, Flensburg, Freiburg im Breisgau, Fulda, Greifswald, Jena, Kiel, Löwenstein, Marburg, Moenchengladbach, Munich, Neustrelitz, Oberjoch, Potsdam-Groß Glienicke, Potsdam, Prerow, Rostock, Soest, Treuenbrietzen, and Vechta.

The raw dataset included quality codes (−1 = no measurement; −2 = missing for this pollen type, but not for others), which were treated as missing values, while 0 (trap was active, but no pollen was detected) was retained. Daily values were aggregated into monthly sums per station, averaged across stations within each federal state, and subsequently averaged to obtain a national monthly mean.

Meteorological data were obtained from the Climate Data Center of the German Meteorological Service (*Deutscher Wetterdienst*) and covered all 16 German federal states from January 2004 to March 2024. Hamburg and Bremen were analyzed jointly due to aggregated data availability. The dataset included monthly averages of temperature (in °C), precipitation (in mm), and sunshine duration (in hours). For analysis, only data from April 2020 to March 2024 were used. Environmental data (temperature, precipitation, sunshine duration, and pollen concentrations) were z-standardized to enable direct visual comparison with SV data, which was standardized accordingly for comparability.

## Statistical analysis

Search terms were first analyzed descriptively at the national, federal state, and city levels. To account for differences in population size across regions, SV was standardized per 100,000 inhabitants. Frequencies and percentages were calculated to describe the distribution of search queries across categories.

To examine temporal patterns, Google Ads and Google Trends time series were decomposed into trend, seasonal and residual components using classical seasonal decomposition. A multiplicative decomposition was applied to Google Ads data, whereas an additive decomposition was applied to Google Trends data. Differences in monthly SV across the top 10 categories were evaluated using a Friedman test, with month-year observations treated as repeated-measures blocks due to the non-normal distribution and seasonal structure of the data. Post hoc pairwise comparisons were conducted using Wilcoxon signed-rank tests with Bonferroni correction to adjust for multiple testing.

Regional and urban differences were analyzed using the non-parametric Kruskal-Wallis test, followed by Dunn-Bonferroni post hoc correction for multiple comparisons. Kruskal-Wallis tests were used for comparability with previous studies in this field. Because all federal states and cities

share the same 48 months, a Friedman test (months as blocks) was additionally performed, followed by paired Wilcoxon signed-rank tests with Bonferroni correction.

P-values $<0.05$ were considered statistically significant, and p-values $<0.01$ were considered highly significant.

The pollen data were systematically checked for completeness. The number of missing measurements was calculated for each station and year, and station-year combinations with 100% missing values were excluded from the analysis. All remaining data was retained to ensure maximum coverage and representativeness. Correlations between SV and each environmental variable (pollen counts, temperature, precipitation, and sunshine duration) were assessed using Spearman's rank correlation coefficient (r) based on paired monthly time series. This method was chosen due to the non-parametric nature and seasonal distribution of the data.

All analyses were conducted using R (version 4.4.2).

## RESULTS

### Description of categories

A total of 49, 275, 340 pollen allergy-related search terms were identified and categorized (Fig. 1). The largest proportion of queries was related to temporal and seasonal aspects (27.25%), followed by treatment options (21.49%) and general information (18.53%). Other frequently represented categories included pollen forecasts (9.92%) and symptoms (7.12%), further highlighting strong public interest in these areas.

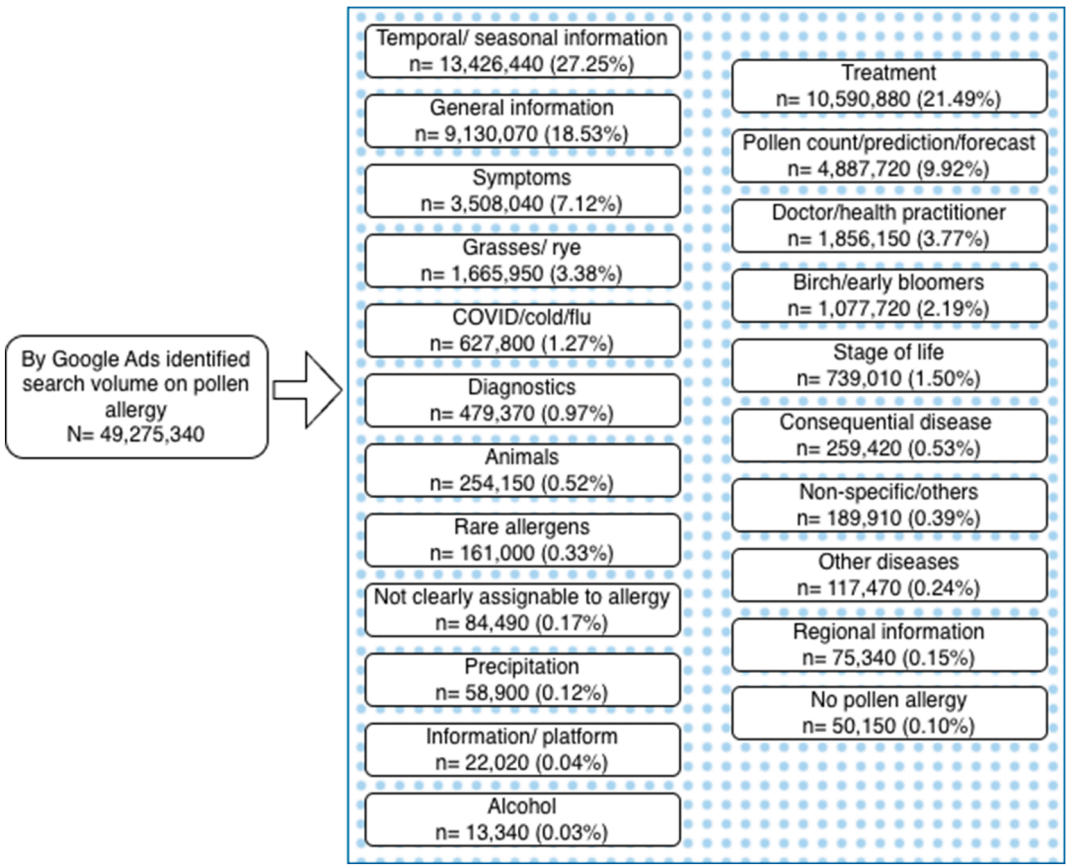



**Fig. 1** Categorization and subcategorization of Google Ads-identified search queries related to pollen allergy in Germany (N = 49, 275, 340) from April 2020–March 2024.

Other relevant categories comprised healthcare professionals (3.77%), specific allergen sources such as grasses (3.38%) and birch (2.19%), and topics related to different stages of life (1.50%), particularly in relation to children and pregnancy. A smaller proportion of search queries focused on topics related to COVID-19, colds or flu (1.27%), suggesting some overlap between allergy-related and infection-related information-seeking behavior.

## Seasonal patterns

To examine seasonal dynamics of allergy-related information-seeking behavior, the monthly SV for the top 10 main categories over a four-year period was analyzed (Fig. 2). The categories temporal/seasonal information, treatment, and general information consistently peaked in spring and early summer months. Especially in 2023, the treatment category exceeded the temporal/seasonal information in SV, suggesting an increased public focus on therapeutic measures during this particular season. SV for biologically linked categories such as grasses/rye and birch/early bloomers followed similar seasonal patterns. Likewise, symptoms and the category pollen count/prediction/forecast showed parallel temporal trends. In contrast, categories like doctor/health practitioner showed relatively stable SV over time, with only minor seasonal fluctuations.

While descriptive analysis identified temporal/seasonal information as the most searched category overall (27.25%), inferential statistical analyses provided further insights. A Friedman test confirmed significant differences in monthly search behavior across categories ($\chi^2(9) = 386.28$, $p < 0.01$). Post hoc Wilcoxon signed-rank tests showed that temporal/seasonal information differed significantly from all other categories. Categories such as treatment and symptoms also showed significant differences compared to several other topics.

Total monthly SV increased from January (SV = 1,845,990) to a peak in April (9,167,300), with a secondary peak in June (8,745,700), and subsequently declined from July onwards, reaching the lowest levels in December (903,940) (Fig. 3).

Long-term Google Trends data (2004–2024) confirmed consistent seasonal patterns in search interest related to pollen allergy in Germany (Fig. 4). RSV regularly peaked in spring, followed by a sharp decline in summer and persistently low levels during autumn and winter. The magnitude of the spring peaks increased over time, with annual peak values rising from ≤53 until 2017 to 77–100 in 2018–2023 (series maximum, RSV = 100, in April 2018). Beyond these annual fluctuations, the trend line indicates a gradual increase in relative search interest over the 20-year observation period.

## Decomposition of time series

Multiplicative decomposition analysis of the Google Ads SV time series (Fig. S1;

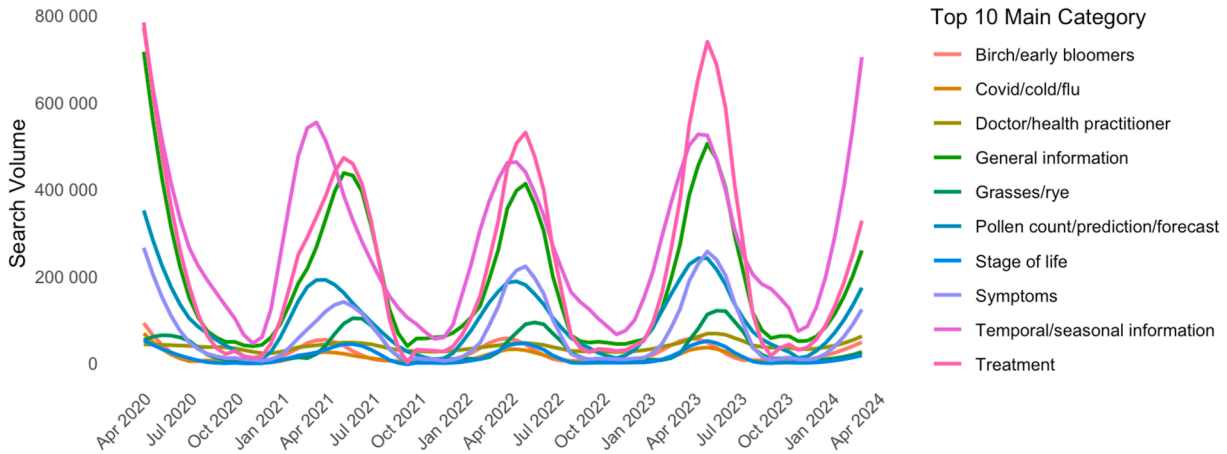



**Fig. 2** Seasonal trends in search volume in the top 10 main categories in Germany from April 2020–March 2024. Lines represent smoothed monthly search-volume trends.

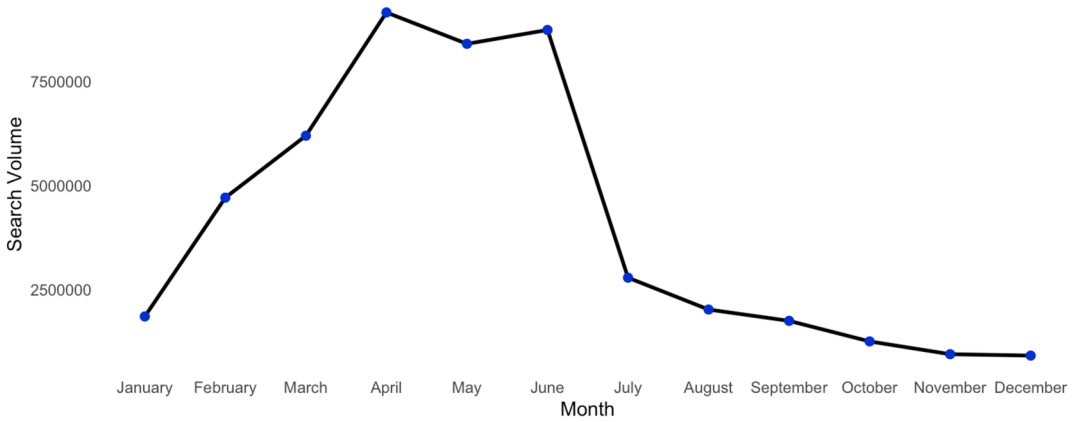



**Fig. 3** Total monthly search volume in Germany from April 2020–March 2024.

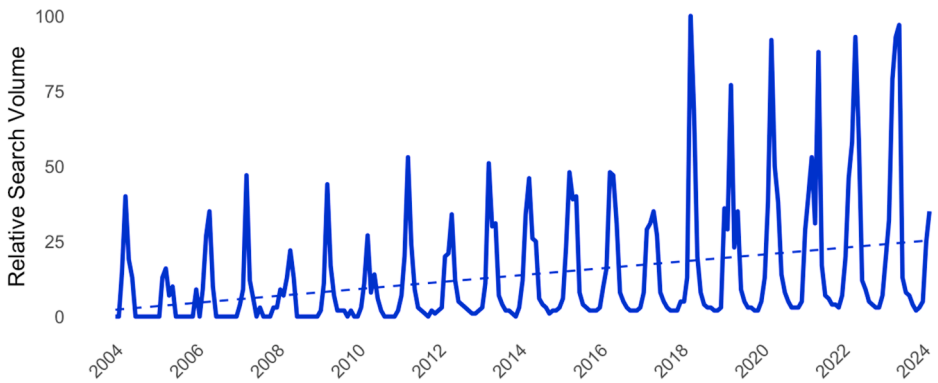



**Fig. 4** Relative monthly search volume for the German term "pollen allergy" in Germany from 2004 to 2024, based on Google Trends data.

Supplementary Materials) revealed individual trend, seasonal, and residual/random components. The seasonal component exhibited a regular cyclical pattern, characterized by pronounced and recurring peaks during the spring season each year. The trend component remained stable until late 2022, after which a clear upward trajectory was observed, indicating a sustained increase in baseline search interest. The residual component showed relatively small and evenly distributed fluctuations, suggesting that most of the variability in the time series could be explained by the seasonal and trend components.

For the Google Trends data, an additive decomposition model was applied, as the relative scaling (0–100) and consistent seasonal pattern across years suggested that an additive structure was more appropriate than a multiplicative one (Fig. S2; Supplementary Materials). The decomposition revealed a pronounced and stable seasonal pattern, with recurring peaks typically occurring in spring and consistently observed across all years. The trend component showed a gradual and continuous increase in baseline interest from 2004 to 2024. The residual component showed moderate fluctuations, with spikes from 2018 onwards, indicating that most variation was well explained by the underlying seasonal and trend components, with only limited irregular events.

## Regional distribution

To explore geographic differences in allergy-related information-seeking behavior, SV was analyzed across Germany's federal states (Fig. 5, A). SV varied considerably between regions, with the highest values observed in Hamburg (SV = 101,320.31), Bremen (79,386.67), Saarland (76,807.28), and Hesse (70,863.76). Overall, western federal states exhibited higher SV compared to the national average, indicating regional variation in search behavior.

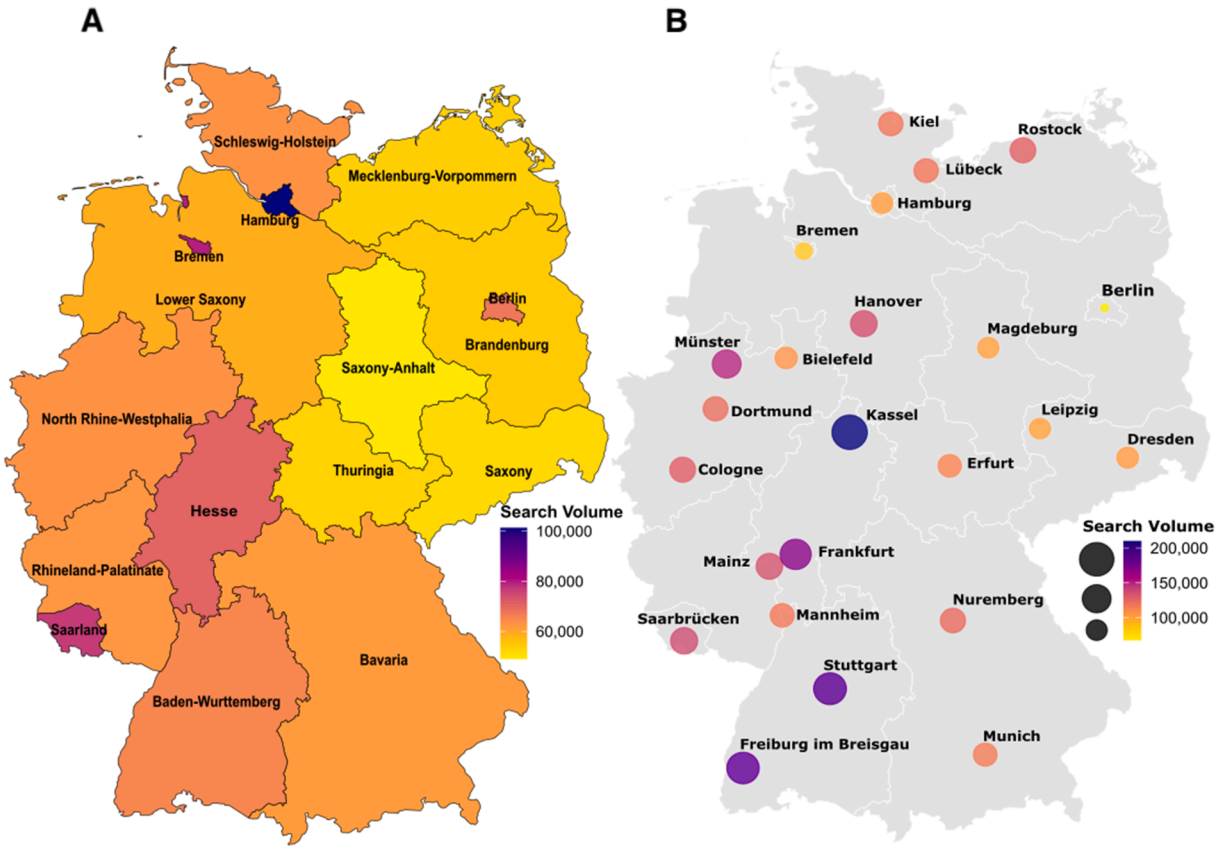



**Fig. 5** Regional Distribution of search volume (per 100 k inhabitants) related to pollen allergy in Germany, shown across federal states (A) and major cities (B).

In contrast, lower SV values were found in several eastern states, including Saxony-Anhalt (48,964.25), Saxony (51,888.67), Thuringia (53,351.14), and Mecklenburg-Vorpommern (53,519.44). A Kruskal-Wallis test confirmed significant differences in relative SV per 100,000 inhabitants across the 16 German federal states ($\chi^2$ (15) = 40.03, $p < 0.01$), supporting the presence of significant geographic heterogeneity. A Friedman test confirmed these differences ($\chi^2$ (15) = 471.5, $p < 0.001$).

Dunn–Bonferroni post hoc analyses revealed that Hamburg had significantly higher SV than several federal states, including Saxony, Saxony-Anhalt, Mecklenburg-Vorpommern, Thuringia, Bavaria, and Brandenburg (all $p < 0.05$ after correction); no other pairwise comparisons remained statistically significant in this test.

Paired Wilcoxon signed-rank tests with Bonferroni correction, which account for the shared months, showed significant differences for all 15 comparisons with Hamburg and for further pairs of federal states.

At the city level (Fig. 5, B), the highest SV was observed in Kassel (209,925.40), followed by Stuttgart (185,070.18), Freiburg im Breisgau (182,419.79), and Frankfurt (170,658.30). In contrast, cities such as Berlin (67,428.45), Bremen (83,303.01), Leipzig (100,055.01), and Magdeburg (100,947.88) had the lowest SV values. A Kruskal-Wallis test confirmed significant differences across German cities ($\chi^2$ (23) = 106.94, $p < 0.01$). A Friedman test confirmed these differences ($\chi^2$ (23) = 781.3, $p < 0.001$).

Post hoc Dunn-Bonferroni comparisons demonstrated that Kassel had significantly higher SV than several cities, including Berlin, Bielefeld, Bremen, and Magdeburg ($p < 0.01$), indicating substantial urban variation in allergy-related information-seeking behavior, with Kassel emerging

as a notable outlier. Paired Wilcoxon signed-rank tests with Bonferroni correction, which accounted for the shared months, confirmed these 4 differences (adjusted $p < 0.001$) and showed significant differences between other cities.

### Environmental factors

To compare the SV values with environmental variables, temporal patterns were visually examined (Fig. S3–S7, Supplementary Material). Temperature and SV showed clear seasonal variation between April 2020 and March 2024, with higher values during warmer months. Notably, peaks in SV tended to occur slightly earlier than peaks in temperature (Fig. S3), suggesting a potential anticipatory information-seeking behavior. Precipitation displayed no consistent seasonal pattern and no apparent visual association with SV (Fig. S4). In contrast, sunshine duration followed a seasonal pattern closely aligned with SV, with largely overlapping peaks during the summer months (Fig. S5).

Birch pollen concentration (April 2020–December 2022) exhibited pronounced spring peaks in 2020, 2021, and 2022, with minimal fluctuations outside the pollen season (Fig. S6). These peaks coincided closely with elevated SV. Grass pollen concentrations showed pronounced peaks in late spring and early summer during the same period (Fig. S7). These peaks broadly coincided with the secondary seasonal peaks in SV, indicating that allergy-related search behavior was associated with the temporal patterns of both birch and grass pollen exposure.

Monthly mean birch and grass pollen concentrations (including zero values outside the pollen season) were correlated with monthly SV using Spearman's rank correlation coefficient. Strong positive correlations between birch pollen concentration and SV were observed across all available federal states ($r = 0.71$–$0.80$, all $p < 0.01$; Table 1). The highest correlations were found in Bavaria and Baden-Württemberg ($r = 0.80$), while the lowest, but still significant, correlations were observed in Schleswig-Holstein.

Grass pollen concentrations were positively correlated with SV across the available federal states, with moderate correlation coefficients ranging from $r = 0.37$–$0.66$ (Table 1). Significant correlations were observed in 9 of 10 federal states. The strongest association was observed in Bavaria ($r = 0.66$, $p < 0.001$), whereas the weakest association was observed in Brandenburg ($r = 0.37$, $p = 0.058$). Although the correlations with grass pollen were generally weaker than those observed for birch pollen, these findings demonstrate that the association between allergy-related search activity and pollen exposure was not restricted to birch pollen.

Temperature, precipitation, and sunshine duration were also correlated with SV (results are shown in Table 1). Temperature showed weak to moderate positive correlations in most states ($r = 0.25$–$0.34$). However, correlations were not statistically significant in Baden-Württemberg, Hesse, and Rhineland-Palatinate. Highly significant and positive correlations were observed for sunshine duration for all states ($r = 0.57$–$0.74$, all $p < 0.01$). In contrast, correlations with precipitation were predominantly negative and mostly not statistically significant ($r = -0.06$ to $-0.39$). Only Rhineland-Palatinate, Schleswig-Holstein, and Saarland showed significant correlations.

## DISCUSSION

This study provides a comprehensive analysis of allergy-related information-seeking behavior in Germany based on more than 49 million search queries collected over 4 years. By integrating Google Trends and Google Ads data with nationwide pollen and meteorological data at national, regional, and city levels, including the COVID-19 period, it offers a detailed spatiotemporal perspective on population-level trends. Accordingly, the main contribution of this study is the integrated, multi-level characterization of allergy-related search behavior rather than the confirmation of seasonal associations alone.

Most search queries were related to seasonal timing, treatment options, and general information. The high demand for temporal information and pollen forecasts underscores the established importance of accurate, real-time pollen data for symptom management. Previous studies confirm that symptom burden and daily impairment in allergic rhinitis are closely linked to pollen concentrations and that location-specific pollen forecasts enable patients to proactively adjust

| Region | Birch r (p) | Grass r (p) | Temperature r (p) | Sunshine r (p) | Precipitation r (p) |
|---|---|---|---|---|---|
| Bavaria | 0.80 (<0.0001)** | 0.66 (<0.0001)** | 0.33 (0.021)* | 0.60 (<0.0001)** | −0.07 (0.63) n.s. |
| Baden-Württemberg | 0.80 (<0.0001)** | 0.51 (0.003)** | 0.27 (0.066) n.s. | 0.57 (<0.0001)** | −0.17 (0.24) n.s. |
| Brandenburg | 0.76 (<0.0001)** | 0.37 (0.058) n.s. | 0.29 (0.047)* | 0.62 (<0.0001)** | −0.07 (0.66) n.s. |
| Berlin | 0.79 (<0.0001)** | 0.47 (0.006)** | 0.31 (0.034)* | 0.65 (<0.0001)** | −0.06 (0.69) n.s. |
| Mecklenburg-Vorpommern | 0.79 (<0.0001)** | 0.43 (0.014)* | 0.31 (0.031)* | 0.71 (<0.0001)** | −0.24 (0.11) n.s. |
| Hesse | 0.78 (<0.0001)** | 0.45 (0.009)** | 0.25 (0.088) n.s. | 0.60 (<0.0001)** | −0.15 (0.30) n.s. |
| Lower Saxony | 0.77 (<0.0001)** | 0.47 (0.006)** | 0.32 (0.026)* | 0.70 (<0.0001)** | −0.22 (0.13) n.s. |
| North Rhine-Westphalia | 0.75 (<0.0001)** | 0.53 (0.002)** | 0.30 (0.038)* | 0.65 (<0.0001)** | −0.17 (0.24) n.s. |
| Schleswig-Holstein | 0.71 (<0.0001)** | 0.44 (0.010)* | 0.32 (0.029)* | 0.74 (<0.0001)** | −0.36 (0.013)* |
| Saxony | 0.71 (<0.0001)** | 0.51 (0.002)** | 0.32 (0.025)* | 0.61 (<0.0001)** | −0.11 (0.45) n.s. |
| Hamburg/Bremen | | | 0.32 (0.024)* | 0.70 (<0.0001)** | −0.22 (0.133) n.s. |
| Saarland | | | 0.33 (0.023)* | 0.66 (<0.0001)** | −0.39 (0.006)** |
| Saxony-Anhalt | | | 0.34 (0.017)* | 0.67 (<0.0001)** | −0.12 (0.43) n.s. |
| Thuringia | | | 0.33 (0.022)* | 0.65 (<0.0001)** | −0.15 (0.32) n.s. |
| Rhineland-Palatinate | | | 0.26 (0.073) n.s. | 0.62 (<0.0001)** | −0.31 (0.031)* |

**Table 1.** Correlation of search volume with pollen counts (birch and grass), mean temperature, mean sunshine duration, and mean precipitation by federal state. *Spearman's rank correlation coefficient (r). **p < 0.01; *p < 0.05; n.s., not significant.*

behaviors and treatments to minimize exposure and symptoms.[7,28] Notably, treatment-related searches accounted for a significant proportion of total SV and temporarily exceeded seasonal search queries, most clearly in 2023. One possible explanation is the publication of the updated S2k guideline on allergen immunotherapy for IgE-mediated allergic diseases in Germany in October 2022, which may have increased awareness of disease-modifying therapies among patients and healthcare professionals.[29] This interpretation is compatible with the time series decomposition of the Google Ads data, which shows a clear upward shift in the trend component from late 2022 onwards.

Additional factors may have contributed. These include increased media coverage of therapeutic innovations, post-pandemic catch-up effects in healthcare utilization, the growing availability of advanced treatment options, and a potentially rising symptom burden associated with prolonged and intensified pollen seasons. Together, these factors may have shifted public interest from symptom management toward causal treatment strategies.

SV demonstrated pronounced seasonality, with a main peak in April and a secondary peak in June, corresponding to the typical patterns of birch and grass pollen exposure in Central Europe. Birch pollen generally peaks in April, whereas grass pollen peaks in June, consistent with pollen monitoring and symptom data from Germany and other European regions.[7,28,30]

Long-term Google Trends data (2004–2024) confirm a stable seasonal pattern with recurrent spring peaks and low activity in autumn or winter. The notable rise in peak intensity since 2018 and the overall upward trend indicate increasing relative search interest. However, the underlying reasons for this increase cannot be determined from Google Trends data alone. Long-term changes in Google use, user demographics, general online health-information-seeking behavior, and platform characteristics may also have influenced the observed trend.

According to a report by the German Meteorological Service, 2018 was exceptionally warm, sunny, and dry, with one of the hottest summers since weather records began.[31] Such extreme weather may have contributed to an earlier and more intense pollen season and prolonged exposure, potentially increasing symptom burden and public interest.

Overall, these findings suggest that pollen allergies represent a substantial public health burden, particularly in the context of dynamic environmental conditions. The observed variation in search activity may reflect changes in symptom burden and population-level information needs and highlights the relevance of digital data for monitoring allergy-related trends.

Beyond temporal dynamics, significant regional variation was observed. Particularly high SV in states such as Hamburg, Bremen, and Saarland may indicate regional differences in disease burden, health awareness, or internet use. Previous studies have reported higher prevalence rates in western compared with eastern federal states, which aligns with the observed SV distribution.[32] Regional age structure may further contribute to this pattern. According to recent demographic data from the Population Update of the Federal Statistical Office (*Statistisches Bundesamt, Destatis, 2026*), eastern states have substantially older populations, whereas the city states of Hamburg, Berlin, and Bremen are among the youngest regions in Germany.[33] As allergic diseases are more prevalent in younger individuals [34,35] and younger populations are more active in digital health information-seeking,[36] age structure may influence regional search behavior.

At the city level, Freiburg im Breisgau, Stuttgart, and Kassel displayed notably high SV. This may reflect regional differences in pollen exposure, demographic structure, or local information-seeking behavior. Stuttgart is located in the Stuttgart Basin, which is characterized by limited ventilation and low wind speeds.[37] Future studies should quantitatively examine whether air pollution contributes to regional differences in SV.

Freiburg, located at the eastern edge of the south-north oriented Southern Upper Rhine Plain, is considered one of the warmest cities in Germany, which may contribute to increased SV.[38] Kassel emerged as the most pronounced city-level outlier. The city is located in the Kassel Basin and is surrounded by higher terrain, which may

contribute to reduced air exchange. Additional checks showed no indication of a calculation error or an effect driven by a single month. A review of locally available healthcare services did not identify an obvious healthcare-related explanation for the elevated SV.

Our analysis confirms close correlations between seasonal environmental factors and search-based information-seeking behavior related to pollen allergies. Strong positive correlations were observed between monthly birch pollen concentrations and SV across all available federal states ($r = 0.71–0.80$, all $p < 0.01$), with the highest correlation coefficients in Bavaria and Baden-Württemberg. Monthly grass (Poaceae) pollen concentrations were positively correlated with SV, although the associations were weaker overall ($r = 0.37–0.66$), with significant correlations observed in 9 of 10 federal states and the highest coefficient observed in Bavaria. These findings are consistent with previous observations by Sitaru et al, who demonstrated synchronicity between pollen counts and search queries in Bavaria and Sweden, and show comparable associations across multiple regions in Germany.[39] Because total SV comprised broad pollen allergy-related searches, the observed associations may reflect the overall seasonal pollen burden rather than exposure to a single pollen type.

Furthermore, because both SV and environmental variables exhibit pronounced seasonal patterns, part of the observed correlations may reflect this shared seasonality rather than a direct exposure–response relationship.

Overall, regional and urban differences in SV may reflect not only differences in disease burden, but also differences in health literacy, internet usage, and urbanization. SV should therefore primarily be interpreted as an indicator of information-seeking behavior rather than direct disease prevalence.

Equally notable is the strong positive association with sunshine duration ($r = 0.57–0.74$), which was highly significant in all federal states. Previous work has identified sunshine duration as an important modulator of outdoor activity and allergen exposure, supporting the observed correlation between SV and hours of sunshine.[40,41] The consistently positive but weaker correlations with temperature ($r = 0.25–0.34$) also suggest increased search behavior during warmer periods. In contrast, precipitation was predominantly negatively correlated with SV, which is biologically plausible, as rainfall reduces airborne pollen concentrations and exposure. The close association between environmental exposure, pollen concentrations, and digital information-seeking behavior suggests that online search data may capture symptom-related burdens in near-real time. Beyond reflecting seasonal patterns, such data may function as an early digital sentinel signal of population-level symptom exacerbation, potentially preceding healthcare utilization. Therefore, search query data could complement traditional pollen monitoring systems and clinical surveillance by providing additional insight into disease burden, public information needs, and shifting therapeutic interests. In the context of climate change and increasingly prolonged pollen seasons, integrating digital behavioral data into environmental health monitoring frameworks may enhance adaptive public responses and support more targeted risk communication strategies.

## Limitations

This study is based exclusively on Google search data and reflects information-seeking behavior of the population rather than confirmed disease prevalence. Since only SV from Google was used as a data source, users of other search engines are not captured. As there is no demographic breakdown of searchers, older populations are potentially underrepresented. The study period partially overlapped with the COVID-19 pandemic, which may have influenced health-related search behavior. Furthermore, bias due to external influences such as advertising, media coverage or scientific publications cannot be ruled out. The use of monthly aggregated data smooths out short-term fluctuations in search interest and may mask temporary peaks.

The search categories included in total SV showed different temporal dynamics. While symptom- and exposure-related queries may respond rapidly to changes in pollen concentrations, diagnostic, treatment-related, and healthcare-seeking queries may show delayed or

less pronounced seasonal patterns. This heterogeneity may attenuate the strength of the correlations with pollen concentrations. However, these categories were intentionally retained because total SV was designed to represent the broader spectrum of pollen allergy-related information-seeking behavior rather than only immediately exposure-driven searches.

Because each query was assigned to a single primary category, secondary intentions in multi-intent queries may not have been fully captured.

Geographically, the analysis is limited to Germany, with incomplete pollen data available for some federal states. This may limit regional comparability. In addition, regional comparisons, particularly those involving city states, should be interpreted with caution, because IP-based geolocation and structural differences between urban and non-urban regions may influence the regional attribution of search volumes.

Linking aggregated regional search and environmental data assumes that searchers were exposed to local pollen levels, which may not always be the case.

## CONCLUSION

This study provides a comprehensive overview of information-seeking behavior related to pollen allergies in Germany. The analysis based on over 49 million search queries over 4 years demonstrates clear temporal, regional, and thematic patterns in pollen allergy-related information-seeking in Germany. Search activity closely aligned with birch and grass pollen concentrations and sunshine duration, indicating that digital search behavior reflects seasonal exposure dynamics. Regional differences suggest that environmental factors, demographic structure, and health awareness influence search volume. The high proportion of treatment-related queries highlights a substantial demand for therapeutic information and underscores the need for accessible, evidence-based health communication. Although search data do not measure disease prevalence directly, they may serve as a low-cost proxy indicator of allergy-related burden. Integrating web-based search data with traditional monitoring tools could enhance near real-time surveillance and support public health strategies.

### Abbreviations

SAR, seasonal allergic rhinitis; IgE, immunoglobulin E; COVID-19, coronavirus disease 2019; SV, search volume; RSV, relative search volume; API, application programming interface; STROBE, Strengthening the Reporting of Observational Studies in Epidemiology

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### Data availability statement

The data that support the findings of this study were derived from publicly available sources and licensed third-party data. Google Trends data were accessed in aggregated and anonymized format. Google Ads Keyword Planner data were obtained in aggregated format for the specified study period. Due to the dynamic nature of these platforms and potential changes in data availability over time, identical retrospective extraction at a later date may not yield identical results.
Meteorological data were obtained from the German Meteorological Service (Deutscher Wetterdienst, DWD), which provides open-access environmental data. Pollen concentration data were obtained under license from a third-party provider and are subject to contractual restrictions. These data cannot be made publicly available.

### Author contributions

S.U. was responsible for conceptualization, methodology, investigation, formal analysis and writing of the original draft. M.H. contributed to methodology and data analysis and provided continuous scientific support throughout the project. S.Z. contributed to study planning and conceptualization and supported the initial data analysis. S.S. was responsible for data acquisition and providing technical support. C.T.-H. contributed to conceptualization and was involved in review. A.Z. contributed to

conceptualization, methodology and writing and was also involved in review and editing. The MELIUS study group was involved in the conception of the study. All authors contributed to data interpretation, critically appraised the manuscript and approved the final version.

### Submission declaration

This manuscript has not been published previously and is not under consideration for publication elsewhere. All authors have approved the manuscript and agree with its submission to this journal. If accepted, the manuscript will not be published elsewhere in the same form, in English or in any other language, without the written consent of the copyright holder. The authors declare that the work is original and does not infringe upon any existing copyright or third-party rights.

### Ethics committee approval

Not required, as only publicly available data were used.

### Conflict of interest and disclosure

S.U. reports institutional funding from the Innovation Committee of the Federal Joint Committee (G-BA) for the MELIUS project (funding code 01VSF23018). S.U. was employed by Bencard Allergie GmbH until March 2024. This employment is unrelated to the present work. C.T.-H. reports institutional funding from the Federal Ministry of Research, Technology and Space (Abrogate project). She reports personal fees for consulting, lectures, and advisory board participation from AstraZeneca, Novartis, Lilly, Sanofi, Stallergenes, ALK-Abelló, Berlin-Chemie, Menarini Pharma, Heuer Dialog GmbH, BMW Group, Signum PR GmbH, and Klinge Pharma. She holds leadership roles in the German Advisory Council on Global Change and as Speaker of the Scientific Board of CK-CARE. A.Z. reports consulting fees and honoraria for lectures from Almirall, Sanofi, Novartis, and Bristol Myers Squibb. M.H. is a current employee of Johnson & Johnson. His work on this manuscript was completed prior to his employment. All other authors declare no competing interests.

### Appendix A.

**MELIUS Study Group**

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.waojou.2026.101500.

### Disclosure of the use of generative AI and AI-assisted technologies

Generative AI was used during manuscript preparation to assist with programming and manuscript language refinement and improve readability. The authors carefully reviewed and edited the output. All analyses, data interpretation, and editorial and scientific decisions were performed by the authors. The authors take full responsibility for the content of the manuscript.

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