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Bibliometric mapping of remote sensing-based crop climate vulnerability: from spectral monitoring to predictive geospatial intelligence

Cartografia bibliométrica da vulnerabilidade climática de culturas baseada em sensoriamento remoto: do monitoramento espectral à inteligência geoespacial preditiva

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Abstract: The intensification of droughts, heatwaves and floods is increasing crop vulnerability and compromising food security, which requires a robust scientific basis to guide agricultural adaptation supported by remote sensing. This study aimed to describe and quantitatively analyse the evolution of research on remote sensing-based crop climate vulnerability, identifying temporal, geographical and thematic patterns. A quantitative, exploratory, descriptive, longitudinal and retrospective bibliometric design was applied to 2,343 Scopus records published between 1985 and 2026, processed in Bibliometrix 5.1.1 and VOSviewer 1.6.20 through productivity, impact and collaboration indicators, together with RPYS. The results show an annual growth rate of 4%, 627 sources, 10,408 authors, 5.17 co-authors per document, 35.3% international collaboration and 19.93 citations per document, with leadership by China, the United States and India. Remote Sensing and Science of the Total Environment concentrated dissemination, while machine learning and Google Earth Engine shaped the recent agenda. The study concludes that the field has reached scientific and technological maturity, consolidated remote sensing as a strategic axis for assessing, modelling and anticipating agricultural vulnerability, and advanced towards predictive approaches with high relevance for climate change adaptation.
Keywords: Crop climate vulnerability. Agricultural drought. Climate adaptation. Google Earth Engine. Machine learning.

Resumo: A intensificação de secas, ondas de calor e inundações está ampliando a vulnerabilidade das culturas e comprometendo a segurança alimentar, o que exige uma base científica robusta para orientar a adaptação agrícola com apoio do sensoriamento remoto. Este estudo teve como objetivo descrever e analisar quantitativamente a evolução da pesquisa sobre vulnerabilidade climática de cultivos baseada em sensoriamento remoto, identificando padrões temporais, geográficos e temáticos. Aplicou-se um desenho bibliométrico quantitativo, exploratório, descritivo, longitudinal e retrospectivo a 2.343 registros da Scopus publicados entre 1985 e 2026, processados no Bibliometrix 5.1.1 e no VOSviewer 1.6.20 com indicadores de produtividade, impacto e colaboração, juntamente com RPYS. Os resultados mostram crescimento anual de 4%, 627 fontes, 10.408 autores, 5,17 coautores por documento, 35,3% de colaboração internacional e 19,93 citações por documento, com liderança de China, Estados Unidos e Índia. Remote Sensing e Science of the Total Environment concentraram a difusão, enquanto machine learning e Google Earth Engine marcaram a agenda recente. Conclui-se que o campo alcançou maturidade científica e tecnológica, consolidou o sensoriamento remoto como eixo estratégico para avaliar, modelar e antecipar a vulnerabilidade agrícola, e avançou para abordagens preditivas com alta relevância para a adaptação às mudanças climáticas.
Palavras-chave: Vulnerabilidade climática de cultivos. Seca agrícola. Adaptação climática. Google Earth Engine. Aprendizagem de máquina.

1 INTRODUCTION

Climate change represents one of the most severe threats to global food security because it intensifies heatwaves, droughts, and floods that reduce agricultural yields and increase price volatility (Kongo & Arreyndip, 2025). Empirical evidence shows that, for each +1 °C increase in temperature, mean yields would decline by approximately -6.0% for wheat, -3.2% for rice, -7.4% for maize, and -3.1% for soybean (Zhao et al., 2017). Besides, simulations by Tigchelaar et al. (2018) project that future warming will raise the likelihood of synchronised production shocks in major maize producing countries, amplifying systemic risks and volatility in agricultural markets. At the interannual scale, climate variability explains between 32% and 39% of global variability in crop yield, indicating high sensitivity of production systems to thermal and hydrological anomalies (Senapati et al., 2025).

The IPCC [Intergovernmental Panel on Climate Change], (2022) Sixth Assessment Report warns that climate change intensifies risks across the four pillars of food security, increasing exposure in vulnerable regions. In 2023, between 683 and 733 million people experienced hunger (FAO [Food and Agriculture Organization], 2023), while global losses of up to 5.5×10^{14} kcal year^{-1} per +1 °C of warming could be only partially mitigated by 2050 and 2100 (Hultgren et al., 2025), underscoring an unprecedented challenge for global agricultural resilience.

Under this context of increasing production vulnerability, the spatial and temporal understanding of crop responses to climate change requires tools that integrate biophysical and climatic information continuously. This need has positioned remote sensing as an essential pillar in agricultural risk assessment (Serkendiz et al., 2025; Yin et al., 2025). This technology generates spatial and temporal indicators of exposure, sensitivity, and adaptive capacity, integrating meteorological and surface variables at unprecedented resolution (Mao et al., 2025).

Driven by the need for spatially explicit and temporally continuous information, remote sensing has emerged not only as a descriptive tool, but also as a robust methodological basis for modelling agricultural vulnerability and anticipating yield losses (Sharma et al., 2025; Sun et al., 2025). Methodologically, it has shown increasing effectiveness for characterising climate change impacts on agricultural systems, enabling near real time monitoring of parameters such as biomass, soil water content, and radiation use efficiency of photosynthetically active radiation (Ahmed et al., 2025). Several studies report that the Standardised Precipitation Index (SPI), Crop Water Stress Index (CWSI), and Normalised Difference Vegetation Index (NDVI) account for approximately 65% of drought studies, while the Temperature Condition Index (TCI) and Heat Impact Stress Index (HIS) represent 23% of heat related applications, with wheat, maize, and rice predominating as model crops (Waqas et al., 2025; Zhang et al., 2023). Operationally, spectral indices derived from Sentinel-2 and Landsat 8 enable yield estimation with R^2 values above 0.80 in regionally calibrated models (Ali et al., 2025). In multitemporal terms, MODIS and Sentinel-2 time series have quantified reductions of up to 0.43 t ha^{-1} under thermal anomalies above +2 °C between 2001 and 2022 (Javari, 2025; Song et al., 2023). Optical SAR fusion improves drought and water deficit detection, with correlation $r = 0.87$ between SAR estimated surface moisture and in situ data (Valle et al., 2023).

Remote sensing of climatic and biophysical conditions has also shown a key role in assessing crop resilience and vulnerability to extreme events (Khan et al., 2025). Kim et al. (2025) showed that combined anomalies of temperature and NDVI explain up to 72% of the spatial variation in heat stress in rice systems in Southeast Asia, demonstrating the capacity of combined indices to anticipate yield losses. Similarly, Smith-Tripp et al. (2022) quantified drought effects on 14 million hectares in the Indus Basin using MODIS and ERA5 series, reporting mean declines of -18% in NDVI and yield reductions of -22% for wheat during El Niño years. In arid regions, integrating thermal, hyperspectral, and microwave sensors has enabled robust characterisation of vulnerability in crops such as maize, barley, and cotton, achieving classification accuracies above 90% under water stress scenarios (Wang et al., 2024).

Despite these advances, critical challenges persist. The thematic concentration on drought and productivity indices has limited exploration of other relevant indicators, such as soil salinity or phenological variability (Chaiyana et al., 2025). Heterogeneity in spatial and temporal resolutions also remains, since combining MODIS products (250 m, 8 days) and Sentinel-2 (10 to 30 m, 5 days) hampers result comparability (Dhillon et al., 2023). In addition, the lack of standardisation in applying vulnerability frameworks, exposure, sensitivity, and adaptive capacity, constrains reproducibility across regions and studies (Hammond et al., 2020). Finally, geographical biases persist, with most research concentrated in Asia, Europe, and North America, while Latin America and Africa remain underrepresented (Monteleone et al., 2023).

Even with the exponential growth of remote sensing based studies, there is still no comprehensive quantitative synthesis that shows how scientific knowledge on crop climate vulnerability has evolved, including thematic patterns, dominant conceptual frameworks, and persistent geographical gaps (Cisse et al., 2026). This gap limits understanding of the field's epistemic maturity and reduces the capacity to steer research agendas towards global climate adaptation objectives, particularly SDG 2 (Zero Hunger, target 2.4, resilient agricultural systems), SDG 13 (Climate Action, target 13.1, strengthening resilience and adaptive capacity), and SDG 15 (Life on Land, target 15.3, sustainable management of agricultural and soil ecosystems) (Hamer et al., 2025; Yeboah et al., 2025; Yin et al., 2025).

Understanding the complexity of remote sensing-based crop climate vulnerability, and guiding effective actions for agricultural adaptation and climate risk reduction, first requires a broad reading of the theoretical, methodological and technological development accumulated over the past three decades. This landscape leads to the central research question. What is the level of scientific development on crop climate vulnerability assessed through remote sensing, and how have its thematic, geographical and methodological structures evolved over time? The twelve specific questions were reorganised into four analytical categories. The first category examines temporal and documentary development, including the evolution of scientific output, the predominance of document types and the distribution of subject areas. The second category analyses scientific actors and collaboration, including the countries, institutions and authors that lead production, the structure of interdisciplinary collaboration networks and the fit of author productivity to Lotka's Law. The third category evaluates dissemination structures, including the journals and publishers that concentrate the literature, the organisation of journal cores under Bradford's Law and the degree of international collaboration among countries and institutions. The fourth category examines intellectual, methodological and thematic evolution, including the historical roots identified by RPYS, the seminal publications, models and conceptual frameworks behind citation peaks, and the emerging trends detected through keyword dynamics and thematic maps.

The general objective of this study is to describe, analyse and interpret the evolution of research on crop climate vulnerability through remote sensing. The study identifies temporal, spatial and thematic patterns, collaboration networks and influential sources. The purpose is to provide an interpretive framework for understanding the current stage of the field, its main structural challenges and its future research agenda in support of agricultural adaptation and the sustainable management of food systems under climate change.

Beyond mapping publication growth and bibliometric structures, this study advances an interpretive contribution to the field. It argues that research on remote sensing based crop climate vulnerability has entered a new stage characterised by the transition from descriptive spectral monitoring towards predictive, multiscale, and increasingly operational geospatial intelligence. At the same time, this transition remains constrained by methodological fragmentation, geographical asymmetries, and the limited translation of satellite based outputs into decision ready vulnerability metrics. By making these patterns explicit, the study seeks not only to systematise the literature, but also to clarify the next priorities for research and cartographic applications in agricultural climate adaptation.

Accordingly, the article not only maps the bibliometric structure of the literature, but also derives a set of propositions on the field's developmental transition, its major methodological bottlenecks, and the priorities that should guide future cartographic and adaptation oriented research.

2 METHODOLOGY

With the aim of characterising the scientific evolution of remote sensing based crop climate vulnerability, bibliometric mapping was applied as a quantitative method grounded in mathematical and statistical models, designed to analyse scientific production, the intellectual structure, and patterns of scholarly communication within the domain (Hoyos-Alayo, 2026a). This approach synthesises trends, identifies influential authors, institutions, and countries, maps collaboration networks, and detects gaps and emerging lines of enquiry, offering an overarching view of the field of crop vulnerability and resilience in relation to remote sensing and climate change (Hoyos-Alayo, 2026b).

The study adopts a quantitative, exploratory descriptive approach, with a non experimental, longitudinal, and retrospective design. The analytical strategy focused on tracing and interpreting the evolution of the literature from the earliest records to the present, including 2026 records, in order to reconstruct trajectories, identify turning points, and assess the degree of thematic consolidation (Bellido-Valdiviezo et al., 2023; García et al., 2025; Hoyos-Alayo, 2026c). The method followed the stages proposed by Luna-Morales et al. (2023): (i) formulation of the general research question and the specific questions, (ii) selection of the reference database, (iii) construction of a reproducible search equation, and (iv) statistical analysis of indicators and visualisation of networks and themes.

Scopus was selected as the sole bibliographic source because it offers broad multidisciplinary coverage, rigorous indexing, exportable citation data and highly structured metadata for authors, affiliations, countries, references and keywords (Manuel Hoyos Alayo, 2025; Manuel Hoyos Alayo & Lourdes Vidal Taboada, 2025). These fields support consistent analyses of productivity, impact and collaboration. The exclusive use of Scopus avoided the additional duplicate removal and metadata incompatibilities that can arise when Scopus and Web of Science are merged. This decision favoured a reproducible workflow and internal comparability across the full corpus. Its main limitation is that some journals indexed only in other databases could remain outside the analysis, a point considered when interpreting the geographical and editorial distribution of the field. The search was executed on 13 February 2026, without language or time restrictions, to maximise retrieval for the domain. The canonical query used was: (TITLE-ABS-KEY ("remote sensing" OR "satellite imagery" OR "earth observation" OR "NDVI" OR "EVI" OR "Landsat" OR "Sentinel" OR "MODIS" OR "geospatial analysis") AND TITLE-ABS-KEY ("climate change" OR "climate variability" OR "global warming" OR "climate impact" OR "drought" OR "extreme weather") AND TITLE-ABS-KEY ("crop*" OR "agricultur*" OR "cropland" OR "farming system*" OR "food crop*" OR "plant production" OR "yield prediction" OR "crop yield") AND TITLE-ABS-KEY ("vulnerability" OR "resilience" OR "risk" OR "adaptation")).

The search equation used named indices and sensor systems as anchor terms, not as restrictive boundaries. NDVI, EVI, Landsat, Sentinel and MODIS were retained because they are dominant descriptors in agricultural remote-sensing studies and increase retrieval when crop vulnerability is discussed through vegetation condition, drought, yield prediction or climate risk. Broader expressions such as remote sensing, satellite imagery, Earth observation and geospatial analysis were included to capture other sensors, indices and platforms. The NOT operator was not applied because it could exclude relevant agricultural studies conducted in mixed landscapes, hydrological drought settings or biodiversity-related agroecosystems. Corpus specificity was therefore ensured through manual thematic screening rather than automatic exclusion.

In this context, 2,732 records were retrieved and exported in Comma Separated Values (CSV) format for statistical processing and visualisation. Prior to analysis, a manual thematic screening was conducted to exclude non relevant documents, ensuring corpus specificity and reducing the “noise” associated with publications lacking an agricultural or climate focus. Metadata were cleaned and organised in spreadsheets (Excel) for preprocessing and coherence checks across fields (authors, affiliations, keywords, and cited references), thereby ensuring the integrity and consistency of the dataset (Hoyos-Alayo, 2025; Osemwegie et al., 2023). This procedure yielded a final corpus of 2,343 records.

The bibliometric analysis was conducted using Bibliometrix 5.1.1 (2025), executed in the R environment, and VOSviewer 1.6.20 (2023), developed by Leiden University. Bibliometrix enabled the computation of productivity indicators (authors, countries, journals), impact indicators (total citations, average citations, and the h, g, and m indices), and scientific collaboration indicators (co-authorship and institutions). It also supported the application of classical bibliometric models such as Lotka’s Law (author productivity) and Bradford’s Law (journal cores) (Aria & Cuccurullo, 2024). VOSviewer was used to construct and visualise keyword co-occurrence networks, co-authorship networks, and bibliographic coupling, applying association strength normalisation and density based node representation (Sulphey et al., 2024; Van Eck & Waltman, 2024).

In addition, the Reference Publication Year Spectroscopy (RPYS) model was applied to identify the historical roots of the field and to detect citation peaks that represent methodological or conceptual milestones in the evolution of research on agricultural climate vulnerability. The combination of these methods enabled mapping of the intellectual structure, thematic evolution, and scientific collaboration networks surrounding the use of remote sensing to analyse crop vulnerability and resilience, providing an integrated account of the status, advances, and prospects of scientific knowledge on agricultural adaptation and climate sustainability.

3 RESULTS

Figure 1 presents a synthetic overview of the development achieved by research on remote sensing based crop climate vulnerability over the period 1985 to 2026. The analysed set comprises 2,343 documents distributed across 627 sources, showing sustained output and broad circulation of the topic across different editorial venues. The annual growth rate of 4% indicates steady expansion, associated with increasing demand for tools capable of tracking the effects of droughts, heatwaves, hydrological anomalies, and other climatic factors on agricultural systems. At the same time, the presence of 5,879 author keywords and 18,119 references reflects a broad thematic base and a progressive construction of analytical frameworks for examining crop exposure, sensitivity, and adaptive response.

It is also evident that this line of research rests on a markedly collective working structure. A total of 10,408 authors participate, with an average of 5.17 co-authors per document and an international collaboration rate of 35.3%, while only 116 authors are linked to single-authored works. This configuration suggests that the assessment of agricultural climate vulnerability through remote sensing requires the integration of agronomic, climatic, geospatial, and computational expertise. Added to this is a mean document age of 4.28 years and an average of 19.93 citations per document, features that position the topic as a recent, active, and increasingly influential agenda. In this sense, the evidence confirms that remote sensing no longer occupies a secondary place in the study of agricultural climate risk, but has instead become a technical and scientific basis for understanding, anticipating, and managing crop vulnerability under climate change.

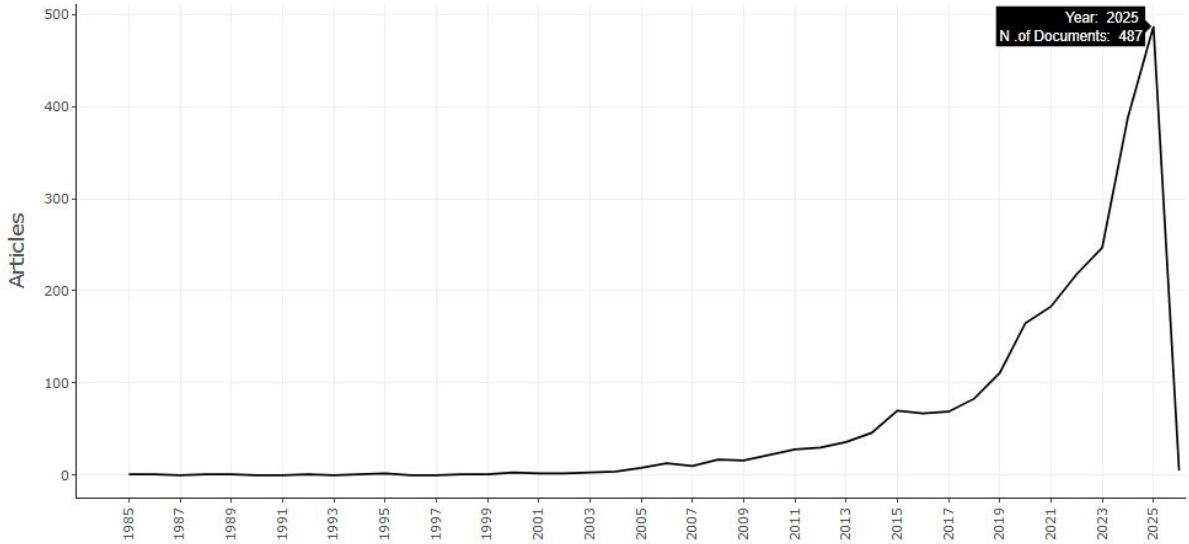
Figure 1 – General bibliometric indicators of the corpus.

Source: Summary of main information produced in Bibliometrix, based on Scopus metadata (2026).

Figure 2 shows a temporal trajectory that makes it possible to recognise how crop climate vulnerability assessed through remote sensing moved from being an emerging interest to becoming an increasingly visible line of work within the agricultural and climate agenda. Between 1985 and 2004, output was low and discontinuous, with values ranging from 0 to 4 articles per year, suggesting an initial stage characterised by isolated approaches and still limited use of satellite data to study the effects of climate on yield, water stress, and the spatial response of crops. From 2005 onwards, a change in pace becomes evident. Annual output rose from 8 publications in 2005 to 46 in 2014, indicating that the observation of agricultural surfaces began to be integrated more frequently into the analysis of droughts, thermal anomalies, and productive variability.

The increase became more pronounced from 2015 onwards. The series rose from 70 articles in 2015 to 111 in 2019, then to 165 in 2020, 218 in 2022, 247 in 2023, 388 in 2024, and reached its maximum in 2025 with 487 documents. This acceleration expresses a clear transition towards approaches that no longer merely describe damage, but seek to anticipate patterns of exposure, sensitivity, and risk in agricultural systems under greater climatic pressure. The low value for 2026, with 5 records, corresponds to the temporal cut-off of the database and does not alter the central growth trend. Taken together, the series confirms that remote sensing has become firmly established as analytical support for examining crop climate vulnerability across scales and contexts that are now decisive for agricultural adaptation.

Figure 2 – Annual scientific production.

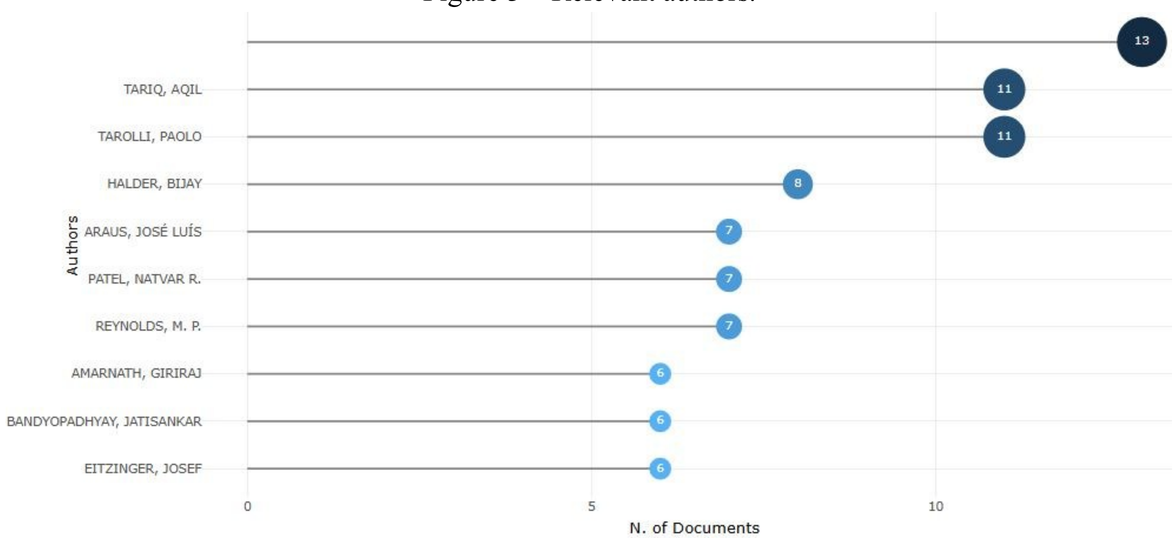


Source: Produced in Bibliometrix (2026) using Scopus metadata.

Figure 3 identifies a small core of authors with recurring presence in the study of remote sensing based crop climate vulnerability. The highest individual record reaches 13 documents, while Aqil Tariq and Paolo Tarolli each account for 11. They are followed by Bijay Halder with 8 contributions, and José Luís Araus, Natvar R. Patel, and M. P. Reynolds with 7. At a closely related level are Giriraj Amarnath, Jatisankar Bandyopadhyay, and Josef Eitzinger, each with 6 contributions. This distribution shows that the topic has been driven by a group of specialists maintaining research continuity in a field where agriculture, climate, Earth observation, and spatial analysis converge.

The pattern also reveals that the construction of knowledge on agricultural vulnerability does not depend on isolated authorship or on extreme concentration. Although there is recognisable leadership, the differences among the main contributors are moderate, suggesting a distributed scientific base and an expansion of the topic across several lines of work. In substantive terms, this is relevant because assessing crop responses to droughts, extreme heat, water stress, and climate variability requires the progressive accumulation of evidence and the continuous refinement of observation methods. In sum, the evidence indicates that remote sensing applied to crop climate vulnerability is advancing on the basis of a specialised community that already provides stability to the field and favours its consolidation as technical support for agricultural adaptation.

Figure 3 – Relevant authors.



Source: Extracted from Bibliometrix (2026).

Figure 4 shows that research on remote sensing based crop climate vulnerability rests on broad

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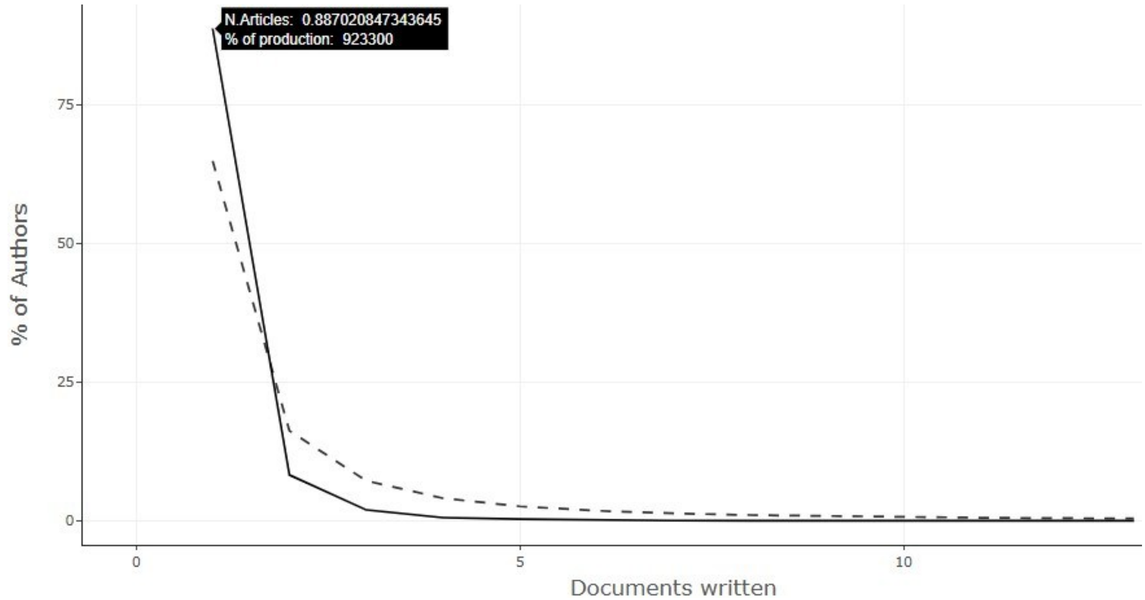
participation, but with uneven continuity. Most authors record only a single contribution, while the proportion falls sharply as the number of works per author increases. From the second document onwards, the curve declines rapidly until becoming marginal at higher productivity levels, indicating that the field attracts many researchers, although only a small group maintains a sustained presence.

This pattern is consistent with the nature of the topic. The assessment of agricultural vulnerability to droughts, extreme heat, water stress, and other climatic pressures brings together specialists in agronomy, remote sensing, climatology, spatial modelling, and data science. However, remaining active in this line of work requires methodological accumulation, access to time series, command of sensors, and the ability to integrate biophysical and climatic variables into consistent interpretative frameworks. For this reason, recurrent output tends to concentrate in a small number of authors, whereas a broad segment participates only occasionally through applications or specific territorial contexts.

In substantive terms, what is observed suggests that the topic is in a phase of expansion with a broad collaborative base, but still dependent on a specialised core that provides analytical continuity. This configuration reinforces the idea that remote sensing applied to crop climate vulnerability already has a critical mass of scientific interest, although its future consolidation will remain linked to the ability to sustain stable, comparable, and adaptation oriented research agendas.

Figure 4 – Distribution of authors by productivity, Lotka's Law.



Source: Extracted from Bibliometrix (2026).

Figure 5 shows that the study of remote sensing based crop climate vulnerability circulates above all in editorial spaces closely linked to Earth observation and applied environmental assessment. One leading source stands out with 253 documents, followed by Remote Sensing with 126 and Science of the Total Environment with 66. Next are Environmental Monitoring and Assessment with 48, Sustainability with 43, Proceedings of SPIE with 41, and International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences with 35. In nearby positions are Ecological Indicators with 33, Land with 31, and Water with 31. This pattern shows that the topic does not develop within a single stream, but rather at an intersection where remote sensing, environmental monitoring, territorial management, and the analysis of agroecosystems exposed to climate change converge.

The distribution also reveals an applied and increasingly operational orientation. The dominant presence of journals centred on remote sensing indicates that measuring crop climate vulnerability depends on satellite series, spectral indices, geospatial platforms, and modelling procedures capable of capturing thermal stress, water deficit, phenological changes, and yield variability. At the same time, the prominent appearance of sources linked to environment, sustainability, land, and water shows that agricultural vulnerability is already interpreted as a territorial and socioecological problem, rather than being restricted to crop behaviour in isolation. Within this framework, the evidence confirms that remote sensing applied to agricultural climate

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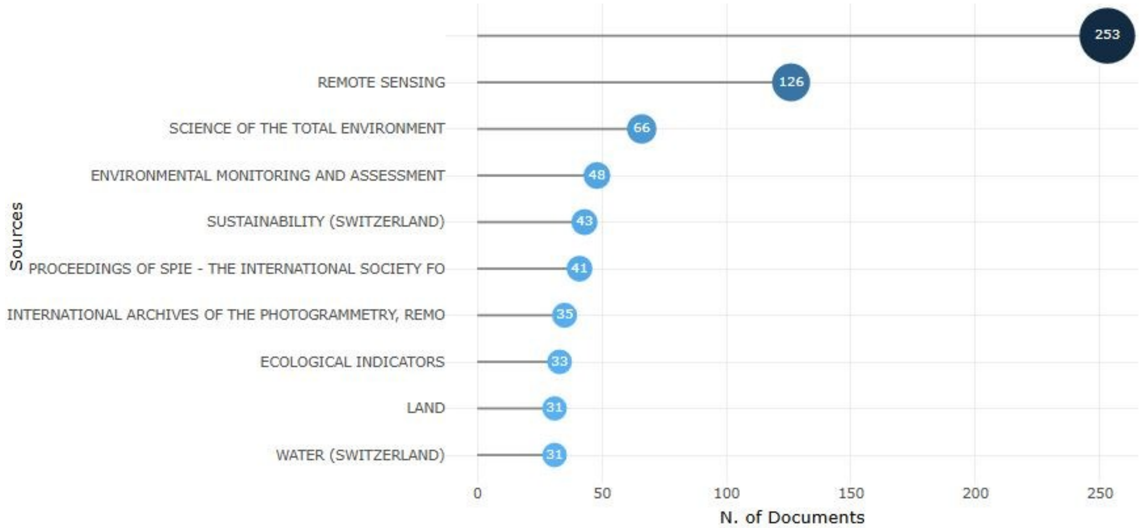
vulnerability has become established as a field with a solid technical anchoring and increasing projection towards the adaptive management of production systems under climate change.

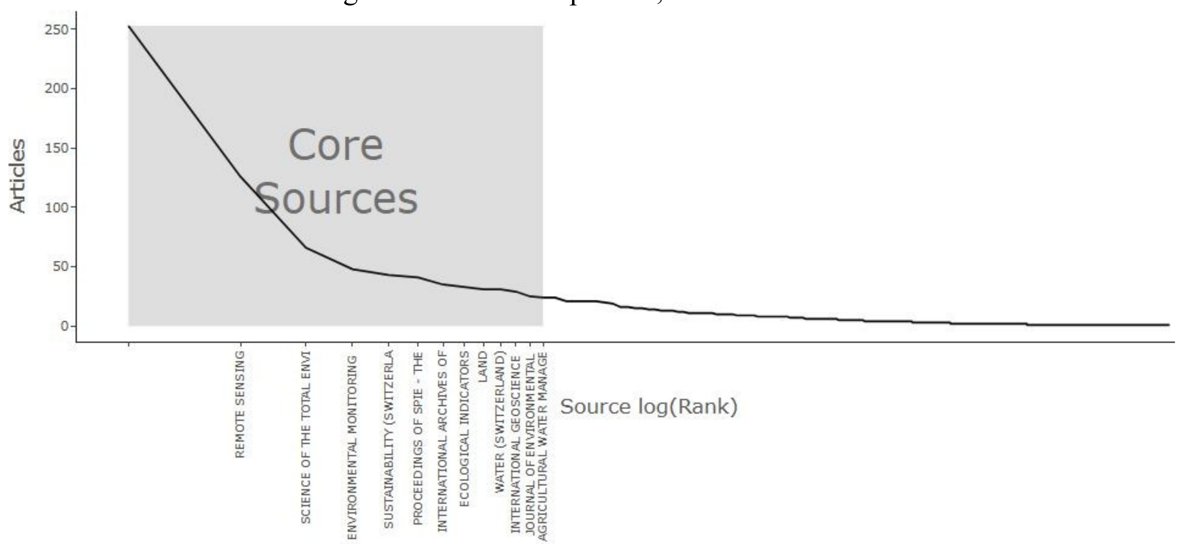
Figure 5 – Leading journals.



Source: Extracted from Bibliometrix (2026).

Figure 6 shows that output on remote sensing based crop climate vulnerability is not distributed evenly across journals, but is first concentrated in a clearly defined editorial core and then rapidly dispersed across a broad set of sources with lower volume. The curve declines sharply from the highest initial values to moderate levels in only a few steps, indicating that a limited fraction of journals absorbs most of the work linking satellite observation, climatic stress, water, soil, productivity, and agricultural adaptation. After this core, the slope flattens and forms a long tail, indicating that the topic also expands into more diverse spaces where regional applications, methodological approaches, and problem specific studies converge.

Figure 6 – Article dispersion, Bradford's Law.



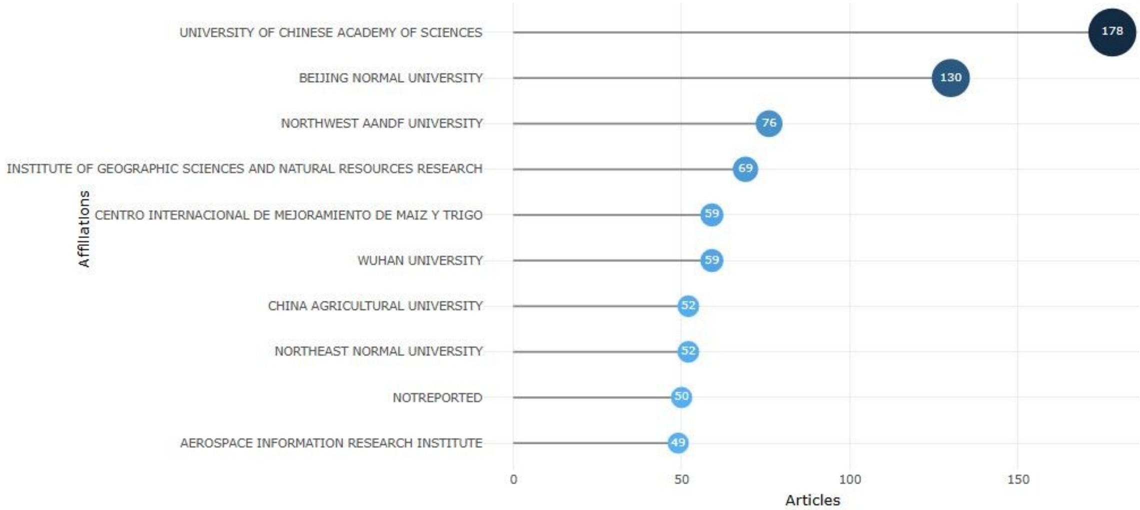
Source: Extracted from Bibliometrix (2026).

This behaviour makes it possible to recognise a diffusion structure already organised around specialised forums that function as points of reference for the analysis of droughts, extreme heat, hydrological anomalies, and crop responses under adverse climatic scenarios. At the same time, the extension of the curve towards numerous secondary sources shows that the topic has moved beyond its initial technical base and now projects into domains linked to sustainability, territorial management, water resources, and environmental assessment. What is observed is not merely editorial concentration, but a sign of thematic maturation. Agricultural climate vulnerability assessed through remote sensing already has a stable scientific diffusion core and, at the same time, a cross-cutting expansion that reinforces its usefulness for understanding production risks and supporting adaptation decisions in agricultural systems exposed to climate change.

Figure 7 shows clear institutional concentration around entities with strong capacity in Earth observation, geospatial analysis, and agricultural sciences. The University of Chinese Academy of Sciences leads with 178 articles, followed by Beijing Normal University with 130, Northwest A&F University with 76, and the Institute of Geographic Sciences and Natural Resources Research with 69. In a second group appear the International Maize and Wheat Improvement Centre and Wuhan University, both with 59 contributions, while China Agricultural University and Northeast Normal University each record 52. There are also 50 documents with no reported affiliation and 49 associated with the Aerospace Information Research Institute. Taken together, this reveals that knowledge generation on remote sensing based crop climate vulnerability is articulated to a large extent from institutions with experience in environmental monitoring, territorial modelling, and agricultural response under climatic stress scenarios.

The predominance of Chinese affiliations does not appear accidental. It reflects substantial installed capacity for working with satellite series, large scale analysis platforms, territorial validation, and broad agroecological scales, all of which are decisive for studying droughts, extreme heat, water availability, and changes in crop vigour. The prominent presence of the International Maize and Wheat Improvement Centre adds a strategic dimension, because it links remote observation with food security, genetic improvement, and the adaptation of production systems in vulnerable contexts. More than simple institutional leadership, what is observed is the consolidation of scientific poles capable of translating satellite data into useful evidence for anticipating risks, guiding agronomic decisions, and strengthening the climate resilience of agriculture.

Figure 7 – Institutional affiliations.



Source: Extracted from Bibliometrix (2026).

Figure 8 shows clear national leadership in output on remote sensing based crop climate vulnerability, with China in first place at close to 500 documents, followed by the United States with just over 400 and India with more than 300. At a second level appear Germany, the United Kingdom, and Italy, with intermediate volumes that clearly exceed one hundred publications, while Australia, France, Ethiopia, and Spain form an additional block with lower, but still relevant, values within the set. This distribution confirms that the analysis of crop exposure and response to droughts, extreme heat, hydrological anomalies, and climate variability is concentrated in countries that have consolidated technical capacities to integrate satellite observation, spatial modelling, and agroclimatic assessment, in line with the aim of the study and with the leadership already identified for China, the United States, and India in the overall corpus.

Asian and North American predominance suggests that evidence generation in this field advances more intensely where robust scientific infrastructures, sustained access to remote sensing data, and active agricultural adaptation agendas under climate change are in place. At the same time, the presence of countries such as Ethiopia among the leading positions is significant, because it indicates that crop climate vulnerability is also being studied intensively in territories where agricultural risk has direct effects on food security, rural

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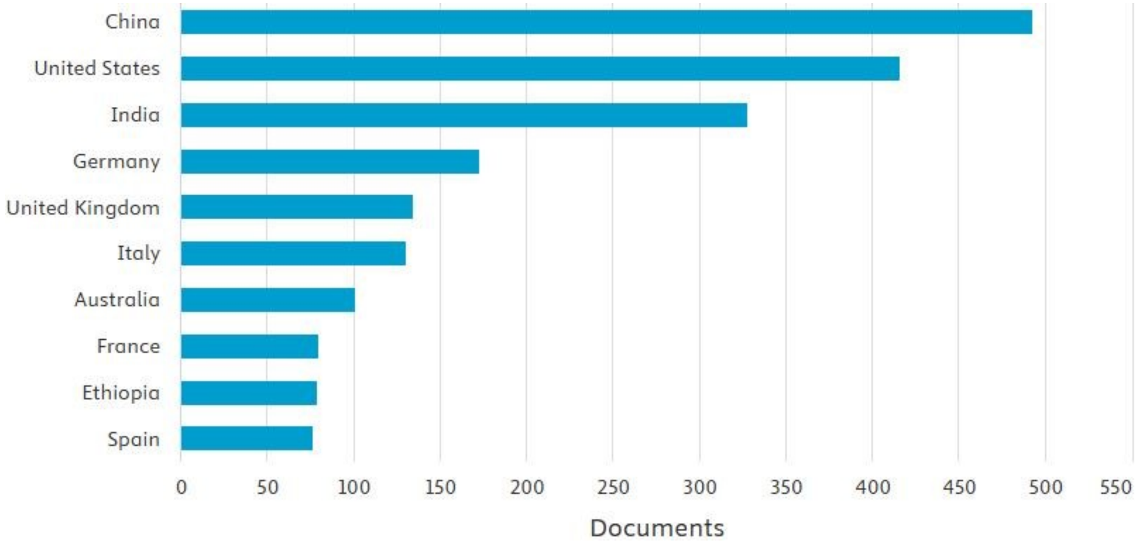
livelihoods, and productive resilience. Taken together, the evidence allows it to be stated that remote sensing applied to agricultural climate vulnerability is taking shape as a global agenda, although with clear centrality among countries that combine climatic pressure, agricultural scale, and the capacity to transform satellite information into useful knowledge for adaptation.

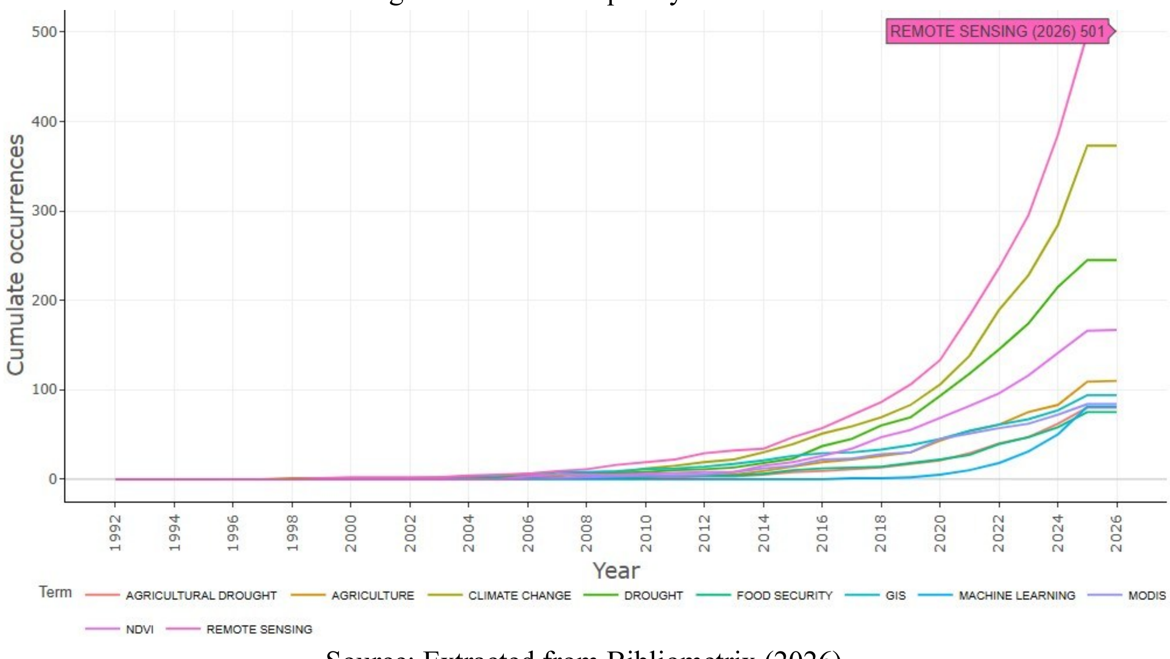
Figure 8 – Output by country.



Source: Extracted from Scopus "Analyse results" (2026).

Figure 9 shows the cumulative evolution of the terms that have structured the study of remote sensing based crop climate vulnerability and makes it possible to recognise a shift from a language centred on observation towards one increasingly oriented to climate risk assessment and decision-making. The highest cumulative values correspond to remote sensing, with 501 occurrences, and climate change, with 373, confirming that the field is built on the articulation between satellite monitoring and climatic pressure. From this base, drought reaches 245 occurrences and becomes established as the most visible problem within the thematic agenda, indicating that agricultural vulnerability has been interpreted above all through the effects of water deficit on crop functioning and productive stability. At the same time, NDVI reaches 167 and agriculture 110, reflecting a combination of biophysical measurement of vegetation condition and an applied reading of agricultural performance under environmental stress.

Figure 9 – Word frequency over time.



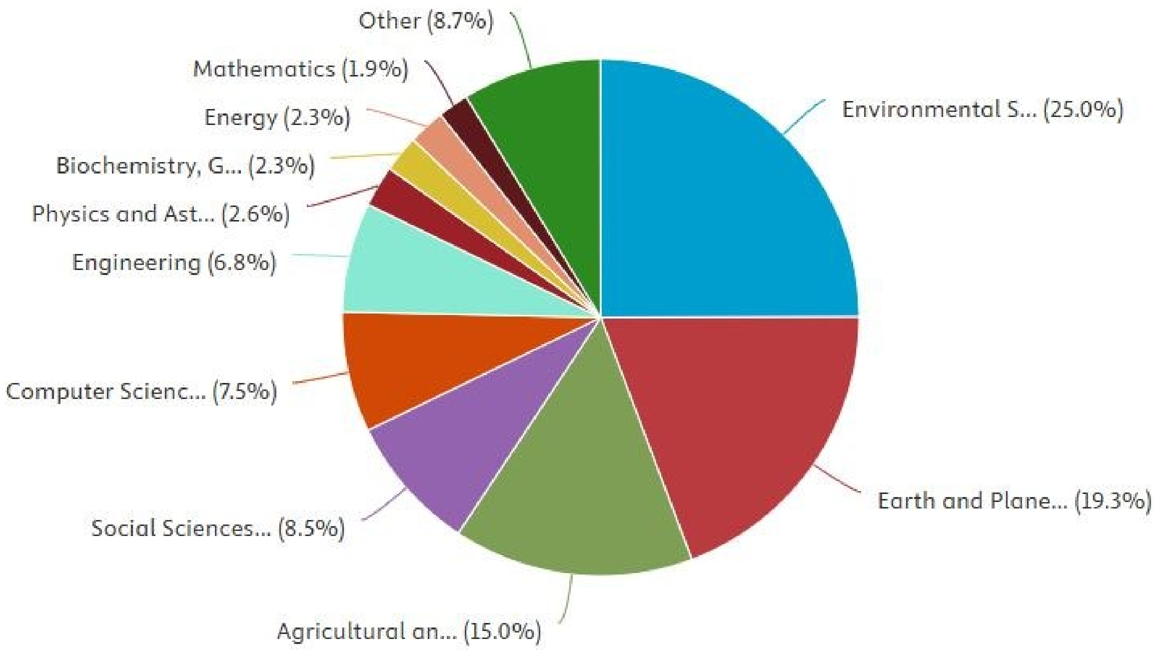
Source: Extracted from Bibliometrix (2026).

The temporal trajectory also reveals a methodological and operational transition. GIS accumulates 94 occurrences and MODIS 84, demonstrating the weight of spatial platforms and satellite series in multitemporal surveillance of crop response. However, the clearest shift appears in the recent rise of machine learning, which since 2017 has increased rapidly to 81 occurrences, already close to agricultural drought, with 80, and food security, with 75. This indicates that the agenda is no longer limited to describing impacts, but is moving towards predictive approaches capable of integrating climate, sensors, spatial patterns, and agricultural performance. Taken together, the evidence confirms that remote sensing based crop climate vulnerability has evolved into a more analytical framework in which drought, spectral monitoring, and intelligent modelling converge as central axes for anticipating risks and guiding agricultural adaptation.

Figure 10 shows that remote sensing based crop climate vulnerability has taken shape as a clearly interdisciplinary field, although with a dominant anchoring in environmental and Earth sciences. Environmental Science accounts for 25.0% of the total and Earth and Planetary Sciences contributes 19.3%, so that almost half of the output is located in areas devoted to the study of environmental processes, surface dynamics, climate, and territorial observation. Added to this is Agricultural and Biological Sciences with 15.0%, confirming that the analysis does not remain at the physical landscape level, but connects directly with crop behaviour, their sensitivity to droughts, extreme heat, and changes in water availability. In thematic terms, this combination indicates that agricultural vulnerability is understood as the result of interaction between climatic forcings, the biophysical response of vegetation, and the ecological conditions of the production system.

The presence of Social Sciences with 8.5%, Computer Science with 7.5%, and Engineering with 6.8% is also noteworthy, as these areas broaden the reading of the problem towards risk management, algorithm development, automation of spatial analysis, and the design of applied solutions. Although with lower relative weight, Physics and Astronomy with 2.6%, Biochemistry, Genetics and Molecular Biology with 2.3%, Energy with 2.3%, and Mathematics with 1.9% add instrumental, analytical, and functional components that reinforce monitoring and modelling precision. Taken together, the evidence shows that remote sensing applied to crop climate vulnerability no longer responds to a single discipline, but rather to a convergence of knowledge that makes it possible to observe, interpret, and anticipate agricultural risk from a territorial, ecological, and technological perspective.

Figure 10 – Publications by subject area.

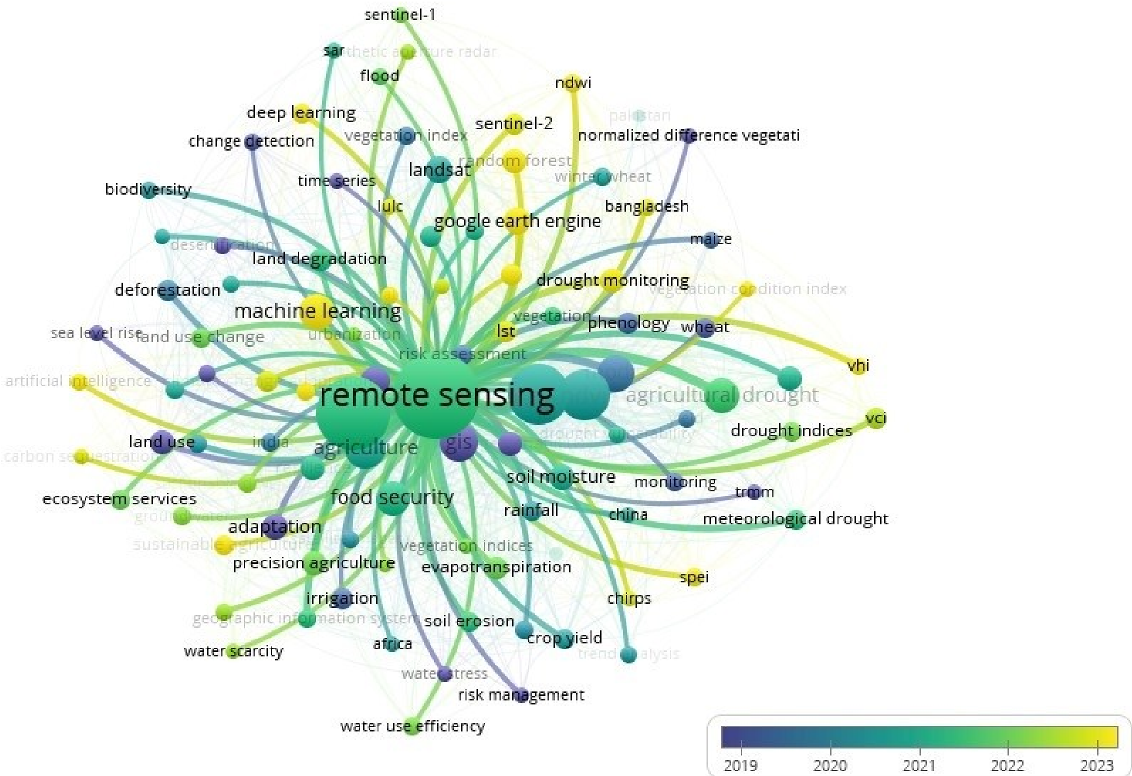


Source: Extracted from Scopus “Analyse results” (2026).

Figure 11 reveals a thematic structure organised around remote sensing as a central node, directly connected with agriculture, agricultural drought, machine learning, food security, soil moisture, GIS, and Google Earth Engine. This arrangement shows that crop climate vulnerability is studied from a basis that integrates satellite observation, biophysical diagnosis, and spatial analysis applied to concrete agricultural problems. The proximity among terms such as drought monitoring, drought indices, meteorological drought, evapotranspiration, rainfall, and crop yield indicates that the main focus lies on the detection of water stress and its effects on crop productive functioning. At the same time, the presence of Landsat, Sentinel-1, Sentinel-2, NDWI, VHI, VCI, and other spectral indicators confirms that vulnerability assessment relies on sensors and metrics capable of capturing changes in moisture, vegetation vigour, temperature, and surface condition with high temporal and spatial resolution.

The network also shows that this field has broadened its scope beyond basic monitoring. The association of machine learning, deep learning, time series, and change detection with agronomic and climatic terms suggests a move towards predictive approaches, useful for anticipating losses, identifying critical zones, and supporting adaptation decisions. In parallel, the connection with adaptation, irrigation, precision agriculture, water use efficiency, phenology, and food security shows a practical orientation linked to risk management and the resilience of production systems. The most recent tones are concentrated in tools such as Google Earth Engine, machine learning, drought indices, VHI, and VCI, while other terms close to the core reflect an already consolidated base. Taken together, the network shows that remote sensing applied to crop climate vulnerability has moved from describing impacts to building integrated systems of surveillance, prediction, and response to droughts and other climatic pressures on agriculture.

Figure 11 – Keyword co-occurrence.

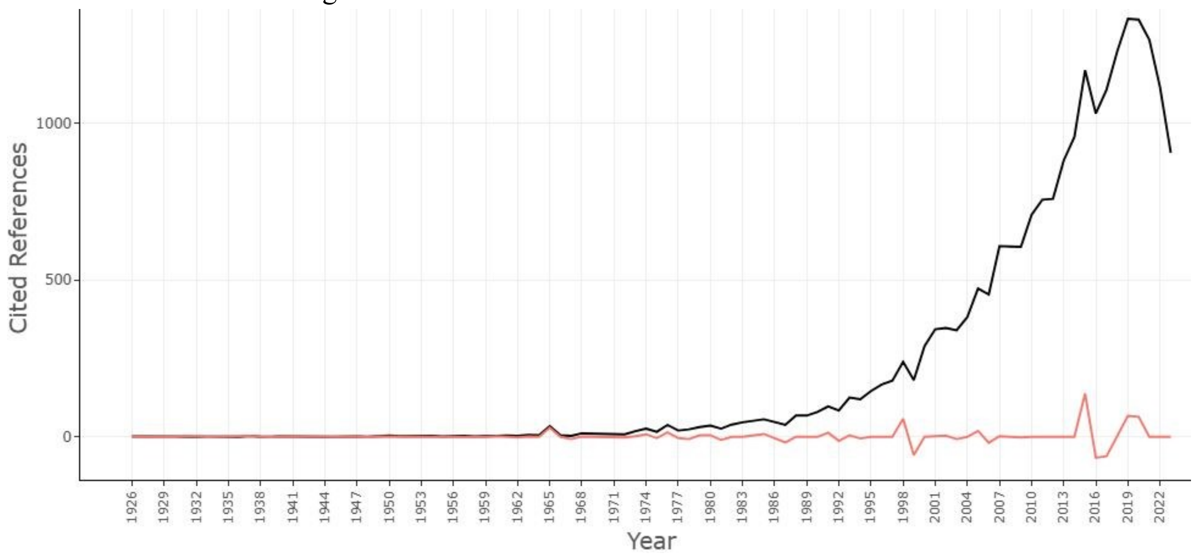


Source: Extracted from VOSviewer (2026).

Figure 12 makes it possible to recognise the historical sequence on which the study of remote sensing based crop climate vulnerability has been built. The main curve remains close to zero until the mid twentieth century, but begins to rise perceptibly from the 1970s onwards and accelerates clearly from the 1990s. Growth becomes much more intense after 2000 and reaches its highest density between 2015 and 2021, with a peak of close to 1,333 cited references in 2019. This trajectory indicates that the field did not arise from a single stream, but from the progressive convergence of drought climatology, remote observation of the land surface, hydrological modelling, and agronomic assessment of crop performance. The decline in 2022 and 2023 does not alter this reading, because it reflects the shorter citation accumulation time of the most recent works.

The deviation line relative to the median makes it possible to distinguish years that functioned as points of intellectual inflection. Among the oldest antecedents, 1965 stands out, associated with the classical formulation of meteorological drought, 1976 linked to land use and land cover classification using remote sensing data, and 1985, when a more precise understanding of drought and its hydrological metrics became consolidated. Next appear 1991 and 1993, years linked to the validation of remote classifications and the use of NDVI profiles for agricultural purposes, followed by 1998, which marked a milestone with guidelines on evapotranspiration and crop water requirements. Later, 2005 reinforced the relationship between vegetation dynamics, drought, and vulnerability, while 2015 stands out as the strongest break because of the centrality reached by drought remote sensing. The renewed impulse of 2019 confirms entry into a more integrated stage, oriented towards operational monitoring and impact assessment. What is observed makes it clear that the current agenda on agricultural climate vulnerability rests on a solid historical base, in which satellite monitoring moved from being an auxiliary tool to becoming central support for diagnosing, anticipating, and managing production risks under climate change.

Figure 12 – Annual distribution of cited references.

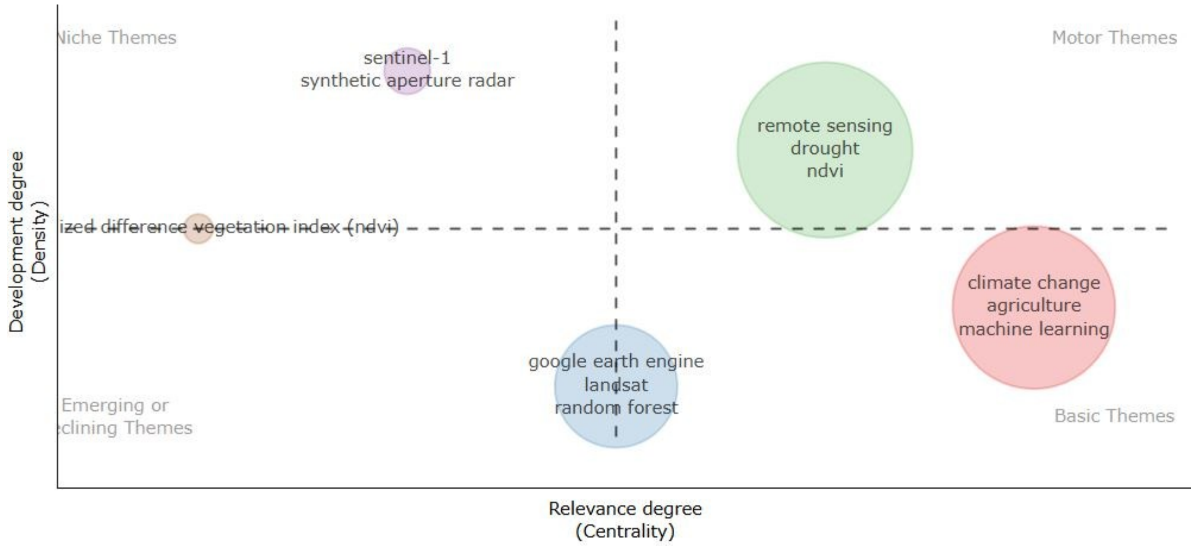


Source: Extracted from Bibliometrix (2026).

Figure 13 shows a thematic organisation in which remote sensing based crop climate vulnerability is structured around four nuclei with different functions within the field. In the zone of highest centrality and density appears the block formed by remote sensing, drought, and NDVI, indicating that spectral surveillance of water stress remains the most consolidated axis for interpreting crop responses under adverse climatic conditions. This is not merely a frequent association, but the core that articulates the biophysical reading of vegetation condition with the operational detection of agricultural drought. In parallel, climate change, agriculture, and machine learning occupy a position of high centrality, although with lower relative density, suggesting that they represent basic themes with broad connecting capacity and strong potential to reorganise the agenda towards predictive, integrative, and adaptation oriented frameworks.

An intermediate block can also be distinguished, composed of Google Earth Engine, Landsat, and random forest, situated in a transitional position. This location reflects a methodological base in expansion, still in the process of consolidation, but already decisive for scaling analyses, automating processing workflows, and strengthening the spatial estimation of agricultural risk. In the more specialised zone are Sentinel-1 and synthetic aperture radar, indicating technical developments with high internal density, useful in contexts where soil moisture, canopy structure, or cloud cover limit optical performance. Finally, normalised difference vegetation index appears displaced towards a quadrant of low centrality, indicating that, although it retains historical and operational value, it no longer monopolises thematic innovation. What is observed makes it possible to affirm that the field is moving from an approach centred on classical drought and vegetation indices towards a stage in which large scale processing platforms, more diverse sensors, and learning algorithms converge in order to anticipate crop climate vulnerability with greater precision.

Figure 13 – Thematic map.



Source: Extracted from Bibliometrix (2026).

3.1 Complementary technical and reproducibility synthesis

Beyond the bibliographic indicators, the corpus shows a clear technical hierarchy in the way crop climate vulnerability is measured. Optical multispectral systems remain the most visible family because MODIS, Landsat and Sentinel-2 are repeatedly associated with NDVI, EVI, NDWI, VHI, VCI, drought monitoring, crop yield and vegetation condition. This pattern indicates two complementary uses. MODIS supports long historical time series for regional drought and vegetation anomaly assessment, while Landsat and Sentinel-2 support higher-spatial-resolution mapping of crop condition, phenology and landscape-level vulnerability.

Radar, microwave and thermal approaches form a more specialised but strategically important line. Sentinel-1, synthetic aperture radar and soil moisture products such as SMAP are linked to soil water status, canopy structure and cloud-independent monitoring, while land-surface temperature, evapotranspiration, rainfall and reanalysis products such as ERA5-Land and CHIRPS connect spectral response with climate drivers. This multi-sensor structure confirms that the field is moving from greenness-based diagnosis towards integrated monitoring of water deficit, heat stress and compound climatic pressure.

The temporal structure of the literature also indicates systematic use of multitemporal data. Terms such as time series, change detection, drought monitoring, phenology and yield prediction show that most recent applications are no longer based on isolated images, but on repeated observations capable of detecting anomaly persistence, seasonal trajectories and interannual transferability. This is central for vulnerability analysis because climate risk depends on duration, recurrence and cumulative stress, rather than the intensity observed on a single date alone.

The computational profile is dominated by machine learning and cloud-based processing. Machine learning, random forest and Google Earth Engine occupy a more central position than deep learning, suggesting that the field currently relies on scalable supervised models and automated geospatial workflows rather than on fully deep-learning-centred architectures. Deep learning appears as an emerging methodological line, mainly linked to classification, prediction and data fusion, while random forest remains one of the most operational algorithms for vulnerability mapping and crop stress detection.

Regarding reproducibility, the exported Scopus metadata do not include a structured field that identifies whether each article provides datasets, source code or repository links. For this reason, an article-level percentage of dataset or code availability was not calculated, because it would require manual full-text verification beyond the bibliometric metadata. The reproducibility signal identified in the corpus is therefore indirect and is linked to open processing environments, public Earth observation products and platform-based workflows. This limitation should be considered when interpreting the operational maturity of the field.

4 DISCUSSION

Figures 1 and 2 indicate that the growth of the field does not respond merely to an increase in publications, but to the incorporation of Earth observation into the core of agricultural adaptation. When output accelerates after 2015, what expands is not a methodological fashion, but a scientific infrastructure designed to track impacts, anticipate losses, and inform risk management decisions (Abdulwahid et al., 2025). This interpretation is consistent with Sarah et al. (2025), who place satellite indicators within the monitoring of the Global Goal on Adaptation (United Nations, 2020), and with Zubair et al. (2025), who show that agricultural drought forecasting already depends on hybrid frameworks combining remote sensing and machine learning. In this context, the observed expansion suggests that crop climate vulnerability is no longer treated as an isolated effect of climate, but is increasingly understood as a problem of continuous surveillance, operational forecasting, and anticipatory response within food systems (Aduko et al., 2025).

Figures 3 and 4 suggest that the relative concentration of recurring authors does not indicate thematic closure, but rather a high technical threshold. Remaining within this agenda requires dense time series, cross sensor calibration, field data, and the capacity to translate spectral signals into agronomically useful variables. This barrier explains why many researchers enter the topic only occasionally, whereas a small core sustains its conceptual and methodological continuity (Ahmed et al., 2025). This interpretation is consistent with Kim et al. (2025), who show that NDVI correction between Sentinel-2 and Landsat-8/9 requires phenology specific calibration, with Sengupta & Chu (2025), who integrate residual learning and sensor networks to estimate soil moisture in near real time, and with Sharma et al. (2025), where the construction of ground truth proves decisive for robust drought detection. In theoretical terms, stable leadership is associated less with numerical productivity than with the ability to articulate measurement, validation, and transferability.

Figures 5 and 6 show that the diffusion of knowledge is organised around journals in which remote sensing, applied hydrology, and environmental assessment share a common space. This pattern carries a substantive implication, because it indicates that crop climate vulnerability is not legitimised within agronomy in isolation, but at interfaces where spatial data must be transformed into usable evidence for irrigation, soil management, degradation monitoring, and adaptation (Goroee & Bazrafshan, 2025). Lakshmi et al. (2025) processed a battery of indices in Google Earth Engine to monitor agricultural drought and irrigation strategies in Türkiye, while Bhattacharjee et al. (2025) integrated remote sensing and SDG 15.3.1 to identify degradation and vulnerability in the trans Gangetic plains. From this perspective, the observed editorial concentration reflects a preference for publication settings in which cartography, GIS, and remote sensing do not describe spatial patterns in isolation, but instead support decisions on productive resilience and resource conservation (Sims et al., 2025).

Figures 7 and 8 show that production is concentrated in China, the United States, India, and a smaller group of countries with strong geospatial capacity, but this concentration should not be read as scientific leadership alone. It also reveals that research follows territories where high climatic exposure, pressure on water and soil, and the need to sustain strategic production volumes converge. Attia et al. (2025) mapped zones of vulnerability and adaptive potential for major crops in Texas, Wang et al. (2025) delineated zonal strategies for compound dry and hot events in the middle Yangtze basin, and Yimam & Woldmariam (2025) applied satellite based assessment of agroclimatic drought in north eastern Ethiopia. Zeleke et al. (2025) reinforce this interpretation by showing that the vulnerability of smallholder farmers requires the integration of biophysical signals and social conditions. Thus, the geography of production does not merely identify countries with greater scientific capacity, but also marks where remote observation becomes indispensable for sustaining agricultural adaptation under persistent risk (Sharma & Dadheech, 2026).

Figures 9 and 11 confirm that drought remains the principal organising axis of the field, although its treatment no longer rests on a limited repertoire of classical indices. The centrality of drought, NDVI, soil moisture, evapotranspiration, machine learning, and Google Earth Engine shows a shift from vegetation vigour proxies towards systems that combine diagnosis, attribution, and forecasting. Mao et al. (2025) demonstrated that spatiotemporal drought forecasting in irrigated agriculture improves through multi source integration, Liou & Thai (2025) proposed a relative evapotranspiration index to characterise drought with greater physical sensitivity, and Lakshmi et al. (2025) showed the value of combining MODIS, CHIRPS, ERA5-Land, and

SMAP within a single analytical workflow. The significance of this transition is clear. Vulnerability is no longer inferred solely from declining greenness, but from the interaction between water availability, land surface temperature, system memory, and crop response across different temporal scales (Song et al., 2023).

Figures 10 and 11 indicate that the field has shifted towards a broader conception of vulnerability, in which the crop is not interpreted as an isolated object, but as part of a socioecological system exposed to cascading impacts. This thematic expansion is consistent with Serkendiz et al. (2025), who propose a framework linking hazard, biophysical drivers, socioecological effects, and socioeconomic outcomes, and with Monteleone et al. (2023), who synthesise crop vulnerability through curves capable of relating event intensity to damage magnitude. At the same time, Sarah et al. (2025) warn that the value of Earth observation for adaptation depends on resolving attribution, disaggregation, and the integration of past and future data. Under this interpretation, the joint presence of environmental sciences, agricultural sciences, computing, and social sciences does not constitute a casual disciplinary mix. It expresses the need to combine spatial measurement, understanding of damage, and the design of adaptive responses with territorial relevance (Sun et al., 2025).

Figures 12 and 13 make it possible to identify a historical trajectory from drought and vegetation monitoring towards the assessment of compound risk and prediction transferable across years and regions. RPYS shows that the foundations of the field rest on milestones that made it possible to measure water, energy, and vegetation condition, while the thematic map confirms that the most dynamic current core incorporates machine learning, Google Earth Engine, random forest, Sentinel-1, and multiple sensors. This evolution is consistent with Hao et al. (2019), who proposed a monitoring and forecasting system for compound dry and hot events, and with Mukherjee & Mishra (2021), who documented the rise of compound droughts associated with heatwaves in a warmer climate. The recent direction of the field also aligns with Zhou et al. (2025), where SAR and optical fusion improves early yield prediction, and with Yu et al. (2026), who show interannual transferability for rice through Sentinel-2 derived GPP. Taken together, the discussion suggests that the agenda is no longer oriented towards mapping stress once established, but towards detecting vulnerability trajectories before productive loss becomes consolidated (Valjarević et al., 2025).

4.1 Propositions that advance the state of the art, future perspectives, and main challenges

The evidence generated in this study supports four propositions that help advance the state of the art of research on remote sensing based crop climate vulnerability.

Research on remote sensing based crop climate vulnerability has moved beyond descriptive spectral tracking and entered a phase of predictive geospatial intelligence. The combined rise of machine learning, Google Earth Engine, SAR, thermal data, and multivariate modelling shows that remote sensing is increasingly used to anticipate vulnerability trajectories, yield instability, and climate related production risks rather than merely document already manifested stress.

This transition remains geographically uneven and epistemically asymmetric. Scientific leadership is concentrated in Asia and North America, while Latin America and Africa remain weakly represented in publication, calibration, and funding networks. As a result, many thresholds, models, and interpretive schemes are derived from a restricted set of agroecological contexts, which limits transferability across tropical, mountain, and semi arid farming systems.

The next frontier of the field is methodological interoperability rather than additional data accumulation. Future progress depends on integrating optical, thermal, hyperspectral, SAR, climatic, and socioeconomic information within comparable vulnerability frameworks grounded in exposure, sensitivity, and adaptive capacity. Without that integration, the field will continue to grow bibliometrically while remaining fragmented analytically.

The central unresolved challenge is the operational conversion of remote sensing outputs into decision ready vulnerability intelligence. The field already shows strong capacity to detect and model stress, but it still requires stronger in situ validation, regional calibration, FAIR oriented data governance, and more robust translation into cartographic products useful for adaptation planning, early warning systems, irrigation management, and territorial agricultural risk governance.

Taken together, these propositions indicate that the present state of the art is no longer defined by the mere expansion of remote sensing applications in agriculture. It is defined by the ability to build transferable, multiscale, and policy relevant cartographic intelligence that links Earth observation, vulnerability theory, and adaptation decision making under heterogeneous climatic conditions.

4.2 Limitations and reproducibility considerations

The interpretation of the results should consider three methodological limitations. First, the corpus was built exclusively from Scopus, which strengthens metadata consistency but may omit records indexed only in other databases. Second, the search equation intentionally privileged retrieval through widely used remote-sensing descriptors and controlled specificity through manual screening. This decision avoided the loss of relevant agricultural studies that combine crop vulnerability with hydrology, land cover, forest-agriculture mosaics or biodiversity-related agroecosystems. Third, the bibliometric export did not allow a robust statistic on data and code availability. Future bibliometric studies should combine metadata analysis with full-text mining to quantify repository use, dataset sharing, code publication and FAIR compliance in crop climate vulnerability research.

5 CONCLUSIONS

This study demonstrates that research on remote sensing-based crop climate vulnerability has evolved from a dispersed set of monitoring studies into a mature scientific domain with a strong technological and collaborative base. Sustained growth in publications, consolidation of an editorial core, rising international cooperation and the increasing presence of cloud platforms, multi-sensor approaches and predictive algorithms confirm that the field has progressed towards higher analytical sophistication. The complementary technical reading shows that MODIS, Landsat and Sentinel-2 remain central for vegetation and drought monitoring, while Sentinel-1, SAR, SMAP, thermal variables and reanalysis or precipitation products strengthen moisture and compound-risk analysis. The recurrent use of time series, change detection, Google Earth Engine, random forest, machine learning and emerging deep-learning workflows confirms the transition towards multitemporal and predictive geospatial intelligence.

The article’s main contribution lies in interpreting that evolution as a transition from descriptive spectral monitoring to predictive and operational geospatial intelligence. This shift advances the state of the art because it redefines remote sensing not merely as an observational tool, but as a framework for anticipating crop vulnerability, supporting adaptive management, and informing climate sensitive agricultural decision making.

At the same time, the study shows that the field’s consolidation remains incomplete. Methodological fragmentation, uneven geographical representation, weak comparability across scales and sensors, and the limited translation of remote sensing outputs into decision ready vulnerability metrics continue to constrain broader applicability.

Future research should prioritise the integration of biophysical and socioeconomic dimensions, the interoperability of sensors and analytical frameworks, stronger territorial validation in underrepresented regions, open and auditable data and code practices, and the production of cartographic outputs directly usable in adaptation planning, early warning systems and agricultural risk governance. Under this reading, the field advances not when it produces more maps, but when it produces more transferable, reproducible and operational knowledge.

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Author' Contributions

Walter Manuel Hoyos Alayo, was responsible for conceptualisation, methodology, software, validation, formal analysis, investigation, data curation, visualisation, writing the original draft, reviewing and editing the manuscript, supervision, and project administration. The author read and approved the final version of the manuscript.

Conflicts of Interest

The author declares no conflict of interest.

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