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Fertilization in Maize Globally and in Mexico: a Bibliometric Analysis from 2000 to 2025
Fertilización en Maíz a Nivel Global y en México: Análisis Bibliométrico del 2000 al 2025

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SUMMARY

Maize (*Zea mays* L.) production plays a fundamental role in global food security due to its importance as a staple food and as an essential component of the basic food basket, as well as its socioeconomic and cultural relevance in Mexico. Maize fertilization is one of the main practices used to increase yield, and maintaining soil health is currently considered a priority. Sustainability and the search for new methods and complementary fertilization approaches have gained importance in order to improve the efficiency of these practices, reduce harmful side effects, and optimize the use of natural and economic resources. This study was conducted to identify and quantify, through bibliometric analysis, the scientific production related to maize fertilization over the past 25 years (2000–2025). Two databases, Scopus and Google Scholar, were used, applying bibliometric methods based on performance analysis (H-index, productivity, and citations) and scientific mapping (keyword co-occurrence) for the corresponding period. VOSviewer and Excel were used to evaluate the bibliometric indicators. The findings revealed a polynomial global trend in scientific publications related to this topic, as well as Mexico's contribution, which showed a linear pattern followed by a decline in recent years. The most prolific authors, predominant journals, leading papers, institutions, the most influential countries, and the main research lines in this field were identified both globally and within Mexico. The main benefits of conducting this study include the global exploration of research themes and ongoing or implemented research lines, as well as facilitating the reorientation and support of future research related to this subject.

Index words: *fertilizer, scientific mapping, Scopus, VOSviewer, Zea mays L.*

RESUMEN

La producción de maíz (*Zea mays* L.) desempeña un papel fundamental en la seguridad alimentaria mundial debido a su prioridad e importancia como alimento básico para la población, siendo un componente esencial de la canasta básica alimentaria, así como de los sectores socioeconómico y cultural en México. La fertilización del maíz es una de las principales actividades para aumentar el rendimiento, y actualmente, mantener la salud del suelo también se considera una prioridad; se prioriza la sostenibilidad y la búsqueda de nuevos métodos y formas de complementar la fertilización, con el fin de hacer estas actividades más eficientes, reducir los efectos secundarios perjudiciales y optimizar el uso de los recursos naturales y la economía. Este estudio se realizó con el objetivo de identificar y cuantificar, mediante análisis bibliométrico, la producción científica relacionada con

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la fertilización del maíz durante los últimos 25 años (2000-2025). Se utilizaron dos bases de datos, Scopus y Google Académico, mediante métodos bibliométricos con análisis de desempeño (índice H, productividad y citas) y mapeo científico (coocurrencia de palabras clave) para el período correspondiente. Se utilizaron los programas VOSviewer y Excel para evaluar los indicadores bibliométricos. Se encontró que existe una productividad global polinómica de publicaciones científicas relacionadas con este tema, así como la contribución de México, con un comportamiento lineal y una disminución en los últimos años. Se identificaron los autores con mayores contribuciones, las revistas predominantes, los artículos principales, las instituciones, los países más influyentes y las líneas de investigación en este campo de estudio, tanto a nivel global como en México. Los principales beneficios de realizar este estudio son la exploración global de los temas y las líneas de investigación en desarrollo o ya implementadas, así como la facilitación de la reorientación y el apoyo a futuras investigaciones relacionadas con el tema.

Palabras clave: *fertilizante, mapeo científico, Scopus, VOSviewer, Zea mays L.*

INTRODUCTION

Maize (*Zea mays* L.) production plays a direct or indirect role in global food security and is a species of economic importance, with 20 million hectares cultivated worldwide (FAO, 2023). To meet the food demand of 9.1 billion inhabitants, the current challenge is to increase global production by up to 70% between 2007 and 2050 (FAO, 2009). Recently, it was reported that in 2024 global maize grain production reached 1.21 billion metric tons, contributed primarily by the United States of America, China, and Brazil (USDA, 2025). In contrast, Mexico contributed with a production of 27.5 million metric tons (SIAP, 2023).

Within the framework of food self-sufficiency, improving crop yields is of paramount importance. However, this objective has not been fully achieved, primarily due to two factors: (a) the limited use of fertilizers and (b) degraded soils and low nutrient availability (Campolo, Ortiz, Guerena, and Lobell, 2020). According to FAO, 33% of the world's soils are degraded, and if the current trend continues, by 2050 up to 90% of soils may reach a critical state of fertility. Considering this alarming situation, research on maize fertilization practices has increased substantially over the past two decades. This research encompasses aspects such as the application of chemical and organic fertilizers, balanced nutrition, nitrogen use efficiency, soil management, environmental impact, and genetic improvement, among others. These approaches highlight the multidisciplinary interest in improving productivity and ensuring sustainable maize production (Yan and Tan, 2019). In recent years, studies related to maize fertilization have focused on particular aspects, which open the opportunity for research such as the one addressed in this work. This study is based on the hypothesis that bibliometric analysis using H-index indicators, scientific productivity, number of citations, and scientific mapping by keyword co-occurrence can serve as an efficient and rigorous method to explore and analyze large volumes of scientific data, allowing for the disaggregation of information and the observation of publication trends using software such as Gephi, Leximancer, and VOSviewer, along with databases such as Scopus and Web of Science (Donthu, Kumar, Mukherjee, Pandey and Lim, 2021; Öztürk, Kocaman, and Kanbach, 2024). Moreover, bibliometric analysis makes it possible to understand collaboration patterns, the intellectual structure, and the evolution of scientific production, as well as to identify recently investigated or emerging topics and potential areas of opportunity within a specific field. The objective of this study was to identify and quantify, through bibliometric analysis, the scientific production related to maize fertilization during the last 25 years (2000–2025), using information available in Scopus and Google Scholar, with the support of Microsoft Excel® and VOSviewer 1.6.20 (Van Eck and Waltman, 2023)

MATERIALS AND METHODS

Search, Filtering, and Collection of Publications for Global Bibliometric Analysis

On the Scopus platform, a search was conducted for papers related to "fertilization maize" OR "fertilization" AND "maize." The expressions used for titles, abstracts, and/or keywords (TITLE-ABS-KEY) were fertilization AND maize. This search yielded a total of 7,103 publications. Subsequently, filtering was carried out using the inclusion and exclusion criteria described in Figure 1.

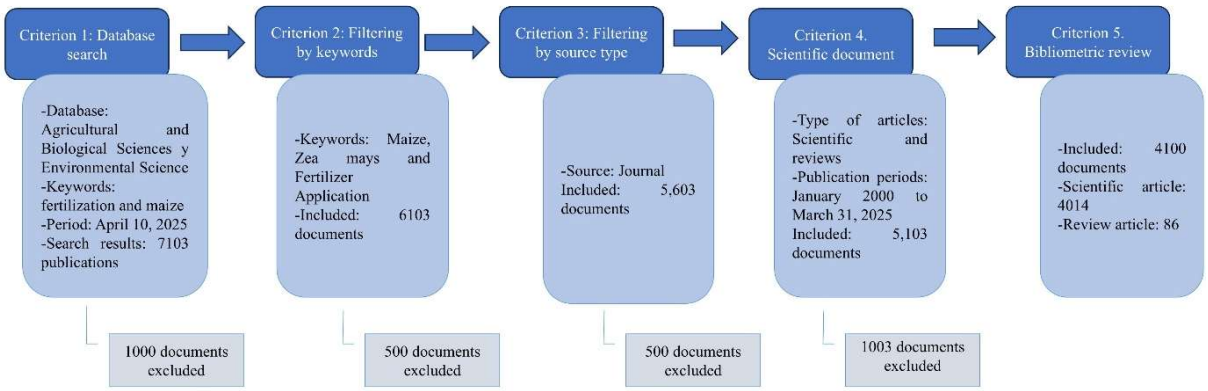

Figure 1. Process of searching, filtering, and selecting publications related to maize fertilization, presented at a global scale.

Search, Filtering, and Collection of Publications for National Bibliometric Analysis

In the specialized search engine Google Scholar, an advanced search was conducted on April 10, 2025, based on five criteria to identify research carried out in Mexico.
Criterion 1. Using the expression "maize fertilization" under the condition "all words" and the search period "2000 to 2025," a total of 519 papers were obtained.
Criterion 2. The search was limited to two types of papers—scientific and reviews—which yielded 132 papers.
Criterion 3. Publications previously identified and collected in Scopus that also appeared in Google Scholar were excluded, resulting in 124 papers (123 scientific papers and 1 review).
Finally, a database was compiled with the records of the 77 and 124 papers obtained from Scopus and Google Scholar, respectively, for a total of 201 papers for Mexico. This number of papers is considered the minimum recommended to conduct a bibliometric analysis (200 publications) (Rogers, Szomszor, and Adams, 2020).

Bibliometric Indicators Analyzed at the Global and National Levels

Once the processes of searching, filtering, and collecting publications were completed, the total records obtained from Scopus and Google Scholar were exported into Excel® and VOSviewer in plain text format for the analysis of bibliometric indicators at the global and national levels. Globally, the analysis included scientific production growth using linear regression with Proc Reg of SAS® 9.4, Cary, NC, USA, 2012 (SAS Institute, 2013), identification of the countries with the highest number of papers, the most representative publications, the performance of the leading authors (H-index, number of publications, and total citations), and scientific mapping (keyword co-occurrence). For Mexico, performance analysis and scientific mapping were carried out, including the trend of scientific production growth through linear regression with SAS® 9.4, the most cited papers, the authors with the highest citation counts, the leading journals with the greatest number of publications, and keyword co-occurrence mapping. The normalization or standardization of proper names and keywords was performed by developing two thesaurus in Microsoft Excel® to evaluate the performance of the main authors and to construct the scientific mapping.

RESULTS AND DISCUSSION

Trend in the Growth of Scientific Production at the Global Level

The evident and steady growth in the literature related to maize fertilization over the past 25 years (2000–2025) can be explained by a polynomial model ($R^2 = 0.98$), as shown in Figure 2. Within the study period, 4100 papers were retrieved, including research papers and review papers. The annual average of publications during the first five years was 53; from 2006 to 2017, the mean increased to 153.5 papers per year; and in recent years (2018 to March 2025), an average of 262 papers were published annually. This trend illustrates a steady growth pattern in scientific productivity related to the subject of study. Regarding the increase in the collected literature over time, the results show that in the first decade of the study (2000–2009), 781 publications were accumulated; in the second evaluated decade (2010–2019), 1839 were compiled; and in the most recent five years and three months (2020 to March 2025), the total reached 1480 papers.

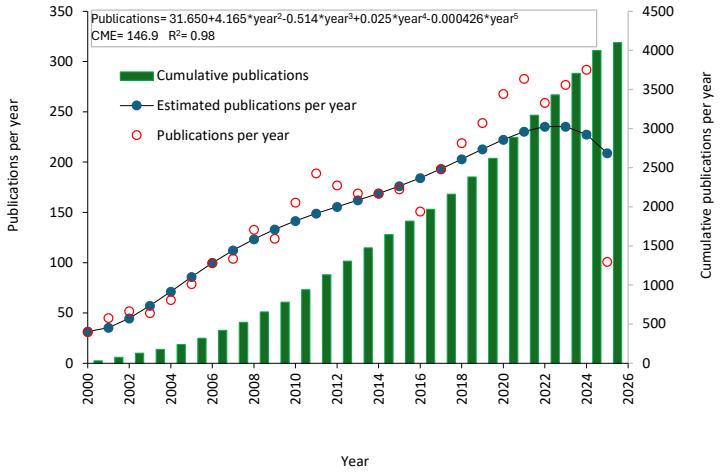

Figure 2. Annual and cumulative publications on maize fertilization from 2000 to 2025, indexed in Scopus.

The first paper related to maize fertilization addressed the impact of fertilization on the evolution of carbon dioxide and nitrogen mineralization in a Dark Red Latosol under different management practices (Marqués, Vasconcellos, Pereira, Franca, and Cruz, 2000). In contrast, the most recent publication on this topic was the paper titled "*Are Gaseous Nitrogen Losses Affected by the Type and Rate of Fertilizer in Maize*?" (Hernández *et al.*, 2025).

Countries with the Highest Number of Publications

The leading country in this field is China, with the highest share of scientific output (26%), followed by the United States of America (11%), Brazil (7%), and Germany (6%) as the most representative contributors (Figure 3). China's strong focus on this field is primarily due to the fact that maize is the second most important crop in the country, accounting for 19% of global production (FAO, 2012), surpassed only by the United States of America, the world's largest maize producer, which contributes 25% (Ranum, Peña, and Garcia, 2014).

China has committed to increasing maize yield in recent years in areas with the potential to improve the productivity of this crop (Meng *et al*., 2013); this has led to its predominance in the field of study, even ahead of the United States of America. In this regard, Mexico contributes 1% of the scientific output, a situation linked to the challenges the country faces in maize production. In 2019, for instance, Mexico imported 16 million tons of yellow maize, mainly from the United States (SADER, 2020). The remaining 23% of publications come from a group of countries, each contributing less than 1%, including Kenya, Belgium, Egypt, and South Africa, among others.

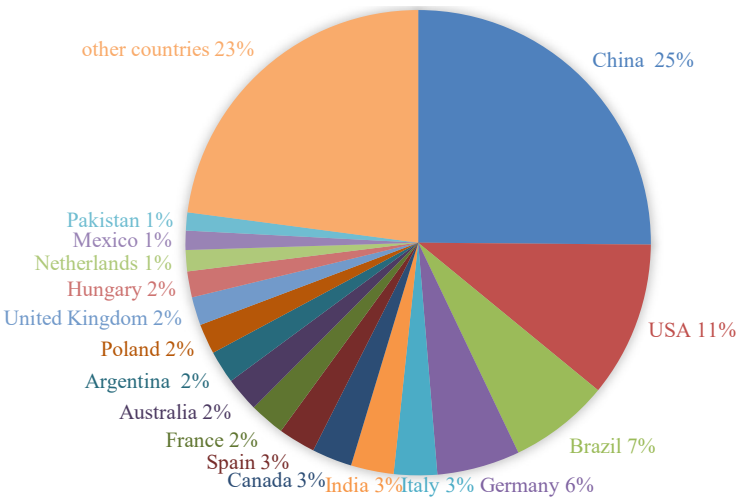

Figure 3. Percentage of publications from each country on maize fertilization (2000-2025) indexed in Scopus.

Authors with the Highest Number of Published Papers

This section presents the top 10 authors with the highest scientific output related to maize fertilization. Zhang Fusuo stands out in first place with an H-index of 26, authoring 34 papers with a total of 3826 citations. He is followed by Liu P., with 26 published papers, 899 citations, and an H-index of 18; Zaidi N., with 25 papers, 851 citations, and an H-index of 18; and Chen X., with 22 papers, 1534 citations, and an H-index of 16. Most of the top 10 authors are from China, except for Zaidi N. from Iran and Szluc P. from the Czech Republic, which underscores China's dominance in this field of study (Figures 3 and 4).

Most Representative Publications

The bibliometric analysis showed that the most highly cited publications worldwide on maize fertilization included "*Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil*" with 715 citations, authored by Rajkovich *et al*. (2012); subsequently, the paper "*Long-term affect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China*" with 691 citations, published by Liu *et al*. (2010), and the third most cited publication with over 500 citations, "*The myth of nitrogen fertilization for soil carbon sequestration*" by Khan, Mulvaney, Ellsworth y Boast. (2007). The aforementioned publications address themes such as the efficient use of fertilizers, increases in biomass or other response variables (Rajkovich *et al*., 2012), the long-term effects of fertilizers and their combinations with organic amendments and their impact on grain yield, as well as soil chemical and biological properties (Liu *et al.,* 2010). They also highlight the collateral effects associated primarily with the use of nitrogen fertilizers (Wang *et al*., 2025). These stand out as the principal publications that broadly elucidate challenges related to the sustainable management of soil fertility, crop nutrition, soil management, and alternatives to increase production while minimizing environmental impacts. The most representative publications on maize fertilization worldwide are summarized in Table 1.

Key Research Topics Worldwide

Through co-occurrence analysis, seven clusters were identified, intrinsically and extrinsically related to the topic of maize fertilization. The keywords with more than 100 occurrences that stood out were: maize (971), nitrogen (232), yield (240), fertilization (209), wheat (116), grain yield (125), phosphorus (106), and nitrogen fertilization (121). The remaining terms (75) fell within the range of 20 to 100 occurrences. The lower threshold for inclusion consisted of considering only those terms with more than 20 occurrences in the co-occurrence analysis, resulting in 83 keywords that make it possible to identify the main research directions in this field of study (Figure 5).

The size of the circles represents the number of occurrences of each term, and the thickness of the lines denotes the strength of the link or connection between the keywords (Figure 5).

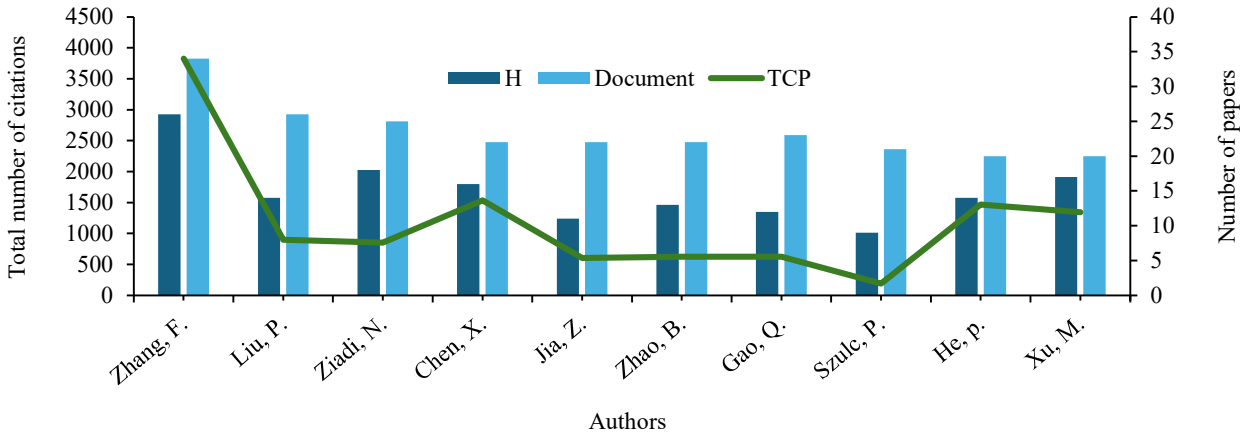

Figure 4. Total number of citations (TCP), number of papers (document), and H-index (H) related to maize fertilization, indexed in Scopus (2000-2025).

Table 1. Notable publications on maize fertilization indexed in Scopus (2000-2025).

Position	Publication	Authors	Year	Journal	Citations	Paper
1	Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil	Rajkovich S.; Enders A.; Hanley K.; Hyland C.; Zimmerman A.eR.; Lehmann J.	2012	*Biology and Fertility of Soils*	715	Scientific
2	Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China	Liu E.; Yan C.; Mei X.; He W.; Bing S.H.; Ding L.; Liu Q.; Liu S.; Fan T.	2010	*Geoderma*	691	Scientific
3	The myth of nitrogen fertilization for soil carbon sequestration	Khan S.A.; Mulvaney R.L.; Ellsworth T.R.; Boast C.W.	2007	*Journal of Environmental Quality*	583	Scientific
4	A visible band index for remote sensing leaf chlorophyll content at the Canopy scale	Hunt E.R.; Doraiswamy P.C.; McMurtrey J.E.; Daughtry C.S.; Perry E.M.; Akhmedov B.	2012	*International Journal of Applied Earth Observation and Geoinformation*	482	Scientific
5	Wheat/maize or wheat/soybean strip intercropping I. Yield advantage and interspecific interactions on nutrients	Li L.; Sun J.; Zhang F.; Li X.; Yang S.; Rengel Z.	2001	*Field Crops Research*	478	Scientific
6	The effects of abiotic factors on induced volatile emissions in corn plants	Gouinguené S.P.; Turlings T.C.J.	2002	*Plant Physiology*	472	Scientific
7	Long-term experiments for sustainable nutrient management in China. A review	Miao Y.; Stewart B.A.; Zhang F.	2011	*Agronomy for Sustainable Development*	471	Review
8	Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain	Zhang A.; Liu Y.; Pan G.; Hussain Q.; Li L.; Zheng J.; Zhang X.	2012	*Plant and Soil*	471	Scientific
9	Crop yield sensitivity of global major agricultural countries to droughts and the projected changes in the future	Leng G.; Hall J.	2019	*Science of the Total Environment*	457	Scientific
10	Effects of compost, mycorrhiza, manure and fertilizer on some physical properties of a Chromoxerert soil	Celik I.; Ortas I.; Kilic S.	2004	*Soil and Tillage Research*	442	Scientific

Cluster 1 (red). Is related to soil in terms of quality, fertility (physical, chemical, and biological), functionality, and sustainability within the production system. The red node includes terms such as zero tillage, soil organic matter, soil enzymes, nitrogen fertilization, microbial biomass, soil respiration, carbon storage, conventional management, no-tillage, sustainable agriculture, production system, manure, among others. The effects of these practices on soil fertility, nutrient availability, microbial fertility, and the overall suitability of soils are essential for sustainable agriculture (Al-Shammary, Al-Shihmani, Fernández, and Caballero, 2024). With respect to tillage systems, Fernández-Ortega, Álvaro, Talukder, Lampurlanés, and Cantero (2023) reported acceptable maize yields and improved water use efficiency when their cropping system combined legumes–maize under zero tillage with medium nitrogen doses. This approach improved three key aspects of the system: productivity, water use, and optimal fertilization. Another important line of research is the long-term evaluation of fertilization through the combined application of organic and inorganic sources and its impact on the improvement, maintenance, and increase of soil organic matter, given that it is the primary source of nitrogen in soils for crops (Yang *et al*., 2020).
Cluster 2 (green). Represents aspects related to the efficient use of nitrogen in agriculture, nitrogen losses in their different forms, and their contribution to greenhouse gas emissions. The main terms that appear in this group include "grain yield", "urea", "nitrogen use efficiency", "nitrous oxide", "nitrogen uptake", "nitrification inhibitor", "nitrate leaching", "drip irrigation", among others. Globally, the nitrogen use efficiency (NUE) in rice, wheat, and maize averages between 36% and 42% (Yu, Keitel, Zhang, Wangeci, and Dijkstra, 2022).

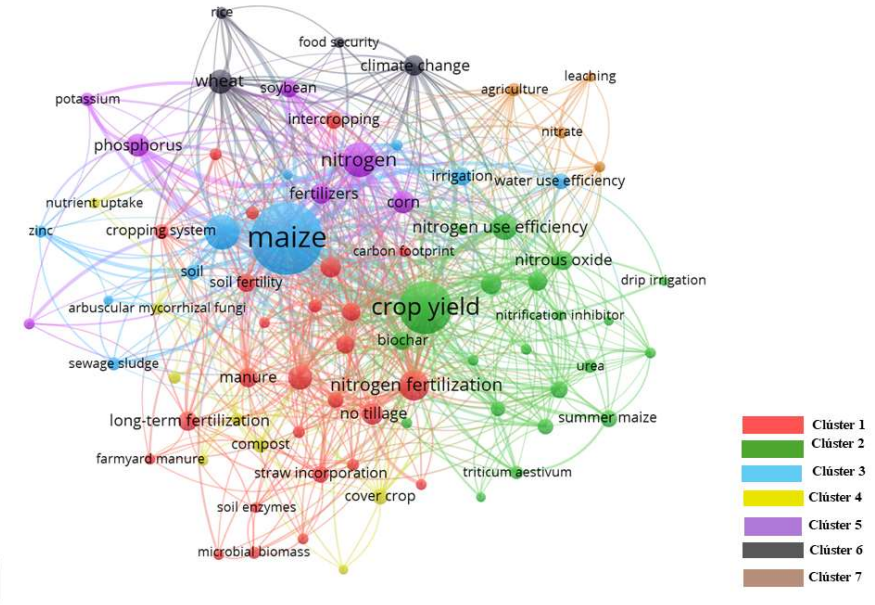

Figure 5. Keywords visualized in VOSviewer with at least 20 occurrences related to corn fertilization globally (2000-2025).

Nitrification and denitrification of N are the main processes that affect nitrogen uptake efficiency in crops (Saud, Wang, and Fahad, 2022). This has promoted the evaluation of nitrification and urease inhibitors (when the N source is urea), with encouraging results in improving crop yield, NUE, and consequently reducing emissions of N_2O, NH_3, and CO_2 (Shi, Wang, Wei, Zhang, and Gao, 2025). Other studies have focused on fertilization techniques (timing, site, source, method of application, and appropriate rate), fertigation through drip irrigation, and the use of high planting density to mitigate the high losses of applied nitrogen (Anas *et al*., 2020).

Studies related to the maize rhizosphere and the solubilization of nutrients from external sources have focused on estimating the rates of biomineralization of ground rock rich in biotite (Fe and Mg), which showed a positive impact on the soil cation exchange capacity through Mg biotite (Krahl *et al.*, 2022). Meanwhile, Plata-Guzmán, Cruz, Carrillos, and Sánchez (2020) evaluated the inoculation of teosinte endophytes (*Burkholderia* sp. and *Klebsiella oxytocica*) combined with 50% of the urea dose in 'Jala' maize. They observed that the bacteria enhanced the exploration capacity of the root system and nutrient uptake, resulting in maize yields similar to those obtained with 100% urea fertilization. Nitrate leaching is of particular concern in irrigated production systems of maize and wheat. This process has been minimized through the use of nitrification inhibitors and intercropping with faba bean (*Vicia sativa* L.), thereby improving nitrogen fertilization efficiency and reducing environmental pollution (Allende-Montalbán, Martín, del Ma, Porcel, and Gabriel, 2022).

Cluster 3 (blue). Highlights aspects related to fertilization, soils, nutrients, heavy metals in soil, and efficient water use. The terms included in this group are "maize," "fertilization," "irrigation," "water use efficiency," "zinc," "soil," "nutrients," "heavy metals," and "sewage sludge." Crop fertilization can be estimated through the plant's internal requirements and the soil's capacity to meet this demand; however, in most cases, the nutrient supply from soil is insufficient, either due to limitations inherent to its properties or its low nutrient reserves. In addition, water availability is increasingly limited, and a greater deficit is projected for the agricultural sector. Consequently, the management of recycled wastewater has become a research trend due to its high nutrient content. Investigations in this field have mainly focused on the biosafety of its use in crops and its effects on soil health (Yerli, Sahin, Oztas, and Ors, 2025). Likewise, sewage sludge subjected to different stabilization processes (e.g., ozonation) has been evaluated during the vegetative stage of maize, showing promising results for aboveground biomass production (Szostek *et al*., 2022).

Cluster 4 (yellow). Addresses topics related to organic fertilizers, compost, manure, and arbuscular mycorrhizae. This cluster includes the keywords "compost," "organic fertilization," "rhizosphere," "green manures," and "nutrient uptake." One study focusing on organic fertilizers, nitrogen, and carbon sequestration was conducted by Das, Choudhury, Hazarika, Mishra, and Laha (2024), where the effect of biochar and different types of organic fertilizers on carbon fractions and potentially mineralizable N was evaluated over a 10-year period in a maize–black bean cropping system.

Their findings demonstrate that the combination of biochar + organic fertilizer increases soil organic carbon, sequestration rates, and different fractions of soluble carbon, whereas potentially mineralizable N (soil storage) decreases as greater amounts of biochar are applied. The importance of this type of research is undeniable, given the challenges related to atmospheric CO_2 levels and the integrated nutrition of crops. Similarly, the use of "green manures" in agricultural systems is being studied as a fertilization alternative, mainly for nitrogen supply and carbon input to soil (Cartagena, Parra, Alvarado, Valverde, and Zambrano, 2020; Jia *et al*., 2025).

Cluster 5 (purple). Highlights aspects related to fertilizers, among which phosphorus- and nitrogen-based fertilizers, as well as productivity-related factors, stand out. Keywords associated with this node include "nitrogen," "phosphorus," "fertilizers," "productivity," and "yield." Factors influencing production can be grouped into controllable and relatively uncontrollable ones. The controllable factors include management practices ("tillage", "planting date", etc.), input application ("fertilization", "pest and disease control", "weed management", etc.), "water management", "genotype", "plant population density", and "topological arrangement", among others. The relatively uncontrollable factors are mainly related to climate (temperature, light, CO_2, precipitation distribution, and frequency) and soil properties (Turrent, Laird, Cortés, and Volke, 2005; Yang, Parsons, and Mao, 2023). In maize, the response to fertilization is closely linked to soil fertility status and the balanced application of nutrients (Parashar and Jain, 2020). Although several studies have addressed nitrogen–phosphorus fertilization, the main variables under consideration remain the optimal ratio of these elements, localized application to improve efficiency (particularly for P), and the evaluation of basal N–P fertilization in soils of different textures (Blandino, Battisti, Vanara, and Reyneri, 2022).

Cluster 6 (gray). Focuses on climate change and food security. Terms such as "climate change," "rice," and "wheat" appear in this node. Maize production is substantially affected by drought or heatwave (a mid-summer drought period characterized by prolonged extreme high temperatures and scarce rainfall); a natural phenomenon that has become more frequent in recent years due to global warming. Research suggests that, to address these challenges, priority research lines should focus on the efficient management of water and nutrients, as well as the genetic improvement of maize; likewise, on the influence of these factors under future environmental conditions. The priority research directions will be defined based on the factor with the greatest negative impact on crop yield (Degife, Zabel, and Mauser, 2021; Kim and Lee, 2023; Rezaei *et al*., 2023).

Cluster 7 (brown). Highlights aspects related to the available forms of N in the soil for crops (ammonium-NH_4^+ or nitrate-NO_3^-) and the mechanisms of nutrient loss, such as leaching. Terms such as "ammonium," "nitrate," "agriculture," and "leaching" appear in this node, along with their relationship to maize fertilization. In this regard, fertilizer application rates in agriculture lead to effects such as the high accumulation of nitrate (NO_3^-) in the soil and its propensity for leaching, directly threatening groundwater quality and, consequently, aquatic biota and human health (Lu *et al.,* 2019).

Bibliometric Analysis for Mexico

In Mexico, a wide range of research is conducted across different areas of knowledge. In the present bibliometric study, the topic of exploration was maize fertilization, where a great diversity of papers was identified, most of them theses, abstracts, and scientific notes, among others. However, the literature presented here was limited to scientific papers and reviews.

Trend in the Growth of Scientific Production in Mexico

Annual scientific production in Mexico on topics related to maize fertilization remained relatively stable until 2018. Subsequently, it showed variations in the following years and declined over the last three years (2023, 2024, 2025). Thus, the overall trend for the period 2000–2025 was initially linear but later followed a quintic function ($R^2 = 0.78$). These variations are mainly attributed to the exploration of new topics that intersect with maize studies in other areas or fields of interest.

In total, 201 papers were published between 2000 and 2025, of which 196 were research papers (97.5%), and 5 were reviews (2.5%). During the evaluation period, at least one publication was recorded each year, except for 2000. The highest productivity occurred in 2018 with 17 papers; in 2019, it decreased to 8, remained partially stable from 2020 to 2022, and then declined sharply from 2023 to 2025 (Figure 6).

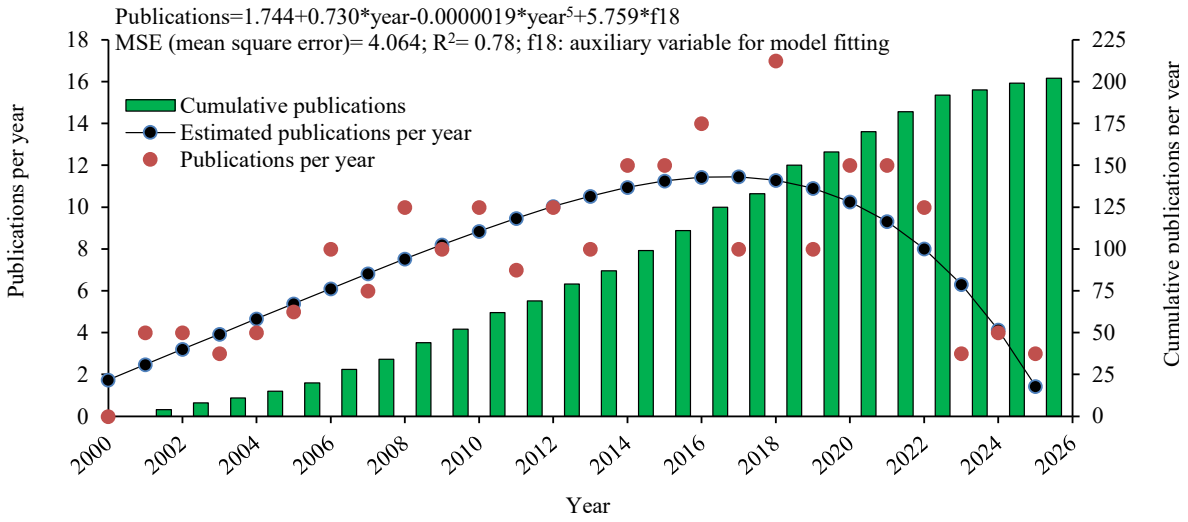

Figure 6. Annual and cumulative publications on maize fertilization (2000-2025) in Mexico, indexed in Scopus and Google Scholar.

Authors with the Most Published Papers

Figure 7 presents the ten national authors with the highest number of publications during the period 2000–2025 on the topic of maize fertilization, all with a minimum of four publications. The most prominent author is Gómez-Montiel (Gómez M.), with a total of 14 papers related to maize production, specifically in genetic improvement and the evaluation of fertilization formulas. He is followed by Cantú A. and Palemón A., with eight publications each, while Hernández G. and Preciado R. occupy the fourth and fifth positions with 7 and 6 publications, respectively.

Main Journals

The main journals that published papers on maize fertilization in Mexico are those related to the primary sector or belonging to institutions focused on agricultural research. *Revista Mexicana de Ciencias Agrícolas* contributed 15% of the published and indexed papers. Its scope includes forestry, agricultural, and livestock research, which has enabled it to receive works developed in this field of study. Other journals with significant contributions include *Terra Latinoamericana*, *Revista Fitotecnia Mexicana*, and *Agrociencia*, accounting for 12%, 6%, and 5% of total productivity, respectively. Additional journals contributing more than 1% are *Agricultura Técnica en México*, *Field Crops Research*, *Agricultural Systems*, and *Agronomía Mesoamericana*. The remaining 40% of publications on this topic are distributed across other international journals, each contributing less than 1%, that is, at least one publication. The participation of the main journals publishing research on maize fertilization in Mexico is presented in Figure 8

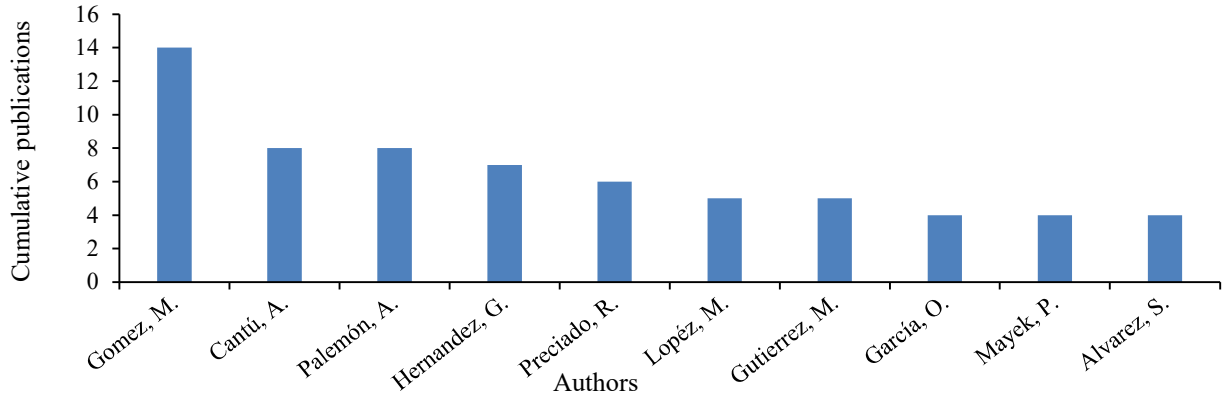

Figure 7. Cumulative publications by author on corn maize fertilization (2000-2025) in Mexico indexed in Scopus and Google Scholar.

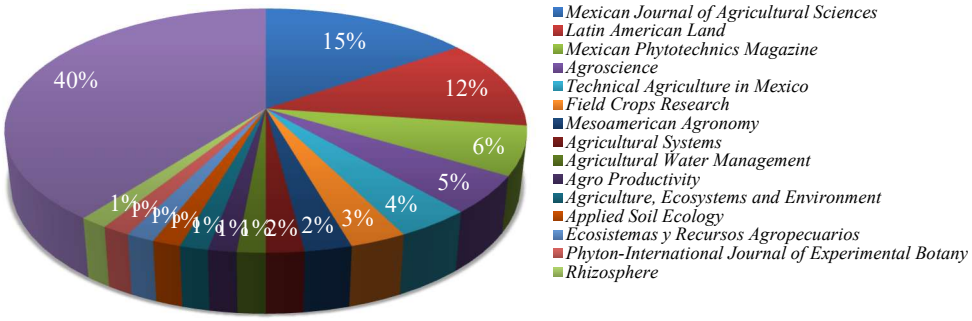

Figure 8. Journal participation in publications on maize fertilization in Mexico (2000-2025), indexed in Scopus and Google Scholar.

Most-Cited Publications from Mexico on Maize Fertilization

Among the most representative publications on fertilization is the scientific paper "Organic Fertilizers and Their Effect on Soil Physical and Chemical Properties and Maize Yield", with 274 citations, published in *Terra Latinoamericana* in 2001 by López and collaborators. Although the title does not explicitly mention the term "maize fertilization," the focus of the study highlights relevant aspects such as the application of organic fertilizers, fertilization rates, and their combinations, which were employed in relation to maize yield as the response variable.

In Mexico, various studies have been conducted on maize cultivation; however, not all of them focus primarily on maize fertilization. Fertilization is considered one of the key factors aimed at increasing yield and improving productivity. In addition, several investigations have addressed the adaptation and development of new maize varieties for different environments. The most representative publications on maize fertilization in Mexico are summarized in Table 2.

Key Research Topics in Mexico

Through co-occurrence analysis, 1131 keywords were obtained, of which those with at least five occurrences were selected as the minimum threshold. This resulted in the grouping of five clusters that, in total, compiled 48 terms frequently found in each cluster (Figure 9), corresponding to:

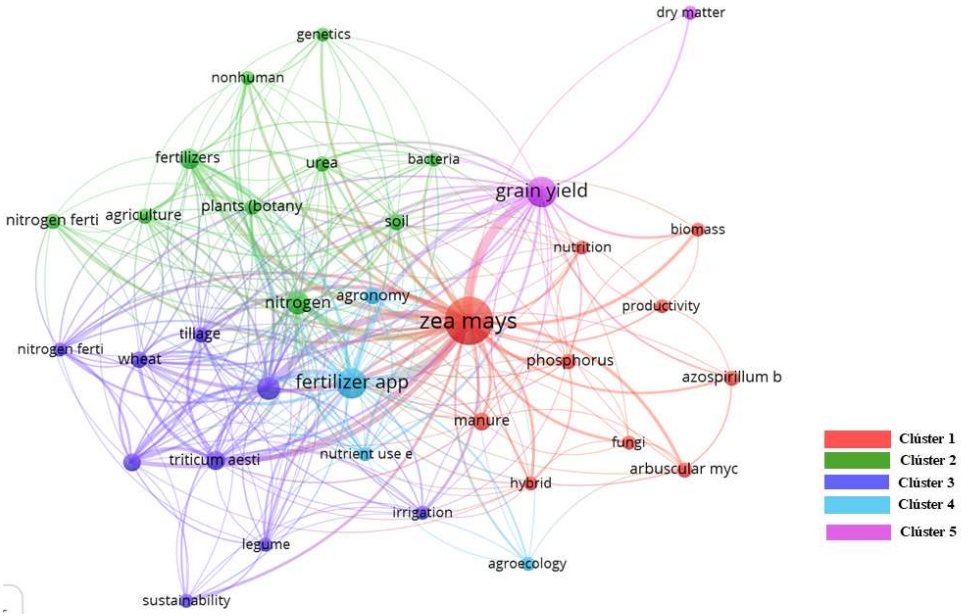

Figure 9. Visualization in VOSviewer of keywords with at least 5 occurrences related to maize fertilization in Mexico (2000-2025).

Table 2. Main publications on maize fertilization in Mexico (2000-2025), indexed in Google Scholar and Scopus.

Number	Publication	Author	Year	Journal	Citations	Paper
1	Organic Fertilizers and Their Effect on Soil Physical and Chemical Properties and Maize Yield	López-Mtz, J. D., Estrada, A. D., Rubin, E. M., y Cepeda, R. D. V	2001	*Terra Latinoamericana*	274	Scientific
2	Integrated Management of Fertilizers and Organic Amendments in Maize Cultivation	Álvarez-Solís J D; Gómez-Velasco D A; León-Martínez N S; Gutiérrez-Miceli F A	2010	*Agrociencia*	152	Scientific
3	Emergy Evaluation of the Performance and Sustainability of Three Agricultural Systems at Different Scales and Management Levels	Martin J F; Diemont S A W; Powell E; Stanton M; Levy-Tacher S	2006	*Agriculture, Ecosystems and Environment*	150	Scientific
4	Plant growth-promoting rhizobacteria inoculation and nitrogen fertilization increase maize (Zea mays L) grain yield and modified rhizosphere microbial communities.	Di Salvo, Luciana P; Cellucci, Gabriel C; Carlino, M Eugenia; de Salamone, Inés E García;	2018	*Applied Soil Ecology*	140	Scientific
5	Application of Organic Fertilizers in Forage Maize Production under Drip Irrigation	Fortis-Hernández, Manuel; Leos-Rodríguez, Juan Antonio; Preciado-Rangel, Pablo; Orona-Castillo, Ignacio; García-Salazar, José Alberto; García-Hernández, José Luis; Orozco-Vidal, Jorge Arnaldo;	2009	*Terra Latinoamericana*	133	Scientific
6	Maize yield in Mexico under climate change.	Ureta, Carolina; González, Edgar J; Espinosa, Alejandro; Trueba, Alejandro; Piñeyro-Nelson, Alma; Álvarez-Buylla, Elena R;	2022	*Agricultural Systems*	121	Scientific
7	Genotypic variation for root traits of maize (Zea mays L) from the Purhepecha Plateau under contrasting phosphorus availability.	Bayuelo-Jiménez J S; Gallardo-Valdéz M; Pérez-Decelis V A; Magdaleno-Armas L; Ochoa I; Lynch J P	2011	*Field Crops Research*	112	Scientific
8	Pollination between maize and teosinte: An important determinant of gene flow in Mexico.	Baltazar B M; Sánchez-Gonzalez J D J; De La Cruz-Larios L; Schoper J B	2005	*Theoretical and Applied Genetics*	110	Scientific
9	Yield response to heat stress as affected by nitrogen availability in maize.	Ordóñez R A; Savin R; Cossani C M; Slafer G A	2015	*Field Crops Research*	95	Scientific

Cluster 1 (red). Focuses on the use of plant growth-promoting microorganisms and their relationship with maize nutrition. The terms are "arbuscular mycorrhizal fungi," "fungi," "*Azospirillum brasilense*," "nutrition," "productivity," and "hybrid." Plant nutrition with biofertilizers and conventional fertilizers has also been addressed, with differential responses in native and improved maize; however, current research is exploring this in relation to environmental conditions and soil type (Ramírez-Silva, Lozano, and Ramírez, 2022). Moreover, the basal application of P in soils is often carried out without considering the initial P content, which can have negative environmental repercussions due to excessive phosphate concentrations. Therefore, the use of arbuscular mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR) has been investigated as a substitute for conventional basal fertilization (e.g., diammonium phosphate) in soils with high P content (Geist *et al*., 2023). In contrast, Di Salvo, Cellucci, Carlino, and de Salamone (2018) inoculated maize with PGPR and observed a positive response in grain yield but also found that rhizobacteria affect N-fixing microorganisms and the physiology of rhizosphere microbial communities during the maize reproductive stage.

Cluster 2 (green). Agriculture and Fertilization. The terms describing this cluster are "bacteria," "fertilizers," "genetics," "nitrogen," "nitrogen fertilization," "soil," and "urea." The dynamics of N in the soil are complex because they largely depend on microorganisms involved in the transformation of reactive forms of N (Morris *et al*., 2018). Therefore, reliable indicators of N availability are lacking when generating fertilization recommendations.

Some approaches consider soil organic matter content to estimate mineralizable N and, based on the literature, use an average value of crop nitrogen use efficiency. Fertilization recommendations still lack precision, not only in Mexico (Alghamdi and Cihacek, 2022). Recently, efforts have been made to improve N recovery under conservation agriculture systems through the incorporation of crop residues, showing positive effects on the uptake of nitrogen and phosphorus (Murphy *et al*., 2016). In two maize varieties, a positive response to phosphorus fertilization has been reported due to increased efficiency in the use of applied N, resulting in higher grain and stover yields, indicating a synergistic relationship between both nutrients (Fosu-Mensah and Mensah, 2016). Similarly, Getnet and Dugasa (2019) reported a significant effect of the application of N, P, and their interaction on final yield and yield components.

Cluster 3 (purple). Related to Crop Yield. The main terms defining this group are "irrigation," "wheat," "nitrogen fertilizers," "crop practices," and "tillage." According to Li, Wang, Li, Lu, and Lu (2020), the most relevant management practices for maize yield and recovery of applied N are optimal planting density and efficient nitrogen fertilization. These authors increased yield in rainfed maize and nitrogen use efficiency solely through rational plant density (75 000 plants ha^{-1}) combined with a slow-release fertilizer. Similarly, Imrán *et al*. (2021) evaluated planting techniques, fertilizer application methods, and different organic sources, achieving higher maize yields when poultry manure was applied prior to weeding and the crop was planted on ridges.

Cluster 4 (blue). Agroecology. This cluster encompasses aspects related to agroecology, with terms such as "agronomy," "fertilizer application," and "nutrient use efficiency." Optimal maize nutrition becomes complex when soils are highly heterogeneous within a region, particularly in a country as diverse as Mexico in terms of climate, vegetation, and relief. The current challenge is the low nitrogen use efficiency (NUE) and, consequently, the difficulty in achieving higher grain yields; research continues on the response of different soil types to fertilization. It has been reported that maize yield decreases by up to 70% in acidic soils where NUE is low. However, when the fertilization source is NO_3^-, NUE increases along with biomass production due to soil reaction to the nitrate source (Wang, Zhao, Zhang, and Shen, 2021). The opposite occurs when ammonium sources are applied, as they contribute to greater soil acidification. Fosu-Mensah and Mensah (2016) indicated that in maize grown under phosphorus fertilization, higher efficiency of applied N was obtained due to increased grain and stover yield, showing a synergistic relationship between both nutrients. Similarly, Getnet and Dugasa (2019) reported a significant effect of N, P, and their interaction on final yield and yield components, except for the number of ears per 10 plants, in rainfed maize.

Cluster 5 (pink). Grain Yield and Dry Matter. This cluster focused on grain yield and dry matter. Plant growth is evaluated through dry matter or biomass production. Mendoza-Elos *et al*. (2006) reported that nitrogen fertilization (100 kg ha^{-1}) increased this variable, and a similar response was observed in grain yield. Both parameters are positively influenced by fertilization, as indicated by Tucuch-Haas *et al*. (2017), who correlated N, P_2O_5, and K_2O contents with grain yield and dry biomass, obtaining significantly different results.

CONCLUSIONS

This bibliometric study on maize fertilization provides a comprehensive global and national overview that makes it possible to understand the progress and technological development carried out in different countries. It also facilitates the identification of knowledge gaps or areas of opportunity to redirect and support research conducted by the scientific community and institutional stakeholders interested in future studies on this topic. Likewise, this research may serve as a useful reference for decision-making in the reallocation of budgets aimed at promoting the development of technologies and innovations in food production for the benefit of society, within the framework of the United Nations 2030 Agenda. At the global level, research has focused primarily on crop yield, with China being the country with the most advanced development in this field. The main topics studied in relation to this area are nitrogen fertilization, the use of nitrogen and phosphorus, and, more recently, climate change. In Mexico, research during the study period on maize fertilization has focused mainly on grain yield and fertilizer application. These works were published in the most influential agronomic journals and carried out by researchers specialized in maize.

ETHICS STATEMENT

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF SUPPORTING DATA

The data used and analyzed in this study, corresponding to certain bibliographic records, cannot be made publicly available but may be provided upon formal request from the interested party.

COMPETING INTERESTS

The authors declare that they have no competing interests.

FINANCING

Not applicable

AUTHORS' CONTRIBUTIONS

C Conceptualization: L.V.V. and C.S.M.H. Metodology: LV.V., O.M.R. and C.A.H.G. Software: L.V.V. and O.M.R. Validation: N.O.G.M. and L.V.V. Formal analysis: LV.V., N.B.P.M. and M.A.S.J. Investigation: L.V.V., N.B.P.M. and M.A.S.J. Data Curation: L.V.V., N.B.P.M. and N.O.G.M. Writing Original Draft Preparation: L.V.V. Writing - Review & Editing L.V.V., M.A.S.J., C.S.M.H. and C.A.H.G. Visualization: N.O.G.M., O.M.R. and C.A.H.G. Supervision: C.S.M.H.

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