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Zinc Deficiency in Calcareous Soils: A Bibliometric Analysis from 1989 to 2024

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Abstract: Zinc (Zn) deficiency in crops is a global issue, particularly in plants grown in calcareous soils, where Zn is often adsorbed or precipitated by calcium carbonates. The aim of this study was to identify and quantify, through bibliometric analysis, the scientific production related to Zn deficiency in calcareous soils over the last 36 years (1989–2024). A total of 374 documents were retrieved through a search on the Web of Science (WOS) platform, specifically in the Science Citation Index Expanded (SCIE) and Social Science Citation Index (SSCI) databases. Of these, only 198 articles were directly relevant to the topic and were used for the analysis. Unidimensional and multidimensional bibliometric indicators were evaluated using Excel and VOSviewer software. The results confirm that the number of articles has increased in recent years. The most influential authors, journals, articles, institutions, and countries in this research area were identified. In addition, collaboration networks between authors and countries, as well as the predominant research topics, were determined. This study provides a comprehensive overview of this field on a global scale and serves as a useful reference for scientists interested in conducting future research on related topics.

Keywords: crops; calcium carbonates; bibliometric indicators; research topics; VOSviewer

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1. Introduction

Zinc (Zn) is an essential element for plants, which is involved in the synthesis of chlorophyll, nucleic acids, and auxins [1]. It also acts as a regulatory cofactor for several enzymes and participates in protein metabolism [2]. Plants absorb this element mainly as the divalent cation (Zn^{2+}) [3], taken from the soil solution by three mechanisms, mass flow, diffusion, and root interception, with diffusion being the predominant mechanism [4]. Zn is considered, together with iron (Fe), manganese (Mn), and boron (B), an element with moderate mobility within the plant [5]. Zn transport is attributed to metal transporters such as the P_{1B}-ATPase family, zinc-regulated transporter (ZRT), iron-regulated transporter (IRT)-like protein (ZIP), natural resistance-associated macrophage protein (NRAMP) family, and cation diffusion facilitator (CDF) family [6]. Insufficient Zn concentration in crops is critical because it reduces plant growth, photosynthetic activity, and fruit size and quality [3].

Calcareous soils present a high $CaCO_3$ content in the parent material, with a pH range from 7.0 to 8.5 [7]. Crops grown in these soils exhibit low levels of Zn because it is adsorbed or precipitated, forming compounds such as $ZnCO_3$ or $Zn(OH)_2$ [8], which are not available for plants [9]. Additionally, in soil, this micronutrient shows an antagonistic relationship with phosphorous, boron, copper, and cadmium [10], further reducing its availability to crops.

Several studies report a decrease in the yield of important annual crops, such as citrus, wheat, maize, barley, rice, and sorghum, grown in soils with high $CaCO_3$ content [11–13]. This type of soil covers about one-third of the Earth's surface and is commonly found in areas where $CaCO_3$ predominates in the parent material, particularly in arid and semi-arid regions, due to its low leaching capacity [7,14]. At a global level, Zn deficiency is one of several agronomic problems in the Mediterranean basin, primarily attributed to the high carbonate content, elevated pH, and low organic matter levels [8]. In Mexico, calcisoils cover an area of 205,192 km^2 (10.4% of the country's total area), primarily concentrated in the states of Tamaulipas, Nuevo León, San Luis Potosí, Coahuila, Chihuahua, and Sonora [15]. Low crop yields have been reported in these states, associated with high $CaCO_3$ concentrations and deficient Zn levels in the soil. In pecan (*Carya illinoinensis*) orchards in northern Mexico, yields decreased by 20% due to the low availability of Zn in the region's calcareous soils [16].

Additionally, low Zn content in crops represents a serious problem for human health, as it leads to low bioavailability of Zn in plant-based foods [17], mainly affecting children, pregnant women, and the elderly [18]. Hussain et al. [19] reported that Zn deficiency in humans affects approximately two billion people worldwide and is prevalent due to the consumption of Zn-deficient cereals and vegetables.

World-class institutions have been established to study calcareous soils with the aim of increasing Zn to sufficient or optimal levels in crops, enhancing agricultural yield and quality of agricultural products, and simultaneously addressing human malnutrition. This problem has been studied for decades in various parts of the world and is widely discussed in the literature available in databases such as the Web of Science (WOS). Li and Li [20] mention that the world's most important and influential research literature is included in the WOS database; they also recognize it as the world's leading search tool.

In recent years, there has been an exponential increase in scientific information accessible in bibliographic databases, driven by recent scientific advances [21]. Consequently, the need has arisen to search for new methods to measure the fluctuation of information available on a topic of interest [22]. For this reason, bibliometrics has gained great relevance. Bibliometrics is a field of research with applications in various contexts [23]. It enables the quantitative and qualitative evaluation of bibliographic information through various techniques and methods, typically using information technologies for data processing [24,25]. One of these techniques is bibliometric analysis, which reveals publication trends, research topics, and the most prolific authors and institutions in a specific field of study [26]. Bibliometric analysis is described as an accepted and accurate method for exploring and analyzing large datasets [22]; its use by the scientific community has increased significantly in recent years. For the future of agriculture, understanding the contributions of scientific groups is essential to achieve integrated research, considering that each scientific community focuses on specific topics according to its own approaches and methods [27].

The aim of this study was to identify research topics associated with Zn deficiency in calcareous soils through a bibliometric analysis conducted over the last thirty-six years. This bibliometric analysis serves as a valuable reference for researchers and policymakers in the Mediterranean region, northeastern Mexico, and other parts of the world where yields of sensitive crops are reduced due to Zn deficiency induced by high $CaCO_3$ content in the soil. This study was conducted using information available on the Web of Science (WOS) platform, specifically from the Science Citation Index Expanded (SCIE) and Social Science Citation Index (SSCI) databases. One-dimensional and multi-dimensional bibliometric indicators were analyzed using Microsoft Excel and VOSviewer software.

2. Materials and Methods

An advanced search for articles related to "Zn deficiency in calcareous soils" was performed in the Web of Science (WOS) database, which indexes articles published in scientific journals within the Science Citation Index Expanded (SCIE) and Social Science Citation Index (SSCI) databases. The search expressions used on 26 July 2024 were "calcareous soil *" AND "zinc deficiency". This search yielded a total of 374 publications. Subsequently, fil-

tering was carried out using exclusion and inclusion criteria, which involved the following three strategies:

Strategy 1: Documents containing the expressions "calcareous soils" and "zinc deficiency" in titles, abstracts, and/or keywords were identified.

Strategy 2: Only scientific articles and reviews directly related to the topic of interest were considered.

Strategy 3: Only articles and reviews published between 1 January 1989 and 31 July 2024 were selected.

After completing the filtering process, 198 publications related to Zn deficiency in calcareous soils (191 scientific articles and 7 reviews) were retrieved for further analysis. This number of documents is approximately the minimum recommended for performing a bibliometric analysis (200 papers) [28]. The bibliographic information retrieved was analyzed using one-dimensional and multi-dimensional bibliometric performance indicators [29] (Table 1).

Table 1. Bibliometric indicators used to analyze the performance of scientific production on Zn deficiency in calcareous soils indexed in the WOS (1989–2024).

One-Dimensional Indicators	Multi-Dimensional Indicators
The growth trend in scientific production	Co-authorship network
Authors with the most published articles	Country co-authorship network
Authors with the most citations	Research hotspots
Main publishing journals	
Most cited articles	
Institutions with the highest production	
Impact of countries	

The growth trend of scientific productivity over the last thirty-six years was measured and graphically represented using Microsoft Excel® software, version Plus 2019. This program was also used to visualize the authors with the most citations and the main journal sources based on the data collected. The other indicators were evaluated using VOSviewer software, version 1.6.20 [30]. Additionally, we used this program to create maps through visualization of similarities (VOS) between themes [31], utilizing data extracted from SCIE and SSCI in text file format.

A first thesaurus was generated to normalize the names of the researchers and to identify the authors with the most published articles (scientists with six or more publications) and the most citations (the top ten scientists). The bibliographic data collected were classified by the number of articles from each source to determine the journals with the highest productivity (sources with four or more articles). Similarly, the selected publications were organized by the number of citations to identify the ten most cited. The institutions with the highest production and the impact of the countries were evaluated based on their published works, highlighting the top ten for each indicator.

In addition, scientific maps were created to show the co-authorship network between authors and countries related to the performance of topics in this field of study. The predominant research themes were identified through a co-occurrence analysis of words [32,33], where a second thesaurus was created to standardize the terms [30]. In this analysis, 809 words were obtained, selecting only those that had more than seven occurrences (n = 56). Multi-dimensional indicators allow us to visualize specific areas of interest, which are classified into clusters. This provides an overview of the fluctuation of scientific information available on this topic.

3. Results

3.1. Growth Trend in Scientific Production

A constant growth in the literature (R^2 = 0.8922) related to Zn deficiency in calcareous soils over the last thirty-six years (1989–2024) is evident, as illustrated in Figure 1. A total of 198 publications were retrieved from the SCIE and SSCI databases in WOS, including

191 research papers (95.9%) and 7 review papers (4.1%). The first article identified regarding Zn deficiency in calcareous soils was "Effect of Zinc Deficiency in Wheat on the Release of Zinc and Iron Mobilizing Root Exudates" [34], published in the *Journal of Plant Source Nutrition and Soil Sciences* in 1989. On the other hand, the most recent article, entitled "Citrus Nutrition in Iran: Lessons from Calcareous Soils" [35], was published in the *Journal of Plant Nutrition* on 24 July 2024. In the first decade of the study period (1989–1998), an average of three documents per year were published, while in the second decade (1999–2008), the production increased to four articles per year. For the period from 2009 to 2018, the average production rose to eight articles per year. Scientific productivity in the last six years (2019–2024) was the highest, with an average of nine papers per year. In 1989, only 1 article was published, while the peak occurred in 2009, with 12 articles. After 1996, at least three papers were produced each year, except for 2002. There was no scientific production on this topic in the years 1992 and 1995. In contrast, the years with the highest productivity were 2009, 2016, and 2017, each with 12 publications.

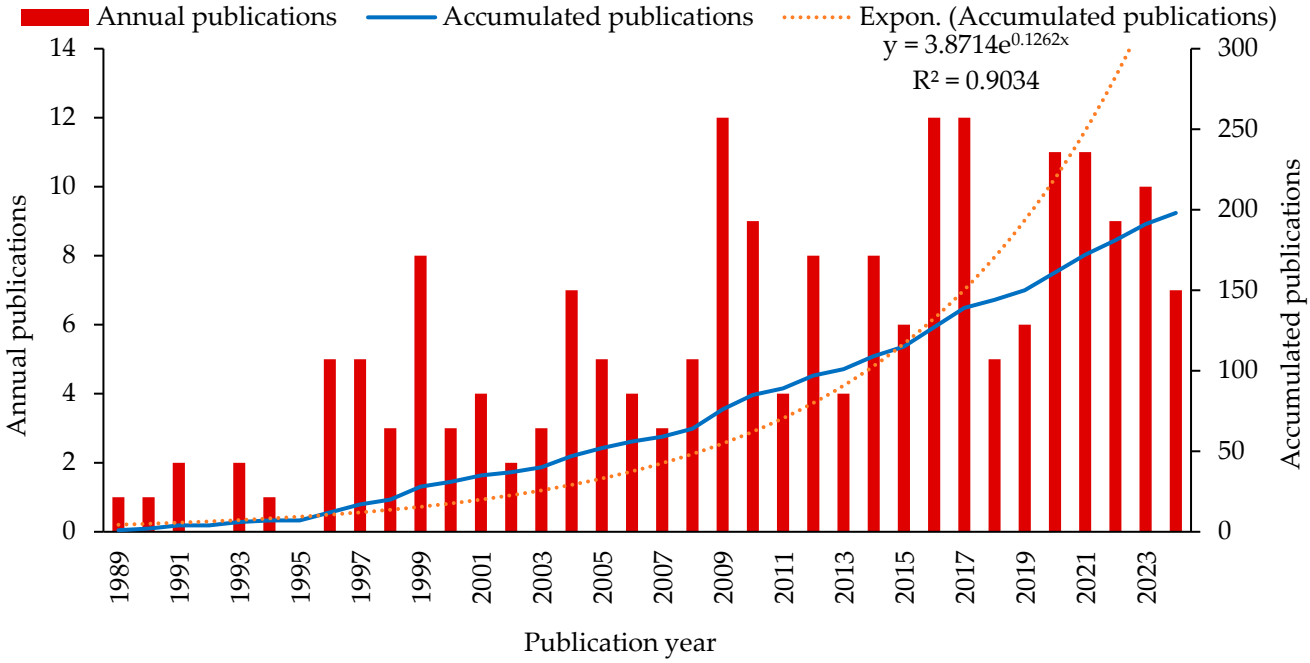

Figure 1. Annual and cumulative number of publications on Zn deficiency in calcareous soils (1989–2024), indexed in the Web of Science (WOS).

3.2. Authors with the Most Published Articles

The analysis of co-authorship revealed 198 publications that recorded a total of 6833 citations, attributed to 618 researchers. Scientists with more than six papers are listed in Table 2. These 13 authors collectively accounted for 24.7% (n = 49) of the published papers and 37.1% (n = 2537) of the total citations, according to a refining process in the WOS platform. Ismail Cakmak (H-index of 80), with 25 publications, was the most productive author; seven of his articles received more than 100 citations. Dr. Cakmak is affiliated with Sabanci University (Türkiye), and his research areas include plant sciences, agricultural food science and technology, chemistry, biochemistry, and molecular biology. He has conducted several studies on biofortification, evaluating the dynamics of Zn in crops such as wheat (*Triticum aestivum*). The second most prolific author was Bülent Torun (H-index of 15), with 10 papers, 3 of which recorded more than 100 citations. Dr. Torun works at Cukurova University (Türkiye), and his research areas include plant sciences, agriculture, food science and technology, biochemistry and molecular biology, and computer science. The third most productive author was Amir H. Khoshgoftarmanesh (H-index of 28), with 10 papers, all of which recorded fewer than 50 citations. Dr. Khoshgoftarmanesh's research

areas encompass plant sciences, agriculture, environmental sciences and ecology, chemistry, and engineering. Most of the authors conducted their studies in agronomic sciences related to crop nutrition.

Table 2. Authors with six or more co-authored articles indexed in the WOS (1989–2024) related to Zn deficiency in calcareous soils.

Rank	Author	H-I	TP	TC	ACA	<50	50–99	>100	Institution
1	Cakmak, I.	80	25	1815	72.6	12	6	7	Sabanci University—Türkiye
2	Bülent, T.	15	10	891	89.1	3	4	3	Cukurova University—Türkiye
3	Khoshgoftarmanesh, A. H.	28	10	175	17.5	10	0	0	Isfahan University of Technology—Iran
4	Ekiz, H.	14	9	984	109.3	2	3	4	Ministry of Food, Agriculture & Livestock—Türkiye
5	Ozturk, L.	42	9	628	69.7	4	2	3	Sabanci University—Türkiye
6	Eker, S.	38	8	565	70.6	2	4	2	Cukurova University—Türkiye
7	Yilmaz, A. M.	13	7	942	134.5	0	3	4	International Maize & Wheat Improvement Center (CIMMYT)—Türkiye
8	Römheld, V.	53	7	503	71.8	4	1	2	University of Hohenheim—Germany
9	Rafique, E.	10	7	99	14.1	6	1	0	University of Lahore—Pakistan
10	Kalayci, M.	16	6	763	127.1	1	2	3	Ministry of Food, Agriculture & Livestock—Türkiye
11	Braun, H. J.	39	6	572	95.3	4	0	2	International Maize & Wheat Improvement Center (CIMMYT)—Mexico
12	Marschner, H.	80	6	435	72.5	2	2	2	University of Hohenheim—Germany
13	Walworth, J. L.	15	6	41	6.8	6	0	0	Arizona University—United States

H-I = H-index; TP = total publications; TC = total citations; ACA = average citations per author; <50 = papers with fewer than 50 citations; 50–99 = papers with citations counts between 50 and 99; >100 = papers with more than 100 citations.

3.3. Authors with the Most Citations

Only 64 authors (10.3%) of the 618 cited have obtained more than 100 citations as of July 2024. Ismail Cakmak registered the highest number with 1815 citations; it is important to note that this is associated with his articles published on this topic (25) (Figure 2 and Table 2). In second place was Hasan Ekiz, who has been cited 984 times. Asif M. Yilmaz (942), Bülent Torun (891), and Mufit Kalayci (753) occupied the third, fourth, and fifth positions, respectively. The five main authors mentioned above work at Turkish institutions. It is also noteworthy that Brian J. Alloway, who is not among the authors with the highest number of articles, appears in this top ten. Dr. Alloway has published only one paper (a review) on this topic, recording 625 citations. On the other hand, Amir H. Khoshgoftarmanesh, with 10 documents that have been cited 175 times, did not appear in this list (Figure 2).

3.4. Main Publishing Journals

This bibliometric study retrieved 83 records from WOS-indexed journals on Zn deficiency in calcareous soils (1989–2024). Table 3 and Figure 3 present the eight main journals that published four or more papers on this topic. These sources contributed 49.4% (98 articles) and 42.2% (2884 citations) of the total publications during the study period. An additional 75 journals accounted for the remaining 50.6% (100 articles) and 57.8% (3949 citations). The *Journal of Plant Nutrition* was the source that published the most arti-

cles, at 36 (18.8%), and recorded 684 citations. The second most prolific was *Communications in Soil Science and Plant Analysis*, with 23 (11.6%) articles and 1495 citations, highlighting it as the most cited source. The third most productive journal was the *Journal of Soil Science and Plant Nutrition*, with 18 (9.1%) articles and 373 citations, followed by the *Journal of Soil Science and Plant Nutrition*, with 5 (2.5%) in fourth place. The sources with four publications (2.0%) were *Applied Soil Ecology*; *Hortscience*; *Journal of Agricultural and Food Chemistry*; and *Journal of the Science of Food and Agriculture*. These top eight journals were categorized in plant sciences, agronomy, soil science, horticulture, and multidisciplinary agriculture, with impact factor (IF) ranging between 1.3 and 5.7. It is worth noting that *Agrociencia* was the only Mexican journal identified among the 83 indexed journals, and it published one article (0.5%).

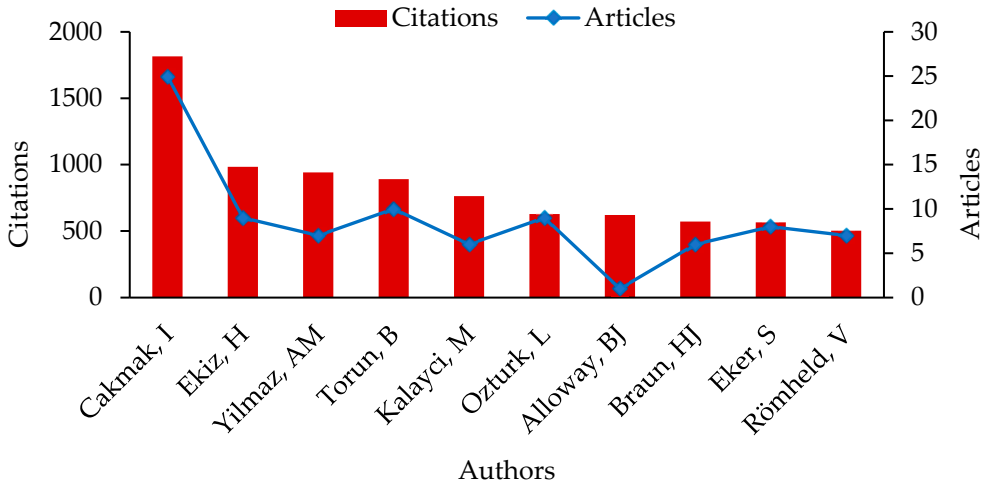

Figure 2. Top ten most cited authors in publications indexed in WOS (1989–2024) related to Zn deficiency in calcareous soils.

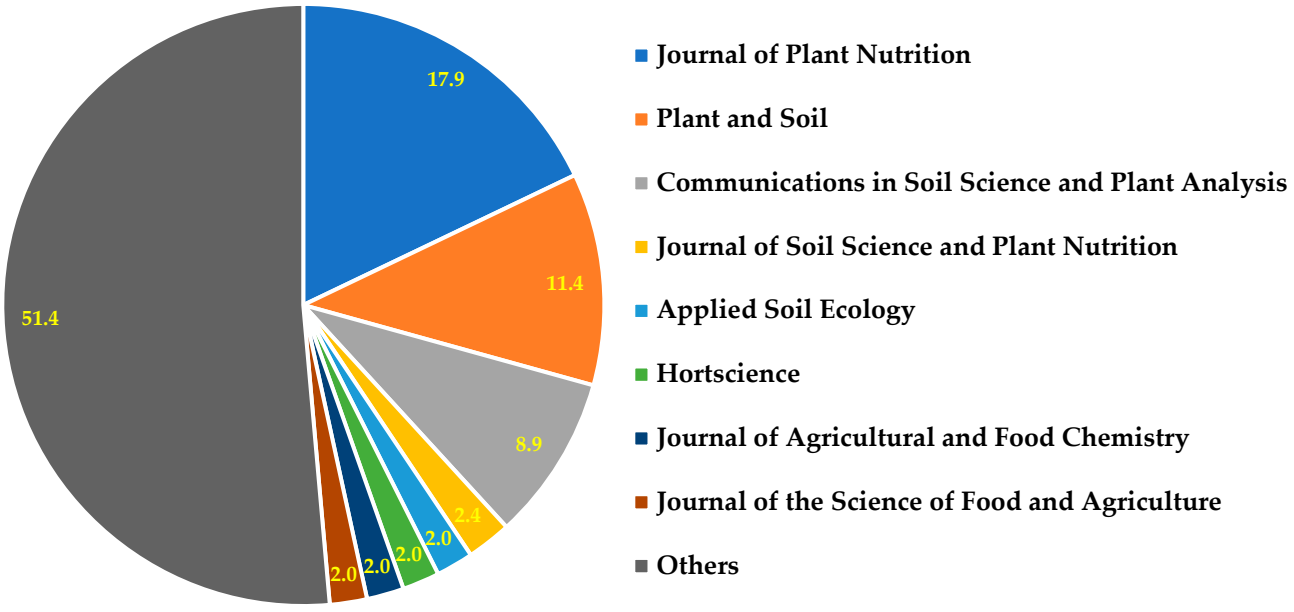

Figure 3. Top 8 indexed journals in WOS (%) on Zn deficiency in calcareous soils from 1989 to 2024.

Table 3. Indexed journals in WOS with four or more published documents (1989–2024) on Zn deficiency in calcareous soils.

Rank	Journal	TP	TC	IF (2023)	JCR Category	Range/JCR Quartile
1	*Journal of Plant Nutrition*	36	684	1.6	Plant sciences	138/265, 3
2	*Plant and Soil*	23	1495	3.9	Agronomy	15/125, 1
3	*Communications in Soil Science and Plant Analysis*	18	373	1.3	Agronomy	67/215, 3
4	*Journal of Soil Science and Plant Nutrition*	5	46	3.4	Plant sciences	60/265, 1
5	*Applied Soil Ecology*	4	81	4.8	Soil science	11/49, 1
6	*Hortscience*	4	45	1.5	Horticulture	19/38, 2
7	*Journal of Agricultural and Food Chemistry*	4	81	5.7	Multidisciplinary agriculture	11/89, 1
8	*Journal of the Science of Food and Agriculture*	4	79	3.3	Multidisciplinary agriculture	16/89, 1
9–83	Others	103	3867	-	-	-

TP = total publications; TC = total citations; IF = impact factor of the journal on the year 2023; JCR = journal citations report.

3.5. Most Cited Articles

The 198 publications collectively received 6833 citations, averaging 34.5 citations per article. Notably, of the 198 articles published between 1989 and 2024, 17 received 100 or more citations. The 10 most cited documents (7 articles and 3 reviews), with citation counts ranging from 138 to 615, are listed in Table 4. Together, these papers account for 32.1% (n = 2199) of the total citations. The most cited article (625 citations), categorized as a review, is titled "Soil factors associated with zinc deficiency in crops and humans" and was published in *Environmental Geochemistry and Health*. It highlights the importance of Zn in plants due to its role in various physiological processes and discusses factors associated with Zn deficiency in crops and, consequently, in humans, considering the high $CaCO_3$ content in the soil as one factor that causes low levels of Zn in plants. The second most cited paper (234 citations), "Zinc deficiency as a critical problem in wheat production in Central Anatolia", was published in *Plant and Soil* and focused on managing Zn deficiency in wheat, a common issue in the calcareous soils of the Central Anatolia, Türkiye. The third most cited article (228 citations), "Zinc deficiency as a practical problem in plant and human nutrition in Türkiye: A NATO-science for stability project", was published in *Field Crops Research* and reported the nutritional status of cereals also grown in the Central Anatolia region. Notably, Ismail Cakmak was the senior author of both the second and third most cited papers.

Table 4. Top ten most cited articles in journals indexed in WOS (1989–2024), dealing with Zn deficiency in calcareous soils.

Rank	Title of Article	Authors	PT	Source	Category	TC
1	Soil factors associated with zinc deficiency in crops and humans [36]	Alloway (2009)	Review	*Environmental Geochemistry and Health*	Public, Environmental, and Occupational Health	625
2	Zinc deficiency as a critical problem in wheat production in Central Anatolia [37]	Cakmak et al. (1996)	Article	*Plant and Soil*	Agronomy	234

Table 4. *Cont.*

Rank	Title of Article	Authors	PT	Source	Category	TC
3	Zinc deficiency as a practical problem in plant and human nutrition in Türkiye: A NATO-science for stability project [38]	Cakmak et al. (1999)	Article	*Field Crops Research*	Agronomy	228
4	Micronutrient constraints to crop production in soils with Mediterranean-type characteristics: a review [39]	Rashid and Ryan (2004)	Review	*Journal of Plant Nutrition*	Plant sciences	198
5	Distribution, movement and plant availability of trace metals in soils amended with sewage sludge composts: application to low metal loadings [40]	Planquart et al. (1999)	Article	*Science of the Total Environment*	Environmental Sciences	183
6	Seed priming enhances germination and seedling growth of barley under conditions of P and Zn deficiency [41]	Ajouri et al. (2004)	Article	*Journal of Plant Nutrition and Soil Science*	Agronomy	160
7	Organic acid behavior in a calcareous soil implications for rhizosphere nutrient cycling [42]	Ström et al. (2005)	Article	*Soil Biology and Biochemistry*	Soil Sciences	148
8	Improving zinc efficiency of cereals under zinc deficiency [43]	Singh et al. (2005)	Review	*Current Science*	Multidisciplinary Sciences	145
9	Root exudates of the hyperaccumulator Thlaspi caerulescens do not enhance metal mobilization [44]	Zhao et al. (2001)	Article	*New Phytologist*	Plant Sciences	140
10	Grain zinc, iron and protein concentrations and zinc-efficiency in wild emmer wheat under contrasting irrigation regimes [45]	Peleg et al. (2008)	Article	*Plant and Soil*	Agronomy	138

PT = publication type; TC = total citations.

3.6. Institutions with the Highest Production

A total of 214 institutions involved in research on Zn deficiency in calcareous soils between 1989 and 2024 were identified through co-authorship analysis. Table 5 lists the 10 leading institutions that published nine or more papers, accounting for 88 articles (44.4%) and 3413 citations (49.9%) of the total retrieved literature, based on a refinement process in the WOS platform. It is important to note that 12 institutions did not have any citation records. The three most productive institutions were Cukurova University (Türkiye), with 24 publications, 1648 citations, and an average of 68.3 citations per article; the Ministry of Food, Agriculture & Livestock (Türkiye) with 16 publications, 1353 citations, and an average of 84.5 citations per article; and Bahauddin Zakariya University (Pakistan) with 12 publications, 202 citations, and an average of 16.5 citations per article. The two most cited institutions on this list are from Türkiye; similarly, the six most cited authors also conduct their studies in this country (Table 5 and Figure 2). Regarding Mexican institutions, the International Maize & Wheat Improvement Center (CIMMYT), with its world headquarters in Mexico, ranked 11th with 6 papers and 572 citations, while the Autonomous University

of Chihuahua ranked 93rd with only one article, which was cited 28 times. The high percentages in Table 5 result from many of the documents involving authors from multiple institutions, according to a refinement process in the WOS platform.

Table 5. Institutions with nine or more published papers indexed in WOS (1989–2024) related to Zn deficiency in calcareous soils, based on the co-authorship analysis.

Rank	Institution	Country	TP	TC	ACP	(%) PI
1	Cukurova University	Türkiye	24	1641	68.3	12.1
2	Ministry of Food, Agriculture & Livestock	Türkiye	16	1353	84.5	8.1
3	Bahauddin Zakariya University	Pakistan	12	202	16.5	6.1
4	University of Agriculture Faisalabad	Pakistan	12	115	9.5	6.1
5	University of Hohenheim	Germany	10	730	73.0	5.1
6	Shiraz University	Iran	10	239	23.9	5.1
7	Isfahan University of Technology	Iran	10	177	17.7	5.1
8	Northwest AF University China	China	10	142	14.2	5.1
9	China Agricultural University	China	9	357	39.6	4.5
10	Sabanci University	Türkiye	9	525	58.3	4.5

TP = total publications; TC = total citations; ACP = average citations per publication. PI = productivity of institutions with respect to the total documents (n = 198), where each document involves authors from different institutions.

3.7. Impact of Countries

A total of 45 countries participated in the published papers on Zn deficiency in calcareous soils, according to the co-authorship analysis. The ten leading countries that published the most articles in the field of study are presented in Table 6. Iran ranked first with 40 papers and 616 citations, resulting in an average of 15.4 citations per publication. Türkiye followed closely in second place, with 38 articles cited 1977 times, averaging 52.0 citations per publication. This predominance is reflected in the bibliometric indicators for "authors with the most citations" and "institutions with the highest production" mentioned above (Figure 2 and Table 5). Pakistan secured third place with 32 papers cited 596 times, resulting in an average of 18.6 citations per publication. Fourth place went to China, which published 28 documents and received 617 citations, yielding an average of 22.0 citations per publication. Mexico ranked tenth, contributing 5 papers cited 115 times, attributable to the efforts of the International Maize & Wheat Improvement Center (CIMMYT) on this subject. Collectively, these top ten countries accounted for 87.89% of the total published papers and 78.8% of the total citations. These percentages are notably high as each document involves authors from multiple countries, as per the refinement process conducted on the WOS platform.

Table 6. Top ten countries with the most published articles indexed in WOS (1989–2024) related to Zn deficiency in calcareous soils.

Rank	Country	Publications	Citations	Average Citations/Publication	(%) PC
1	Iran	40	616	15.4	20.2
2	Türkiye	38	1977	52.0	19.1
3	Pakistan	32	596	18.6	16.1
4	China	28	617	22.0	14.1
5	United States	18	403	22.3	9.1
6	Spain	16	287	17.9	8.1
7	Germany	11	583	53.0	5.5
8	India	8	324	40.5	4.0
9	Australia	7	327	46.7	3.5
10	Mexico	5	115	23.0	2.5

PC = productivity of countries with respect to the total documents (n = 198), based on co-authorship analysis, where each document involves authors from different countries.

3.8. Co-Authorship Network

The results indicated that 615 authors contributed to the 198 papers, demonstrating the collaboration network among them, with a co-authorship index (CI) of 3.1. The 53 most productive authors formed fifteen clusters, with a threshold of at least three documents per researcher considered. The number of papers authored by each researcher is represented by the size of the circles. The thickness of the links (total link strength) between scientists reflects their collaboration based on the number of co-authored articles. Each cluster is represented by a specific color, indicating the relationship among those authors. The group with the highest number of researchers (cluster 1, red) included Torun, B., Ekiz, H., Eker, S., Yilmaz, A. M., Kalayci, M., Gültekin, I., Marschner, H., Römheld, V., and Erenoğlu, E. B., most of whom are affiliated with Turkish institutions. The second research group (cluster 2, green) comprised Fahad, S., Hussain, Saddam., Ali, M. A., Danish, S., Hussain, Sajjad., Datta, R., and Sarwar, N., primarily affiliated with organizations in Pakistan. In the third node (cluster 3, blue) were Cakmak, I., Ozturk, L., Hans, J. B., Karanlik, S., Tolay, I. and Yazici, A., who are associated with Turkish institutions such as Sabanci University, Cukurova University, Mustafa Kemal University, Akdeniz University, and the International Maize & Wheat Improvement Center (CIMMYT). Notably, the main research groups were predominantly formed by Turkish scientists (Figure 4).

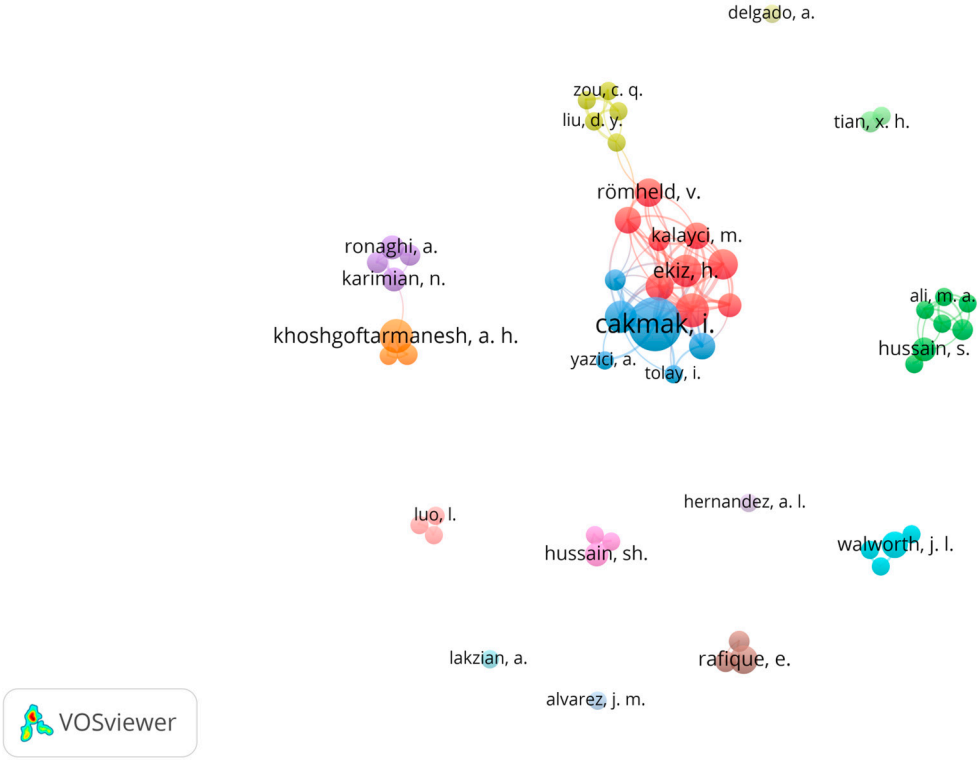

Figure 4. Visualization in VOSviewer of research groups (co-authorship network among authors) on Zn deficiency in calcareous soils.

3.9. Country Co-Authorship Network

The total number of publications, considering contributions from different countries, was 263, indicating the collaboration network among them. The co-authorship analysis revealed that 45 countries participated in the articles published on Zn deficiency in calcareous soils between 1989 and 2024. The top 14 countries were grouped into four clusters, with a threshold of at least four papers per country. The size of the circles represents the number of documents per country, while the thickness of a link (total link strength) describes the collaboration among countries based on the number of co-authored articles. Each cluster is defined by a specific color, which illustrates the relationship between those countries. In the first group (cluster 1, red), three Asian countries (Pakistan, China, and India),

two European countries (Spain and Czech Republic), and one African country (Egypt) collaborated. The second node (cluster 2, green) was led by Türkiye, with its main collaborators being Germany, the United States, and Mexico. In the third group (cluster 3, blue), academics from Australia worked together with scholars from England. The fourth node (cluster 4, yellow) was composed of Iran and its main collaborator, Switzerland. The link strength (LS) values indicated that Pakistan (LS = 18) and China (LS = 15) had the highest collaboration with other countries. Türkiye (38 documents and 1997 citations) registered an LS of 11, while Iran, with 40 publications and 616 citations, recorded an LS of 8 (Figure 5).

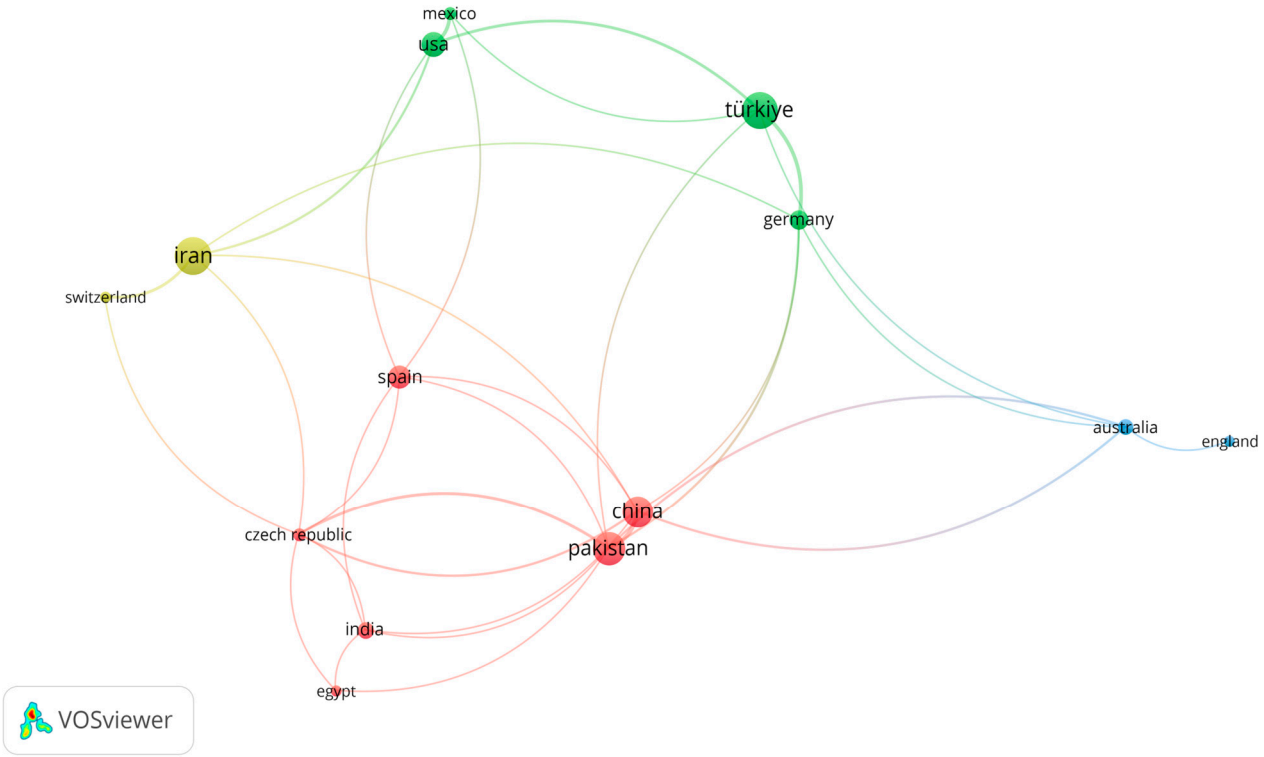

Figure 5. Visualization in VOSviewer of countries with the highest production (network of co-authorships between countries) on Zn deficiency in calcareous soils.

3.10. Research Hotspots

The co-occurrence analysis identified 809 keywords that were most frequently used in the publications. Terms with more than seven occurrences (n = 56) were grouped into five clusters, identifying the main trends and gaps in this field of study. The size of the circles indicates the number of occurrences of the term, while the thickness of a link (total link strength) denotes the relationship between the keywords. In this network, each cluster is represented by a specific color, indicating that terms and groups with the same hue are related. Among those with at least 20 occurrences were "zinc" (69), "deficiency" (68), "*Triticum aestivum*" (55), "growth" (40), "plants" (34), "yield" (33), "phosphorus" (29), "nutrition" (29), "*Zea mays*" (28), "manganese" (25), "cultivars" (24), "availability" (24), "biofortification" (21), and "micronutrients" (21). For the 56 keywords with more than seven occurrences, the total link strength values ranged between 20 and 35 (Figure 6).

The five clusters, each illustrated with a specific color, were as follows: Cluster 1 (red) consisted of 14 keywords, with "deficiency" as the main term (68 occurrences, LS = 335); Cluster 2 (green) included 12 keywords, led by "*Triticum aestivum*" (55 occurrences, LS = 314); Cluster 3 (blue) contained 11 keywords centered on "manganese" (25 occurrences, LS = 115); Cluster 4 (yellow) comprised 11 keywords with "zinc" as the primary term (69 occurrences, LS = 311); and Cluster 5 (purple) had 8 keywords featuring "grain yield" (22 occurrences, LS = 128) as the main term.

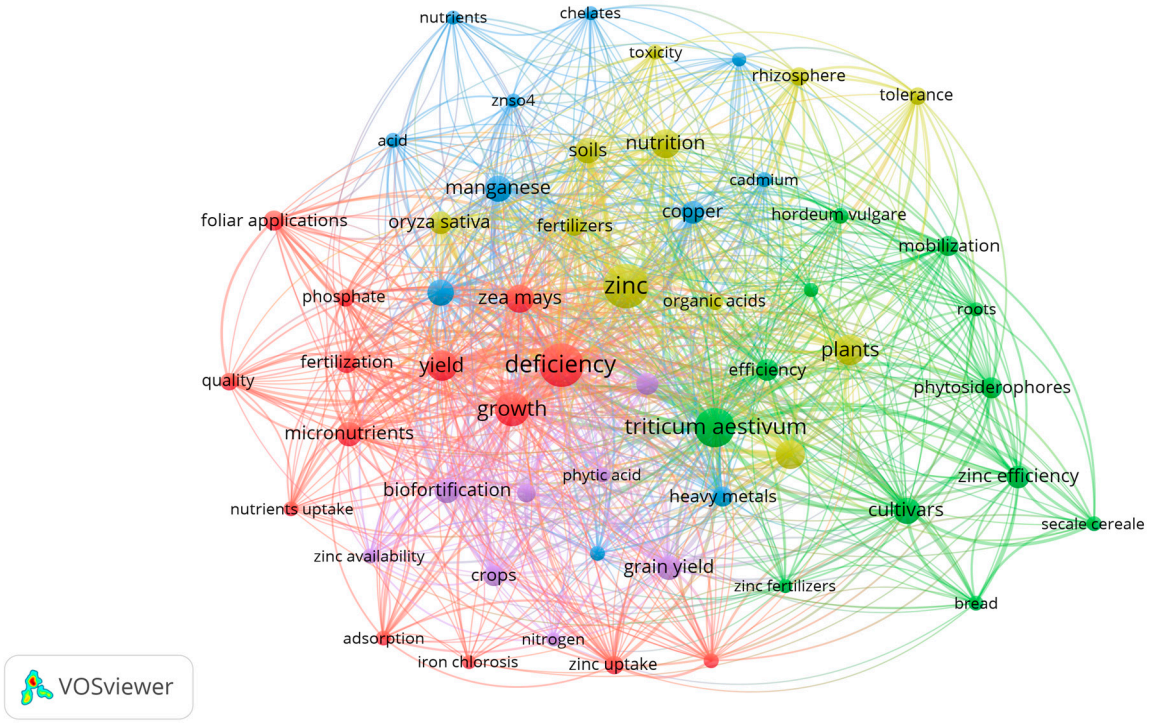

Figure 6. Visualization in VOSviewer of keywords with at least seven occurrences related to Zn deficiency in calcareous soils, grouped into clusters.

Cluster 1 (red) highlights the intrinsic and extrinsic factors that regulate Zn concentration and uptake, which, in turn, modulate plant metabolism. It is composed of the terms "nutrient uptake", "zinc uptake", "adsorption", "deficiency", "zinc concentration", "fertilization", "foliar applications", "growth", "iron chlorosis", "micronutrients", "quality", "yield", and "*Zea mays*".

Cluster 2 (green) focuses on the efficiency of Zn in plants, particularly emphasizing the mobilization processes of Zn in calcareous soils and the main crops that have been evaluated. The terms in this group include "efficiency", "zinc efficiency", "mobilization", "translocation", "phytosiderophores", "roots", "*Triticum aestivum*", "*Hordeum vulgare*", "*Secale cereale*", "cultivars", "zinc fertilizers", and "bread".

Cluster 3 (blue) addresses the interaction of Zn with other elements, such as cadmium, copper, and manganese. The keywords included in this node are "absorption", "acid", "availability", "cadmium", "chelates", "copper", "heavy metals", "manganese", "nutrients", "speciation", and "$ZnSO_4$".

Cluster 4 (yellow) encompasses the various functions of Zn in plants. This cluster also highlights several factors that can influence the nutritional status of Zn in plants, including soil properties, characteristics of the rhizosphere, fertilizers used in nutritional management, interactions between Zn and other nutrients (e.g., phosphorus), and crop tolerance to calcareous soils. The keywords of this node are "zinc", "plants", "soils", "nutrition", "fertilizers", "organic acids", "phosphorus", "rhizosphere", "tolerance", "toxicity", and "*Oryza sativa*".

Cluster 5 (purple) pertains to the bioavailability of Zn in foods, highlighting biofortification as a promising strategy to enhance Zn accumulation in plant-based foods. The terms included in this group are "bioavailability", "biofortification", "phytic acid", "accumulation", "crops", "zinc availability", "grain yield", and "nitrogen".

4. Discussions

Low Zn levels are estimated to affect approximately half of the world's soils [46]. Consequently, Zn deficiency in plants has garnered widespread interest due to its substantial

impact on the yield of numerous crops, particularly those grown in calcareous soils [47]. Despite this, no bibliometric approach has been conducted to identify the key research topics related to Zn deficiency in calcareous soils on a global scale.

In this bibliometric study, 198 publications related to Zn deficiency in calcareous soils were retrieved through the WOS platform in the period between 1989 and 2024. Consequently, the data are limited to publications indexed in the WOS database. We analyzed scientific productivity using bibliometric indicators and visualized research hotspots using VOSviewer software. Several reviews have addressed the functions, deficiency factors, and dynamics of Zn in plants. For instance, Broadley et al. [48] discussed the essential role of Zn in plants in their review article titled "Zinc in Plants." Similarly, a recent review entitled "Citrus Nutrition in Iran: Lessons from Calcareous Soils" [35] highlights the causes and consequences of Zn deficiency in citrus grown in calcareous soils in Iran.

The results of this study revealed a consistent increase in the volume of literature on Zn deficiency in calcareous soils over the last thirty-six years, highlighting the growing interest of scientists and policymakers in addressing this agronomic challenge that affects various crops worldwide.

A total of 198 publications were recorded, accumulating 6833 citations. The most cited authors were Ismail Cakmak, Hasan Ekiz, Asif M. Yilmaz, Bülent Torun, and Mufit Kalayci. These researchers have primarily focused on topics related to Zn nutrition and calcareous soils, with their affiliations predominantly based in Türkiye. This suggests the existence of a collaborative network among these authors.

The primary journal sources included the *Journal of Plant Nutrition*; *Plant and Soil*; *Communications in Soil Science and Plant Analysis*; *Journal of Soil Science and Plant Nutrition*; and *Applied Soil Ecology*. These journals collectively published over 40% of the total articles.

The results indicate that Iran, Türkiye, Pakistan, China, and the United States are the predominant countries in this area of research. Soils with high calcium carbonate content are prevalent across large regions of Iran and Türkiye [49], as both countries are situated in the Mediterranean region, where calcareous soils are predominant. Hacisalihoglu [50] reported that 50% of agricultural soils in India and 45% in Türkiye exhibit low zinc (Zn) content. The geographical locations of these countries may elucidate the heightened concern and interest of governments and researchers in this field of study.

The primary institutions contributing to the body of literature on Zn deficiency in calcareous soils are in Türkiye, Pakistan, Iran, and China. Notable institutions include Cukurova University, Bahauddin Zakariya University, Isfahan University of Technology, Northwest A&F University, and Shiraz University.

The predominant terms allowed the classification into five clusters, highlighting the research hotspots and trends related to Zn deficiency in calcareous soils over the past thirty-six years (Figure 6).

Cluster 1, represented in red, elucidates the essential factors involved in the Zn concentration and uptake. Zn acquisition by plants is governed by various soil physicochemical processes, including adsorption, precipitation with phosphate ions, and competition with other micronutrients, as well as the molecular mechanisms regulating Zn uptake (Figure 6). Zn transport has been reported to be facilitated by metal transporters such as the P_{1B}-ATPase family, zinc-regulated transporter (ZRT), iron-regulated transporter (IRT)-like protein (ZIP), natural resistance-associated macrophage protein (NRAMP) family, and cation diffusion facilitator (CDF) family [6]. Likewise, transporters plant cadmium resistance (PCR), vacuolar iron transporter (VIT), and yellow stripe-like (YSL) have been reported to be involved in the transport of micronutrients in plants [51]. Additionally, Yang et al. [52] demonstrated that the activity of the OsZIP9 transporter regulates Zn and Co uptake in rice roots. Kalayci et al. [53] investigated the effects of zinc fertilization on wheat cultivars, focusing on grain yield, Zn concentration in grains and shoots, and agronomic efficiency. Their findings highlighted that, due to variability in yield response to fertilization, the evaluated cultivars are significant sources of key genes required for Zn uptake. Recent research has emphasized

the dynamics of Zn in plants, including its absorption, transport, accumulation, and roles in metabolic processes [3,6,52]. This area presents significant potential for future studies.

Cluster 2, represented in green, focuses on aspects related to Zn efficiency in calcareous soils (Figure 6). A key feature of this cluster is the role of phytosiderophores (PS), which are believed to enhance Zn uptake under deficiency conditions in calcareous soils. These compounds are synthesized by cereal crops such as wheat, maize, and rice [54]. Several studies have been evaluated to evaluate the acquisition mainly of Fe by cereal crops (*Poaceae*) grown in calcareous soils, where PS is released into the rhizosphere to act as chelators [55]. Phytosiderophores facilitate the uptake of both Fe and Zn in rice plants [56]. Similarly, in calcareous soils, PS has demonstrated the ability to mobilize significant amounts of Zn, Mn, and Cu [57]. Cakmak et al. [58] examined the effect of Zn nutrient status on PS release in three wild grass species (*Hordeum murinum*, *Agropyron orientale*, and *Secale cereale*) under controlled environmental conditions. Their results showed that Zn-deficient plants significantly increased PS release, a response absent in plants with sufficient Zn levels. Inoculation with solubilizing bacteria is emerging as a new method for nutrient supply facilitated by interactions between these microorganisms and plants [59]. Ali et al. [60] note that solubilizing bacteria make Zn available to crops through the secretion of siderophores, which act as metal-chelating molecules in calcareous soils. In a study on wheat plants grown in pots, the effect of five bacterial strains with Zn-solubilizing properties (*Pseudomonas fragi*, *Pantoea dispersa*, *Pantoea agglomerans*, *Enterobacter cloacae*, and *Rhizobium sp.*) on growth and Zn content in shoots, roots, and grains was evaluated. A significant increase in root dry weight and Zn content was observed in plants inoculated with *Pseudomonas fragi* compared to the control (Zn-fertilized plants) [61].

Cluster 3, represented in blue, addresses the interaction of Zn with other elements and traditional sources of Zn fertilization (Figure 6). The antagonistic relationship between Zn and elements such as phosphorus, boron, copper, and cadmium in the soil can lead to reduced Zn availability for plants [62–64]. In calcareous soils, chelates are commonly used to supply micronutrients, primarily iron and zinc. However, the use of chelating agents may also enhance the leaching and solubility of heavy metals in the soil [65]. Foliar fertilization is a recommended method for supplying nutrients to crops grown in calcareous soil through frequent applications [66]. However, synthetic chelates and $ZnSO_4$, which are commonly used sources, exhibit low absorption by leaves and limited translocation of Zn within the plant [67]. The effectiveness of synthetic chelates (EDTA, DTPA, or EDDHA) and zinc sulfate ($ZnSO_4$) in correcting Zn deficiency in crops has been investigated over the years; however, the results have not been particularly promising. In this context, an intriguing avenue for future research would be the evaluation of new sources of Zn fertilizers on the yield and quality of crops grown in calcareous soils, such as nanofertilizers, aminochelates, or solubilizing bacteria. Kumar et al. [68] report that zinc oxide nanoparticles (ZnO NPs) have garnered significant interest in crop studies in recent years, highlighting ZnO NPs as a viable alternative to traditional fertilizers. ZnO NPs are a more plant-available source of Zn due to their particle size (<100 nm) [69] compared to their micrometer- or millimeter-sized (bulk) counterparts [70]. However, inadequate dosages can result in plant phytotoxicity [71]. In wheat cultivated in calcareous soil, ZnO NP doses of 1 and 2 kg ha^{-1} significantly increased grain yield, straw yield, and concentrations of zinc, nitrogen, phosphorus, and potassium in grains, compared to plants treated with 4 kg ha^{-1} of DTPA-Zn [72]. Aminochelates represent a novel source of fertilizers, demonstrating higher foliar uptake compared to sulfates and synthetic chelates when applied foliarly [67]. Additionally, aminochelates enhance the translocation of elements such as Zn in plants [73]. Foliar applications of the aminochelate Biomin® (2 g L^{-1}) increased the chlorophyll index, number of lateral shoots, shoot dry weight, number of fruits, plant yield, and leaf nitrogen concentration compared to the control in tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus*) and green bean (*Phaseolus vulgaris*) gown in calcareous soil [74].

Cluster 4, represented in yellow, elucidates the metabolic functions of Zn in the plant (Figure 6). It is unique among metals for being involved in the activity of all six types of enzymes:

oxidoreductases, transferases, hydrolases, lyases, isomerases, and ligases [75]. The role of Zn in the synthesis of auxin, protein, and chlorophyll has also been reported [76,77]. Zn confers tolerance to crops under salinity stress conditions by protecting plant cells from oxidative damage, enhancing the activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX) [78,79]. In addition to this, low Zn levels in plants decrease the activity of the anhydrase carbonic (photosynthetic enzyme) [80]. For instance, mandarin trees fertilized with increasing concentrations of Zn (1, 2, 3, 4, 5, 10, 15, and 20 mM) exhibited an increase in biomass with higher Zn dosage; however, a decrease in photosynthetic rate, stomatal conductance, transpiration, and chlorophyll content was noted at elevated Zn levels [81]. In this cluster, the term 'tolerance' is also emphasized. Some fruit crops can tolerate relatively high amounts of $CaCO_3$ through the scion-rootstock interaction [82]. However, selecting a specific rootstock is complicated by its influence on important factors such as growth, yield, disease resistance, and tolerance to cold or drought stress conditions [83]. In orchards in northeastern Mexico, 'Valencia' orange (*Citrus sinensis* L. Osbeck) is mainly grafted onto sour orange (*Citrus aurantium*), acquiring tolerance to the calcareous soils of this region [84]. However, this rootstock is highly sensitive to the citrus tristeza virus (CTV) [85]. In the calcareous soils of the Mediterranean region, 16 peach rootstocks were evaluated based on agronomic, fruit quality, and nutritional parameters of 'Big Top' nectarine. Among them, 'Adesoto 101', 'Cadaman®', 'Garnem®', 'GF 677', 'PADAC 04-01', 'PADAC 04-03' and 'PADAC 99-05' were evaluated, Cadaman®', "Garnem®", "GF 677", "PADAC 04-01", "PADAC 04-03", "PADAC 99-05", "PADAC 9902-01", "Penta", "PM 44 AD" and "PM 105 AD" showed an optimal and high level of zinc in their leaves [86].

Cluster 5, represented in purple, highlights recent topics of interest, with a particular focus on 'biofortification' and 'phytic acid' (Figure 6). Recent reviews indicate that Zn deficiency in crops persists in several countries, adversely affecting growth and, consequently, human health. The presence of low Zn levels in foods is a significant concern for human nutrition, particularly affecting vulnerable populations such as children, pregnant women, and the elderly [43]. Globally, around 1.1 billion people (17% of the world's population) are at risk of Zn deficiency, which has been linked to adverse pregnancy outcomes, stunted growth, premature deaths, immune system dysfunction, neurobehavioral disorders, and inadequate recovery following COVID-19 [47]. Biofortification is a promising strategy to enhance the bioavailability of Zn in foods through agronomic practices or conventional crop breeding [87]. Several studies have indicated that high concentrations of phytic acid in cereal grains, often resulting from the application of phosphate fertilizers, reduce Zn availability for human consumption [88]. The antagonism between phosphorus and zinc in plants has been extensively studied [89]; moreover, both nutrients frequently exhibit deficiency in calcareous soils [90]. Therefore, future research should explore innovative methods for managing Zn and P deficiencies in cereals grown in calcareous soils while preserving their nutritional value for humans.

5. Conclusions

In this study, a bibliometric analysis of 198 publications related to Zn deficiency in calcareous soils was conducted. The analysis focused on articles and reviews indexed in the Web of Science platform from 1989 to 2024. This research highlights the growth trend, as well as the primary authors, articles, journals, institutions, and countries associated with this topic. Additionally, co-authorship networks among authors and countries were identified, along with the determination of research hotspots. The number of publications on Zn deficiency in calcareous soils has shown an increasing trend over the last thirty-six years in response to the problem it causes in agriculture and, consequently, in human health. Most of the publications on this topic come from Iran and Türkiye, where interest in Zn deficiency is linked to the origin of the soils. Ismail Cakmak, Torun Bülent, and Amir Hussain Khoshgoftarmanesh were the most prolific authors, and they focused most of their

studies on the Mediterranean region, as Zn deficiency is prevalent in the large areas of calcareous soils.

Key research topics identified include the intrinsic and extrinsic factors regulating Zn concentration and uptake, the efficiency of Zn in plants, the interaction of Zn with other elements, the functions of Zn in plants, and the bioavailability of Zn in foods. In the future, Zn deficiency in calcareous soils can be addressed through different avenues of research: improving the understanding of the metabolic and biochemical processes of Zn in plants; understanding the molecular barriers in roots that need to be overcome for efficient Zn uptake in deficient soils; evaluating Zn solubilizing agents; developing and testing new fertilization technologies (e.g., aminochelates and nano-fertilizers); assess plant genetic variation as a strategy to promote crop tolerance; and study the rate of phosphorus fertilization that can reduce Zn concentration in crops and impact on human health.

This bibliometric study provides a comprehensive overview of this field on a global scale, offering a valuable reference for scientists and policymakers interested in future research in this area.

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