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REVIEW ARTICLE

Zinc status in public health: exploring emerging research trends through bibliometric analysis of the historical context from 1978 to 2022

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Abstract
The current study aims to provide a roadmap for future research by analyzing the research structures and trends in scholarly publications related to the status of zinc in public health. Only journal articles published between 1978 and 2022 are included in the refined bibliographical outputs retrieved from the Web of Science (WoS) database. The first section announces findings based on WoS categories, such as discipline heterogeneity, times cited and publications over time, and citation reports. The second section then employs VoSViewer software for bibliometric analysis, which includes a thorough examination of co-authorship among researchers, organizations, and countries and a count of all bibliographic databases among documents. The final section discusses the research's weaknesses and strengths in zinc status, public health, and potential future directions; 7158 authors contributed to 1730 papers (including 339 with publications, more than three times). "Keen, C.L." is a researcher with the most publications and a better understanding of zinc status in public health. Meanwhile, the USA has been the epicenter of research on the status of zinc in public health due to the highest percentage of publications with the most citations and collaboration with the rest of the world, with the top institution being the University of California, Davis. Future research can be organized collaboratively based on hot topics from co-occurrence network mapping and bibliographic couplings to improve zinc status and protect public health.

Keywords Zinc · Deficiency · Supplement · Public health · Health · Bibliometric analysis · Nutrition · Malnutrition

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Introduction

Zinc is an essential micronutrient that participates in numerous biochemical reactions in the human body (Frassinetti et al. 2006). Zinc is required for at least 300 enzymes to function properly, including the immune system, gene expression, cell growth, and division (Basabe-Desmonts et al. 2007; Shyamal et al. 2016; Chasapis et al. 2020; Suganya et al. 2020). Furthermore, zinc is necessary for the proper development and function of many organs and systems, including the brain, heart, and pancreas (Plum et al. 2010). Acyzol, a zinc-containing medicine, effectively treats various health conditions (Aliev et al. 2019). Low zinc levels are associated with an increased risk of cardiovascular disease, depression, autism spectrum disorder (ASD), Alzheimer's disease, cancer, and diabetes (Little et al. 2010; Khan et al. 2016). As a result, it is critical to assess zinc status and treat zinc deficiency in all cases, as zinc's unique properties may have a significant therapeutic impact in curing some illnesses.

Zinc deficiency is a global public health issue that disproportionately affects developing countries where malnutrition is common (Narváez-Caicedo et al. 2018). One in every five people worldwide is zinc deficient, and the deficiency prevalence rises with age (Kawade 2012). Inadequate zinc levels in the body can cause a variety of health issues, including an increased risk of developing chronic diseases such as cancer and heart disease, stunted growth, weakened immunity, impaired wound healing, cognitive impairment, and impaired cognitive function (Prasad 2008; Maggini et al. 2010; Chasapis et al. 2012; Aslan et al. 2021). Because it can be difficult for people to get enough zinc from their diet, it is critical to consume enough zinc to meet the body's needs. The recommended dietary allowance (RDA) for zinc for adults is 8 to 11 mg/day, but this can be increased depending on age, gender, and activity level (Zhang et al. 2018).

Zinc deficiency has become less common in recent decades due to improved dietary intake and absorption and increased zinc use in medical treatments (Krebs 2013). Numerous methods for increasing zinc intake include eating zinc-rich foods, taking dietary supplements, and applying topical products (Maret and Sandstead 2006). Zinc-rich foods include oysters, beef, crabmeat, poultry, legumes such as soybeans and lentils, milk products such as yogurt and cheese, nuts and seeds, brewer's yeast extract supplements, and fortified breakfast cereals (Basharat et al. 2019). Supplementation may be necessary in some cases, as zinc from food may have low bioavailability.

Zinc supplementation is a low-cost and simple way to prevent deficiency and relieve disease symptoms in many patients (Krebs 2013). However, knowing the potential side effects and acute zinc poisoning from ingesting too much zinc at once is critical. Some people may experience nausea, vomiting, fatigue, diarrhea, stomach pain, and constipation due to taking zinc supplements (Razzaque 2020). Furthermore, zinc may interfere with other medications or supplements (Fosmire 1990). As a result, before taking zinc supplements regularly, weighing the risks and benefits is critical.

Zinc status is affected by factors such as age, pregnancy, and infection and reflects both recent and long-term dietary intake (Walsh et al. 1994). Previous research has found that zinc status can help predict morbidity and mortality (Doerr et al. 1998; Barnett et al. 2010). Potential interventions, such as raising awareness about the importance of getting enough zinc in your diet and providing tips on how to eat more zinc, could help with zinc absorption and dietary intake (Roohani et al. 2013; King et al. 2015). Other challenges, such as increasing the availability of zinc-rich food and preventing the accumulation of environmental zinc in the body, must still be addressed to improve zinc status in the population even further (Roohani et al. 2013). As a result, ongoing research is required to improve zinc status and protect public health. Other challenges, such as increasing the availability of zinc-rich food and preventing the accumulation of environmental zinc in the body, must still be addressed to improve zinc status in the population even further (Roohani et al. 2013).

Bibliometric analysis is a statistical technique used to quantify and examine existing publications in academic research to identify trends and patterns (Chen et al. 2019; Kasavan et al. 2021a). As a result, this study aims to conduct a bibliometric analysis of worldwide scientific publications relating to zinc's status in public health and its key elements. This study's overview provides a comprehensive bibliometric analysis of peer-reviewed English articles published on the Web of Science (WoS) database between 1978 and 2022. The research outputs will then aid in directing scholars or funding organizations toward the gaps and exploration categories in the zinc status-public health-related research activities and provide the reader with some insights. These categories include top disciplines-related, times cited and publications over time, famous journals-related, experts defined based on author-co-authorship, most active organizations, and countries, hot keywords-related, and total link strengths among documents.

Methodology

Search strategy and bibliographic database

Bibliometric analysis employs statistical techniques to assess published works in a particular discipline. Using bibliometric measures based on published studies allows for evaluating research outcomes and the study's impact based on citations (Khalil and Gotway Crawford 2015; Ali et al. 2022). The Web of Science (WoS) database is the most comprehensive among its competitors (Google Scholar, PubMed, and Scopus) (Kasavan et al. 2021b). It has a more consistent and reliable record of accomplishment in analyzing literature for multidisciplinary disciplines (Kasavan et al. 2021a). Thus, the WoS database was used for this investigation to locate relevant papers, and only journal research articles were considered for analysis.

We searched for ((“zinc deficiency”)OR(“zinc intake”) OR(“zinc status”))AND((“public health”)OR(“human health”)OR(“health”)) in all fields to identify zinc status in public health. The search lasted many years (1971–2023). There were no refined WOS indexes, and the publications were limited to English journal articles. To avoid any bias caused by the WOS database's ongoing update, the work of looking up necessary publications was only done once on July 29th, 2022. The data plug-in for bibliographies in WoS (https://www.webofscience.com) is also useful for analyzing citation report results. The TreeMap chart displaying the top 20 highest results based on WOS categories was downloaded directly from the source. Data such as times cited, publications over time, and the rank of cited publications were available on the WoS website under the “Citation reports” tab.

The Clarivate Journal Citation Reports (JCR) database determined the journal impact factor (JIF) and average JIF. For further analysis, the bibliographic databases of all the papers were selected and exported in the plain text file format compatible with the VOSviewer application (Version 1.6.18). The VOSviewer software provides various features to manage the diagrams effectively, including zoom, explore, scroll, and defined cluster items to examine the chart thoroughly. The program offers different visualizations, allowing the viewer to focus on the diagram's overall design or its more specialized elements (Heersmink et al. 2011). Using VOS mapping approaches, it is possible to analyze trending meta tags, clustering analysis, and examine collaborative links within a research topic (Ma et al. 2022).

Elements in the network mapping are labeled with titles and depicted on the diagram as circles or frames. The size of the title and circle determined the weight of the keywords. As a result, the title and frame of the component would grow in direct proportion to its weight. The element's color indicates the component's segment, and the paths between them show the connections between the elements. A chain of co-authorship, co-occurrence, and bibliographic coupling linkages can be generated using bibliographic data. Because full counting is used, the weight of each link is the same. Figure 1 depicts the approach we took.

Bibliometric analysis and mapping using VOSviewer

To demonstrate the collaborative nature of this field's research, the units of analysis were defined as authors, organizations, and countries (along with regions). The analysis type was set to co-authored publications, with a maximum of 25 authors per document. The analysis thresholds for authors, organizations, and countries were as follows: (1) authors, the minimum number of documents per author was three; (2) organizations, the minimum number of documents of an organization, was ten, followed by a minimum number of citations of none; and (3) countries, the minimum number of documents of a country was five. As a result, the extent of co-authorship publication served as an indicator of collaboration in this study. According to Zhang et al. (2020), the formula used to determine the authors' “Publication ratio on the topic in %” is as follows:

$$\text{Publication ratio}(\%) = \frac{\text{Total author}'\text{s articles on topic}}{\text{Total author}'\text{s articles}} \times 100$$

Co-occurrence analysis was used to investigate the relationships between terms used in co-authored publications to identify research clusters, research directions, and the emergence of new research areas (Andrade et al. 2019). To classify the cluster of hot keywords, “co-occurrence” and “author's keywords” were chosen, and the threshold was set to at least eight occurrences of the author's keywords. In this study, the author's keyword frequency analysis is used to understand better the areas of research that are particularly active in the area of zinc status in public health. Furthermore, it effectively developed a comprehensive understanding of the research issue and outlined potential future research directions.

A full counting analysis of “bibliographic coupling” and “document” was carried out. The simultaneous citation of the same work in two documents is called bibliographic coupling (Ma et al. 2022).

Results and discussion

Quantitative and qualitative's findings

The WoS database search produced 2127 publications about the public health implications of zinc status. Although all the years (1971–2023) were searched, the keyword search results appeared to begin in 1978. As a result, we limited the bibliometric study to fully operational databases from 1978 to 2022 (45 years); 1767 journal articles, 294 reviews, 144 proceeding papers, 51 book chapters, 25 meeting abstracts, 20 editorial materials, and results from early accesses,

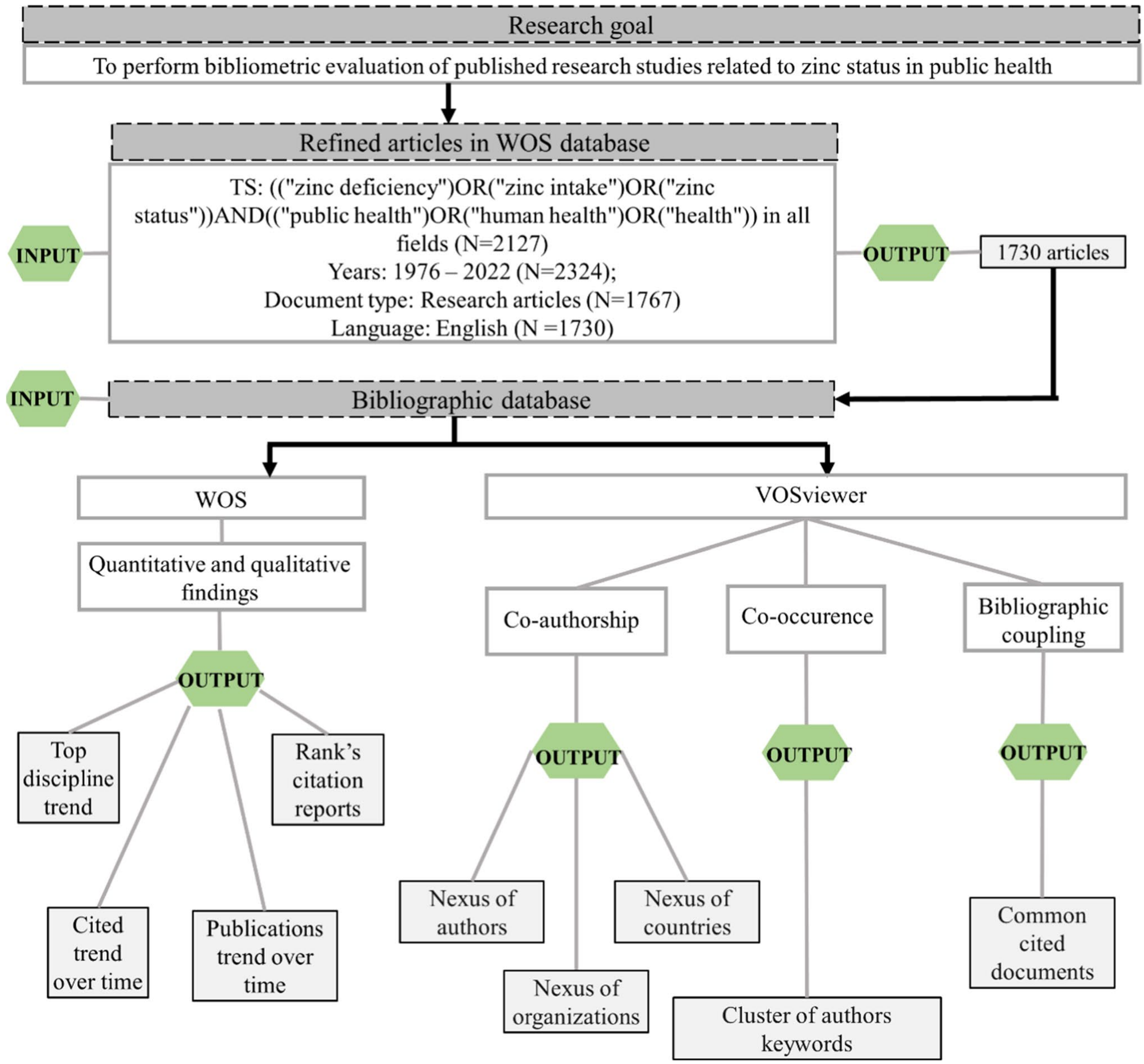

Fig. 1 Bibliometric analysis research design

letters, notes, corrections, and data papers were among the document categories used to compile the conclusions. Additionally, 83% of the total number of publications displayed are journal articles.

The Science Citation Index Expanded (SCI-EXPANDED), Conference Proceedings Citation Index–Science (CPCI–S), Emerging Sources Citation Index (ESCI), Social Sciences Citation Index (SSCI), Book Citation Index–Science (BKCI–S), Book Citation Index–Social Science and Humanities (BKCI–SSH), Art and Humanities Citation Index (A&HCI), and Index Chemicus were the WoS indexes used in this study (IC). The 1767 journal articles' metadata pie chart visualization revealed that they were published in at least 10 different languages, with 1730 (or 97.9%) being in English (lingua franca). Spanish (17), Portuguese (6), German (5), French (2), Hungarian (2), Turkish (2), Chinese (1), Russian (1), and Slovenian (1) were the languages used in the remaining publications (2.1%) (see Fig. 2). Only works published in English (1730) were subsequently chosen as the main sources of data for additional bibliometric research.

Heterogeneity disciplines based on WOS categories

The Web of Science results highlight 108 disciplines pertinent to zinc status research and public health. This idea is

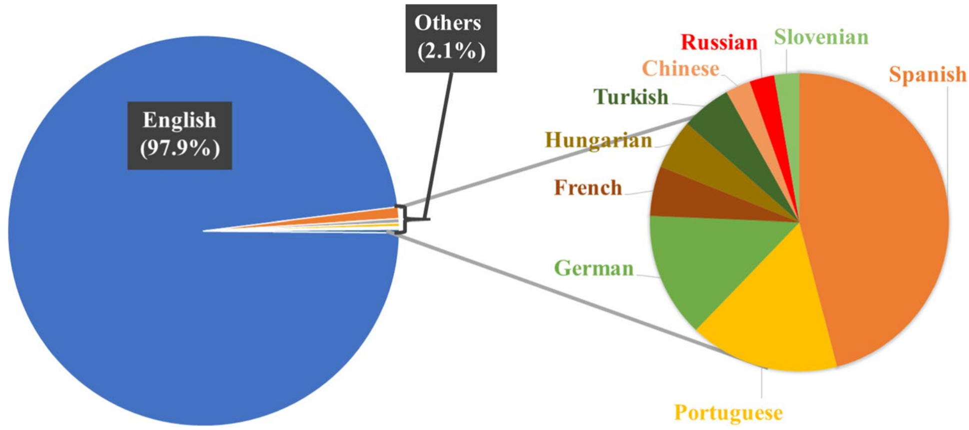

Fig. 2 Pie chart from 1978 to 2022 showing the many languages used in publications about the status of zinc in public health

Fig. 3 The WOS categories used to create the treemap of the first 20 disciplines related to zinc status in public health from 1978 to 2022. The number displayed in each box corresponds to the total number of publications for that discipline

illustrated in Fig. 3, which shows a tree map of the makeup of the first 20 groups. Out of 1730 publications, the most significant categories are those in nutrition dietetics (592 publications or 34.16%), biochemistry molecular biology (262 publications or 15.14%), endocrinology metabolism (144 publications or 8.32%), public environmental, occupational health (130 publications or 7.51%), pediatrics (84 publications or 4.85%), and multidisciplinary sciences (77 publications or 4.45%), as shown on the visualization chart in Fig. 3. Together, these six groupings represented 74.5% of the total number of publications (1730).

Times cited and publications over time

The WOS search engine's chosen keywords and criteria led to the first discovery, which is the quantification of publications and citations in the field of research on zinc status in public health; 1730 records, from one in 1978 to 55 in 2022, were uncovered. Even if the number of articles fluctuated every year from 1978 to 2022, Fig. 4 demonstrates the tendency for publications related to "zinc status" and "public health" to increase throughout those years. The biggest number of papers were published in 2019, 2020, and 2021, with 90, 88, and 91, respectively. This coincides with the World Health Organization's (WHO) designation of the Coronavirus Disease 2019 (COVID-19) pandemic (Samad et al. 2021).

SARS-CoV-2, the virus that created COVID-19, started the world's healthcare challenges since patient morbidity and mortality are much more substantial (Jothimani et al. 2020). Therefore, combating COVID-19 has taken importance (Fenner and Cernev 2021). Te Velthuis and colleagues claim that in vitro tests demonstrate zinc inhibits coronavirus and arterivirus RNA (ribonucleic acid) polymerases. Based on findings from cell culture tests, the same group also asserted that zinc ionophores can stop virus growth (te Velthuis et al. 2010). Zinc is said to operate as an antiviral immunity agent, enhancing innate and acquired immunity (Read et al. 2019; Jayawardena et al. 2020; Kumar et al. 2020). Since there is no known effective treatment for COVID-19, these specific hypotheses have strengthened the researcher's conviction that micronutrients zinc, which has an immune-boosting effect, and antiviral processes will have a favorable impact on therapy.

Core journals on the zinc status in public health

Table 1 includes the top 20 active journals between 1978 and 2022 and the quantity of publications on zinc status in public health published in each. The top 20 publications accounted for 638 research articles, or over 36.87%, of the total. With a focus on Nutrition & Dietetics, the Journal of Nutrition published the most research articles on "zinc status" and "public health" (article count: 150, JIF: 4.687, and rank Q2 in the year 2021). Nevertheless, this one does not have the highest impact factor of the top 20 journals listed in Table 1's ranking. A Q1 journal in the Multidisciplinary Sciences category, Proceedings of the National Academy of Sciences of the United States of America Science, was ranked first in impact factor (JIF: 12.779) but 13th in publication number (16 articles).

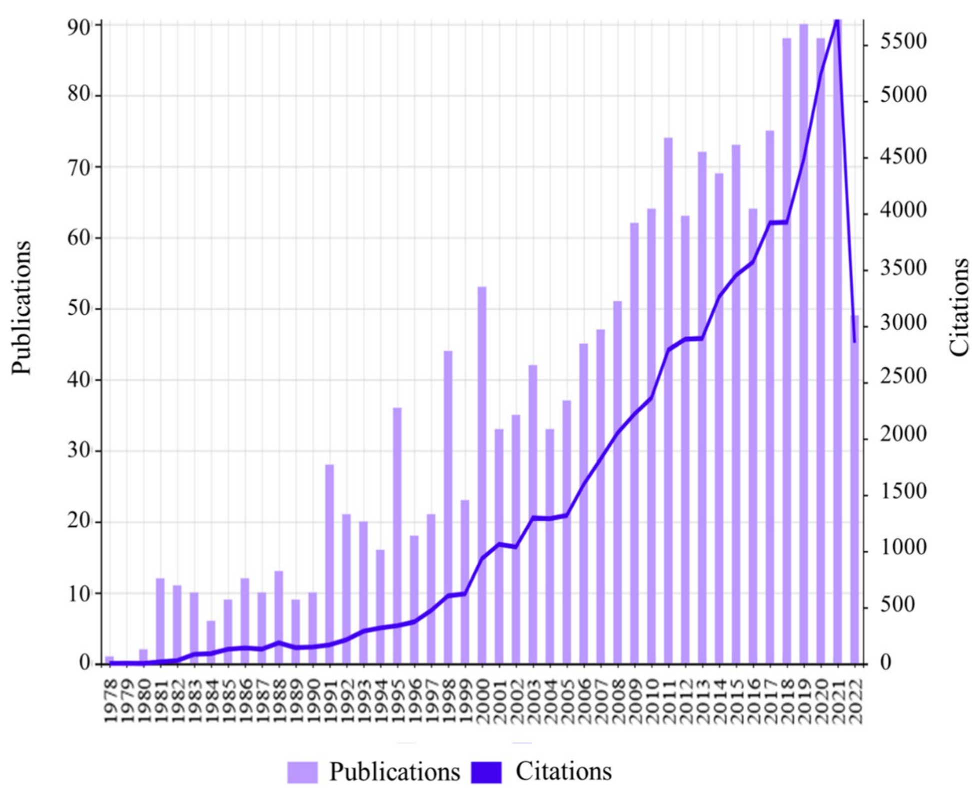

Fig. 4 Zinc status in public health: trends, volume, and number of publications and citations from 1978 to 2022

Table 1 The top 20 active journals from 1978 to 2022 address zinc status in public health, together with the number of articles, the journal impact factor (JIF), categories, ranks, and the journal's share of the contribution

No	Publication titles	Sum	Journal impact factor (JIF)	Category/edition-rank	% of 1730 article
1	Journal of Nutrition	150	4.687	Nutrition & Dietetics/SCIE-Q2	8.67%
2	American Journal of Clinical Nutrition	95	8.475	Nutrition & Dietetics/SCIE- Q1	5.49%
3	Nutrients	56	6.706	Nutrition & Dietetics/SCIE-Q1	3.24%
4	Biological Trace Element Research	49	4.081	Biochemistry & Molecular Biology/SCIE-Q3 Endocrinology & Metabolism/SCIE-Q2	2.83%
5	PLoS One	36	3.752	Multidisciplinary Sciences/SCIE-Q2	2.08%
6	Journal of Trace Elements in Medicine and Biology	30	3.995	Biochemistry & Molecular Biology/SCIE-Q3 Endocrinology & Metabolism/SCIE-Q3	1.73%
7	Journal of Biological Chemistry	29	5.486	Biochemistry & Molecular Biology/SCIE-Q2	1.68%
8	British Journal of Nutrition	22	4.125	Nutrition & Dietetics/SCIE Q3	1.27%
9	Journal of the American College of Nutrition	21	3.571	Nutrition & Dietetics/SCIE-Q3	1.21%
10	Nutrition	18	4.893	Nutrition & Dietetics/SCIE -Q2	1.04%
11	Food and Nutrition Bulletin	17	2.244	Nutrition & Dietetics/SCIE-Q4 Food Science & Technology/SCIE-Q3	0.98%
12	Journal of Nutritional Biochemistry	17	6.117	Biochemistry & Molecular Biology/SCIE-Q1 Nutrition & Dietetics/SCIE-Q1	0.98%
13	Proceedings of the National Academy of Sciences of the United States of America	16	12.779	Multidisciplinary Sciences/SCIE-Q1	0.92%
14	Public Health Nutrition	16	4.539	Public, Environmental & Occupational Health/SCIE-Q2 Nutrition & Dietetics/SCIE- Q2	0.92%
15	Scientific Reports	16	4.996	Multidisciplinary Sciences – SCIE-Q2	0.92%
16	Proceedings of the Society for Experimental Biology and Medicine	15	2.714	Medicine, Research & Experimental/SCIE-Q1	0.87%
17	Journal of Health Population and Nutrition	13	2.966	Public, Environmental & Occupational Health/SCIE-Q3 Environmental Sciences/SCIE-Q3	0.75%
18	European Journal of Clinical Nutrition	12	4.884	Nutrition & Dietetics/SCIE-Q2	0.69%
19	Journal of Laboratory and Clinical Medicine	10	2.795	Medicine, Research & Experimental/SCIE-Q2 Medical Laboratory Technology/SCIE-Q1 Medicine, General & Internal/SCIE-Q1	0.58%
20	Pediatric Research	10	3.953	Pediatrics/SCIE-Q1	0.58%

The second-most important publication was the American Journal of Clinical Nutrition Field, which published 95 articles with an impact factor of 8.475 in the major category of Nutrition & Dietetics. Nutrients, the third-highest publishing category, contained 56 papers with an impact factor of 6.706. Journal of Trace Elements in Medicine and Biology (30 publications), Journal of Biological Chemistry (29 publications), British Journal of Nutrition (22 publications), Journal of the American College of Nutrition (21 publications), Nutrition (18 publications), and other journals have since published articles related to the keyword's search (see Table 1). For the top 20 journals, the average impact factor was 4.8879.

The 20 top journals included the 11 categories mentioned earlier, including (1) nutrition and dietetics (ranks: Q1, Q2, Q3, and Q4); (2) biochemistry and molecular biology (ranks: Q1, Q2, and Q3); (3) endocrinology and metabolism; (4) multidisciplinary sciences (ranks: Q1 and Q2); (5) food science and technology; (6) public, environmental, and occupational health; (7) environmental sciences; and (8) medicine, research, and experimental (rank: Q1). Based on Table 1, all of the stated categories were subject to the edition of Science Citation Index Expanded (SCIE), and a total of nine were ranked Q1, ten were ranked Q2, eight were ranked Q3, and one was rated Q4. These showed that most publications that discussed the status of zinc in public health had an impact rating in the top quartile.

Citation reports

A document's influence can be ascertained by citation analysis, which reflects the sources and information used in the document and their relative weight. There have been 66,380 citations to a total of about 1605 articles as of today (July 29th, 2022). The top ten empirical studies on zinc status in public health that have received the most citations are listed in Table 2 below. The piece "Global burden of childhood pneumonia and diarrhea" by Fischer Walker et al. 2013, which appeared in the April issue of "The Lancet" with JIF 202.731, received the most citations (1399) (Fischer Walker et al. 2013).

The next two articles, "Zinc and immune function: the biological basis of altered resistance to infection" and "Associations between antioxidant and zinc intake and the 5-year incidence of early age-related maculopathy in the beaver dam eye study," both appeared in 1998 and received 1006 and 620 citations, respectively. The following article had an impact factor of 4.687 and was titled "Dietary factors influencing zinc absorption." It was printed in the journal of nutrition. "The role of zinc in growth and cell proliferation," the fifth-most-cited article, performs admirably given that it was published in 2022 and has already accumulated more than half as many citations as the second-most-cited piece from 1998.

Because only Q1 and Q2 were included in the quartile rankings, as shown in Table 2, the top ten most referenced papers came from high-impact studies. Additionally, those articles discussed the effects of zinc deficiency on infant development (ranks 1 and 3), the importance of zinc (ranks 2 and 5), and the insufficiency of zinc (ranks 6, 7, 9, and 10). Thus, a general idea about some important questions about the status of zinc in public health that have drawn attention from researchers was given by reading the most cited papers. The bibliometric network analysis of the most popular author's keywords is followed by further explanations of the most important research themes.

Bibliometric analysis and counting method

Authors and co-authorship among authors

20 writers produced more than 15 research articles during the 45-year study period, bringing the total number of researchers involved in this study to 7158. Table 3 lists the top 20 most productive writers who produced more than 15 works on public health and zinc status. The most prolific author of the study is "Keen, C.L." with 64 articles (3.70%), followed by "Krebs, N.F." (40 articles, 2.31%), "Hambidge, K.M." (39 articles, 2.25%), "Cousins, R.J." (36 articles, 2.08%), and "Prasad, A.S." (36 articles, 2.08%). The 15 authors that were left produced between 15 and 30 papers.

These publication ratios would provide a %age-based representation of each author's contributions to publications published on the topic's subject compared to unrelated subjects. However, the writers' publishing rates showed inconsistent results. According to Table 3, "Cousins R.J.," "Eide, D.J.," "Prasad, A.S.," "Andrews, G.K.," and "Miller, L.V." were the top five authors with the greatest publication

Table 2 The top ten articles on zinc status in public health that received the most citations between 1978 and 2022, along with the overall number of citations, journal rankings, and journal impact factor (JIF)

Rank	Article (year)	Total citation	Journal (quartile's rank)	Journal impact factor (JIF)
1	Global burden of childhood pneumonia and diarrhea (2013)	1309	The Lancet (Q1)	202.731
2	Zinc and immune function: the biological basis of altered resistance to infection (1998)	1006	American Journal of Clinical Nutrition (Q1)	8.475
3	Associations between antioxidant and zinc intake and the 5-year incidence of early age-related maculopathy in the beaver dam eye study (1998)	620	American Journal of Epidemiology (Q2)	5.363
4	Dietary factors influencing zinc absorption (2000)	574	Journal of Nutrition (Q2)	4.687
5	The role of zinc in growth and cell proliferation (2022)	535	Journal of Nutrition (Q2)	4.687
6	Estimating the Global Prevalence of Zinc Deficiency: Results Based on Zinc Availability in National Food Supplies and the Prevalence of Stunting (2012)	503	PLoS One (Q2)	3.752
7	Human zinc deficiency (2000)	490	Journal of Nutrition (Q2)	4.687
8	Induction of a New Metallothionein Isoform (MT-IV) Occurs During Differentiation of Stratified Squamous Epithelia (1994)	490	Biochemistry (Q3)	3.221
9	Identification of a family of zinc transporter genes from Arabidopsis that respond to zinc deficiency (1998)	483	Proceedings of the National Academy of Sciences of the United States of America (Q1)	12.779
10	Soil factors associated with zinc deficiency in crops and humans (2009)	471	Environmental Geochemistry and Health (Q2)	4.898

Table 3 Analysis using scientometrics of the most active authors on the topic of the study pertaining to the total number of articles generated

Authors	Articles on the topic	Total articles	H-index	% of 1730 article	Publication ratio
Keen, C.L	64	922	83	3.70%	6.94%
Krebs, N.F	40	387	53	2.31%	10.34%
Hambidge, K.M	39	414	56	2.25%	9.42%
Cousins, R.J	36	104	40	2.08%	34.62%
Prasad, A.S	36	177	58	2.08%	20.34%
Eide, D.J	30	124	61	1.73%	24.19%
Lonnerdal, B	28	1027	91	1.62%	2.73%
Gibson, R.S	27	283	51	1.56%	9.54%
Brown, K.H	26	269	60	1.50%	9.67%
Oteiza, P.I	24	208	50	1.39%	11.54%
Ho, E	23	196	47	1.33%	11.73%
Andrews, G.K	22	143	60	1.27%	15.38%
Beck, F.W.J	18	157	36	1.04%	11.46%
Mcclain, C.J	18	185	84	1.04%	9.73%
Hurley, L.S	17	378	50	0.98%	4.50%
Fraker, P.J	16	138	42	0.92%	11.59%
Miller, L.V	16	108	27	0.92%	14.81%
Kelleher, S.L	15	195	40	0.87%	7.69%
King, J.C	15	153	22	0.87%	9.80%
O'Dell, B.L	15	260	48	0.87%	5.77%

ratios, with respective scores of 34.62%, 24.19%, 20.34%, 15.38%, and 14.81%. Furthermore, it is evident that despite "Keen, C.L.," with an H-index of 83, being the author of most articles on zinc status-public health, the proportion of his publications on the issue only accounts for about 7% of his total outputs.

There were 7158 authors recorded in the co-authorship exploratory investigation of all 1730 articles, with a limit of 25 authors per document. This number then fell to 339 by counting authors who had at least three publications. The network map of authorship analysis in Fig. 5 shows that 12 primary clusters in a substantial group of linked items are involved. A close connection exists between cluster "Brown, K.H." (cluster 1) and clusters "Knoell, D.L." through "Killilea, D.W." (cluster 7), "Gibson, R.S." (cluster 3), "Ho, E." (cluster 2), "Kelleher, S.L." through "Chung, C.S." (cluster 5), and clusters "Hossain, M.B.," "R (cluster 6). In the meantime, the networks "Krebs, N.F." (cluster 1) and "Gibson, R.S." (cluster 3), "Manary, M.J." (cluster 10), and "Wiering, F.T." are connected (cluster 12).

Next, the group "Kelleher, S.L." connects to group "Keen, C.L." (cluster 4) via group "Lonnerdal B.O." and group "Chowanadisai, W." (cluster 6). Then, "Broadley, M.R." connects cluster "Bailey, K.B." (cluster 3) to cluster "Joy, E.J.M." (cluster 8). Furthermore, last, hub "Attia, J." (cluster 11) is linked to cluster 9 by "Shi, Z." Authors who co-occur more frequently are typically positioned closer together. In the figure, the clusters represent groupings of authors who are closely related. Additionally, they are organized in this fashion due to inter- and intra-institutional cooperation. The number of articles increases with the size of the author's nodes. Consequently, the authorship relationships and most active research network groups on the status of zinc in public health research were displayed in this network map (Fig. 5).

Organizations and co-authorship among organizations

Using VOSViewer, a co-authorship analysis was performed using the counting method of organizations, and clusters were made using the association strength method; 51 institutions were found out of 1849 organizations by excluding documents with fewer than ten documents. Table 4 lists the top 15 universities' overall link strengths, publications, citing articles, and nations from 1978 to 2022 (45 years). Except for the University of Otago (New Zealand) and the University of Buenos Aires (Argentina), the bulk of the institutions is from the USA. Since 13 of the top 15 institutes for zinc status in public health research are in North American regions, the other two are in Oceania and South America.

University of Colorado (54 publications, 3.12%), Wayne State University (39 publications, 2.25%), University of Florida (38 publications, 2.20%), and The Ohio State University were next in line, with 130 publications, or 7.51%, of the total number of articles published (36 publications, 2.08%). According to the results, the University of California, Davis, the University of Colorado, and Wayne State

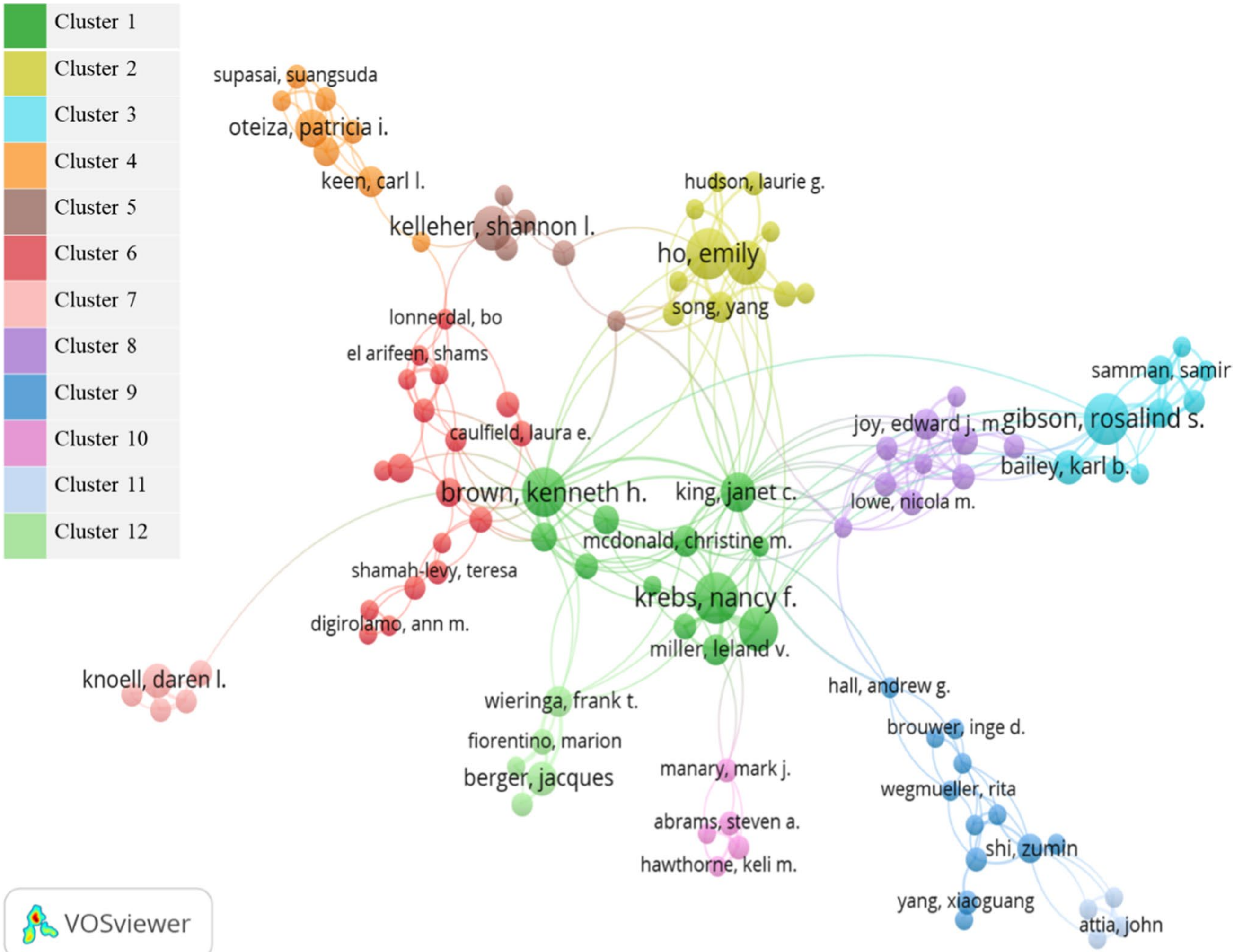

Fig. 5 Network mapping of authors' co-authorship that published articles on zinc status in public health from 1978 to 2022

Table 4 The most active organizations produced articles on zinc status in public health from 1978 to 2022

Organizations	Countries	Documents	% of 1730 article	Citations	Total link strength
University of California, Davis	USA	130	7.51%	6844	59
University Colorado	USA	54	3.12%	2943	35
Wayne State University	USA	39	2.25%	5226	26
University of Florida	USA	38	2.20%	2377	2
The Ohio State University	USA	36	2.08%	1586	19
University of Otago	New Zealand	34	1.97%	954	20
University of Wisconsin	USA	31	1.79%	1783	15
Johns Hopkins University	USA	30	1.73%	3315	24
University of Missouri	USA	30	1.73%	2932	15
Harvard University	USA	29	1.68%	1302	26
University of Kansas	USA	27	1.56%	2140	9
Oregon State University	USA	25	1.45%	866	13
The Pennsylvania State University	USA	24	1.39%	704	6
University of Michigan	USA	22	1.27%	1511	29
University of Buenos Aires	Argentina	21	1.21%	1377	14

University were the only three universities to rank among the top three in both categories (number of publications and citations). Nevertheless, among these top 15 universities, the University of California, Davis (6844 citations), came in first, followed by Wayne State University (5226 citations), Johns Hopkins University (3315 citations), University of Colorado (2943 citations), and University of Missouri (2943 citations) (2932 citations).

The density visualization map of the co-authorship among institutions is shown in Fig. 6. Each point in the item density representation has a color that corresponds to the object density. Default color schemes include blue, green, and yellow. The closer a point gets to yellow, the more neighboring objects there are and the heavier they are. On the other hand, the smaller the number of things around a point, the fewer and lighter the objects close by, and the closer the color of a point are to blue (Jan van Eck and Waltman 2018). The University of California, Davis, which represented the most papers and received the best overall link strength scores (59), had the most intense yellow color on the map. According to the intensity of the yellow color component, the University of Colorado came in second.

The University of Colorado's measure was around half that of the University of California, Davis, as is evident from comparing the sizes of the two colleges' surrounding neighborhoods. These match the total number of papers in the information displayed in Table 4. This information provides a priceless window into institutional research trends regarding zinc status in public health. With the most papers published, citations, and levels of research collaboration, we can infer that the University of California, Davis, is the leader in the subject. Additionally, the cluster density item demonstrated the relationships between institutions. The three most notable examples are (1) the University of California, Davis, which collaborates with Cornell and Thomas Jefferson Universities; (2) the University of Colorado and the University of Washington; and (3) the University of Florida, which collaborated with Wayne State and the University of Wisconsin.

Countries and co-authorship among countries

In 108 different countries, research on the status of zinc was conducted. According to the quantity of papers published, the top ten most productive nations, which together contributed 88.73% of all publications, are shown in Fig. 7a. With 964 publications, the USA had the highest % of articles, followed by China (94), Australia (86), India (77), and England (77) (74 articles). The USA (50,665 citations) scored first out of these top ten nations in terms of the total number of citations, followed by India (3146 citations), England (2429 citations), Australia (1920 citations), and China (1875 citations). According to these statistics, the top five countries, in terms of the quantity of publications and citations, were equal, except for the ranking.

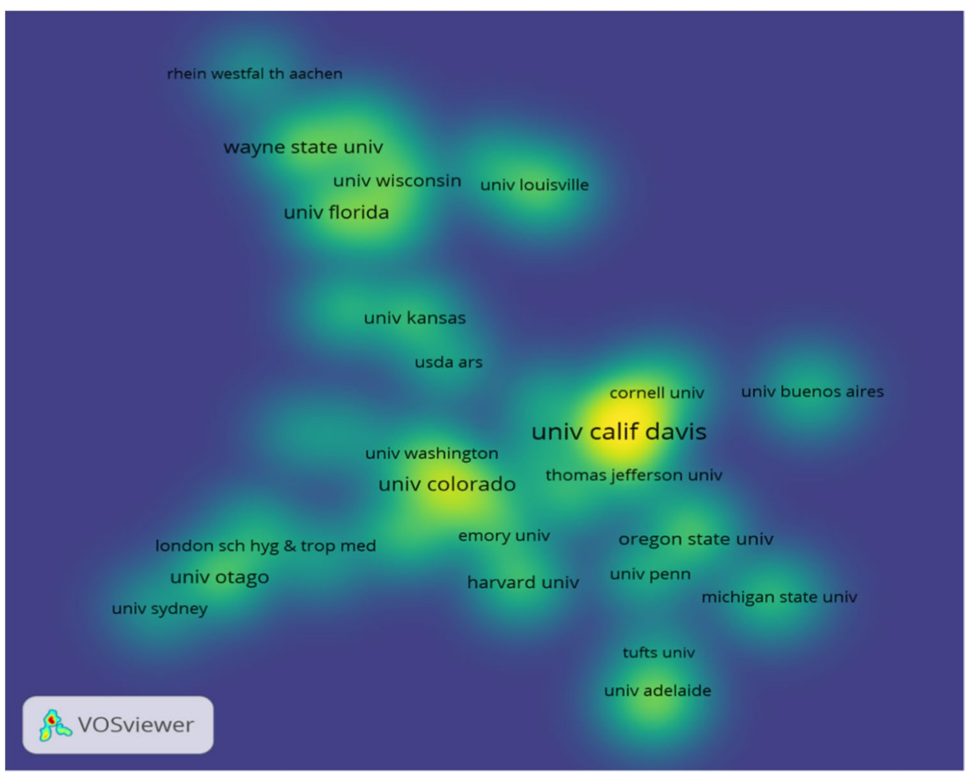

Fig. 6 Density visualization of co-authorship of the organizations that published articles related to zinc status in public health from 1978 to 2022

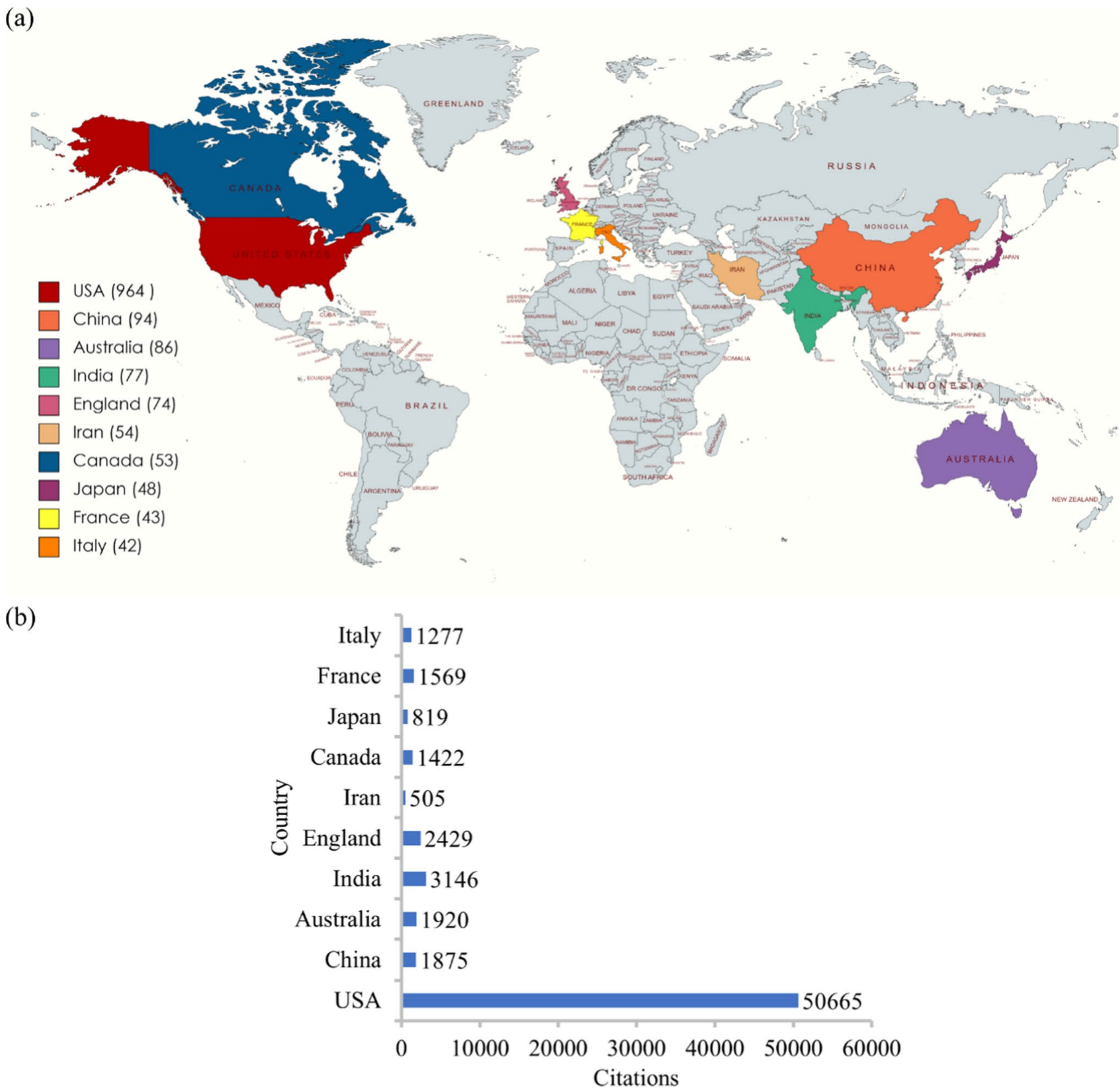

Fig. 7 (**a**) Map showing the top ten countries in terms of productivity for articles on zinc status in public health from 1978 to 2022. (**b**) A bar graph showing the overall number of citations from each country

Only 56 countries finally met the threshold by counting co-authorship, for which a country has at least five documents. Figure 8 illustrates the co-authorship among zinc status-public health research across nations, highlighting the collaboration between authors from different countries. Strong links and links themselves are frequently signs of cross-border cooperation and collaboration in science on a particular topic. Most articles will be described periodically by a nation with a larger node. According to the network visualization of co-authorship analysis across nations, which produced more than half of all 1730 publications, the USA is the focus of the study (964 articles, or 55.72%). They also worked closely with other countries, including China, India, Bangladesh, Brazil, France, Indonesia, Canada, and Egypt. In addition, Fig. 8 showed that the author's collaboration was centered in the USA, and Fig. 7b demonstrated that country as having gotten the most citations, totaling 50,665.

In the Middle East, Prasad from Detroit, Michigan's Wayne State University School of Medicine, found the first case of human zinc insufficiency in 1963 (Prasad et al.

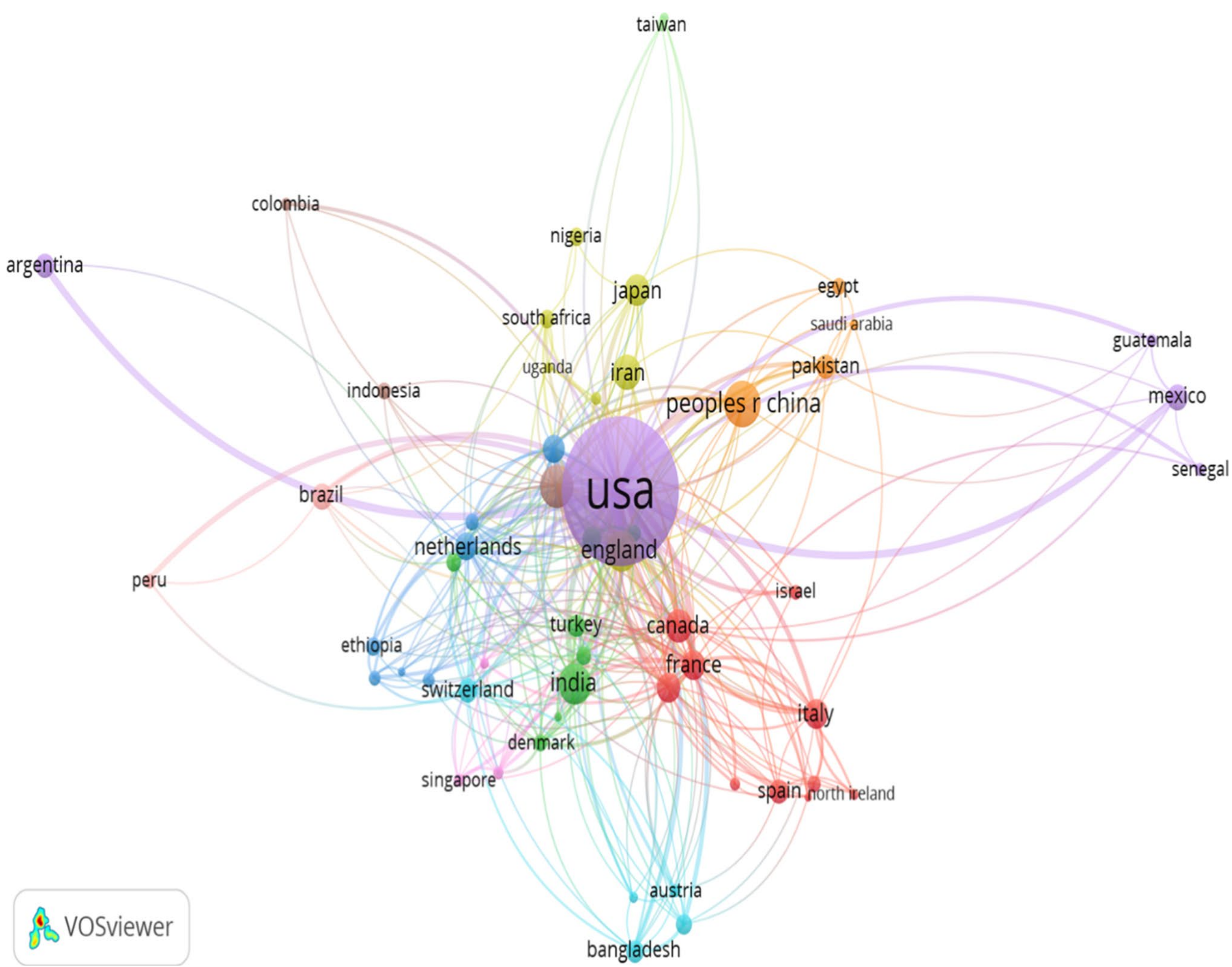

Fig. 8 Network mapping of countries' co-authorship published articles on zinc status in public health from 1978 to 2022

1963). They discovered a high frequency of zinc deficiency in the Middle East, where people regularly consume foods like unleavened bread, cereals, and grains. This diet is strong in phytate and fiber, which lowers zinc bioavailability (Fraker and Leucke 1981). Following that, in 1974, the US (United States) National Academy of Sciences proposed the recommended daily amount (RDA) for zinc (Hart et al. 2022). Additionally, since 1978, the Food and Drug Administration (FDA) of the USA has required zinc inclusion in complete parenteral feeding fluids (Prasad 2014).

Growth of research based on co-occurrence network mapping and cluster analysis.

To identify the problems addressed in the following research and create articles that stand out, it is crucial to look at the co-occurrence of important terms. Additionally, understanding the research's trends and main direction through keyword analysis will help discover research hotspots and gaps. This study's evaluation of co-keyword links is based on the "author's keywords" from the chosen papers from 1976 to 2022. The 1730 articles contained a total of 3168 keywords that were marked, and 100 keywords that exceeded the thresholds were found in investigations with at least eight keyword occurrences. The VOSviewer program's bibliometric mapping algorithm was then used to categorize and systematically link the terms (Fig. 9).

The label and dot sizes represent the association's frequency (freq) and power for each keyword. The connecting line's thickness reveals how closely related two objects are to one another. On the other hand, network visualization uses a distinct color to indicate each kind of cluster. The significance of zinc (blue), biologically processed zinc deficiency (purple), unhealthy growth (red), dietary intake and nutrition (yellow), zinc supplementation (green), and elements related to zinc and health (green) are the six clusters that the author's keywords for zinc in public health research can be categorized into based on the results of the cluster

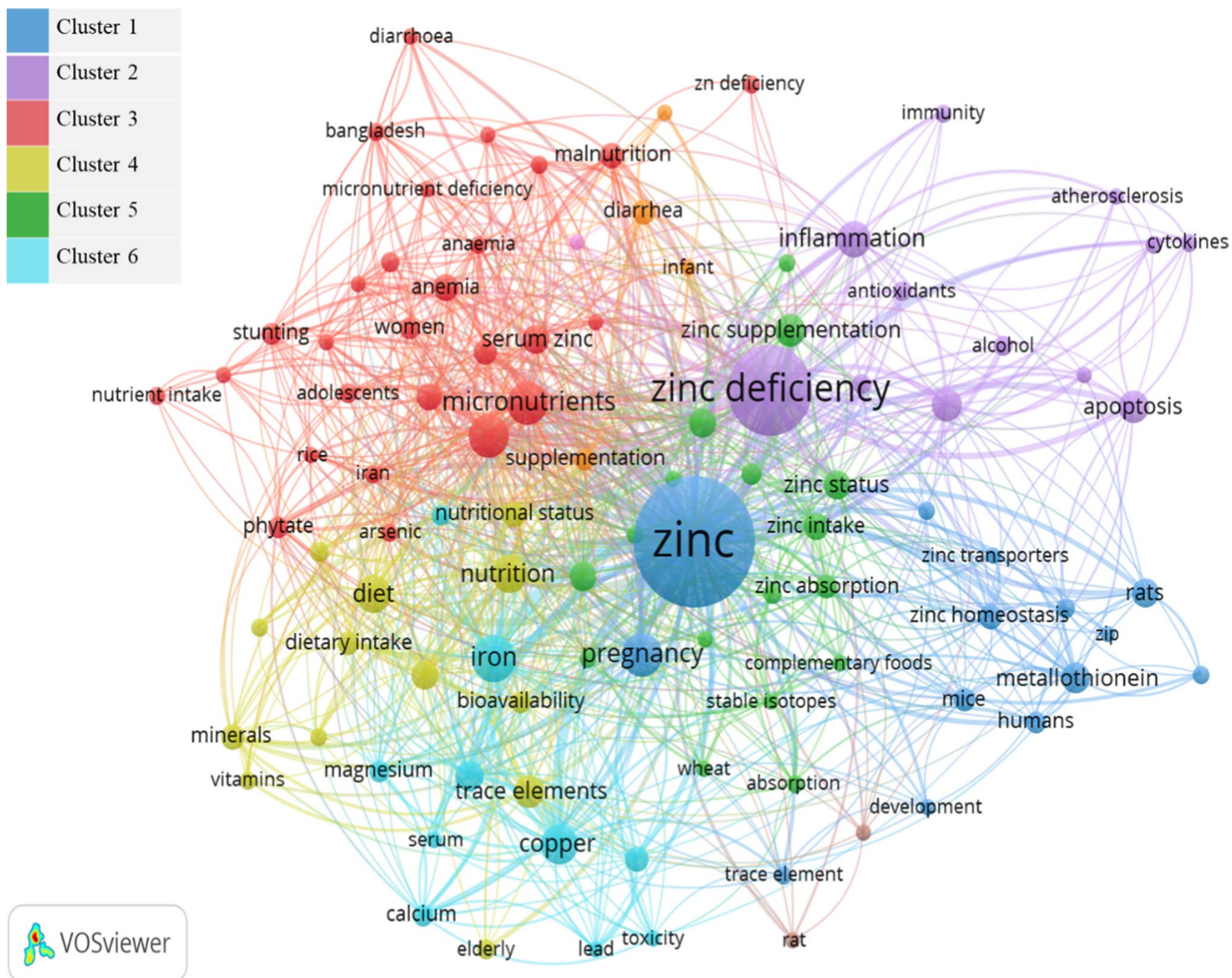

Fig. 9 Network mapping of co-occurrence of the author's keywords of the published articles related to zinc status in public health from 1978 to 2022

analysis (light blue). These clusters are carefully explored to create an integrated understanding of zinc in public health research. The details of keywords' usage in the study are shown in Table 5.

Cluster (1): significance of zinc (blue) Zinc plays several biological roles in the human body. Wound healing, biochemical processes, growth and development, the production of proteins and DNA, gene expression, and immune system operations are some of these processes (Basabe-Desmonts et al. 2007; Shyamal et al. 2016). Three % of the human genome comprise zinc finger domains, a phenomenon in which four cysteine and histidine residues work together with one or more zinc ions to stabilize DNA (Freake and Sankavaram 2013). Ebola, Marburg, Sindbis (SINV), Ross River, Murine Leukemia (MLV), hepatitis B (HBV), and human immunodeficiency virus type 1 (HIV-1) viruses are just a few of the viruses that have been reported to be inhibited by zinc finger antiviral protein (ZAP or ZC3HAV1) (Gao et al. 2002; Bick et al. 2003; Müller et al. 2007) Zinc also prevents the replication of respiratory viral diseases such the flu, hepatitis C, and rhinoviruses (Berg et al. 2001; Tellinghuisen et al. 2005; Tang et al. 2017). Additionally, the therapy and infection of COVID-19 may be impacted by zinc (Doboszewska et al. 2020; Ghanei et al. 2022). Through antiviral activity and immune system boosting, it could be used to lower the severity of SARS-CoV-2 conditions and reduce respiratory tract infections (Jothimani et al. 2020; Kumar et al. 2020; Boretti and Banik 2022; Chinni et al. 2021). Diet and supplements are the main sources of body zinc for pregnant women. Depending on prenatal nutrition, this could play a key role in determining the fetus's overall health (Mousa et al. 2019). Therefore, careful modulation of zinc homeostasis may reduce the need for an elevated zinc

Table 5 Output of clusters based on co-keyword analysis of zinc and public health

Cluster (color)	Author's keyword	Links	Total link strengths	Occurrences	Remarks
Cluster 1 (blue)	Zinc	98	865	504	Significance of zinc
	Pregnancy	42	120	57	
	Zinc homeostasis	19	36	19	
	Metallothionein	19	51	30	
	Humans	11	23	15	
	Rats	13	34	25	
	Mice	16	28	18	
	Development	9	15	8	
	Gene expression	6	13	10	
Cluster 2 (purple)	Zinc deficiency	79	315	240	Biological processes zinc deficiency
	Inflammation	26	63	39	
	Oxidative stress	28	56	32	
	Immunity	6	12	10	
	Atherosclerosis	9	19	8	
	Cytokines	8	17	11	
	Antioxidants	12	18	12	
	Aging	15	27	12	
	Free radicals	9	16	8	
Cluster 3 (red)	Children	50	139	57	Unhealthy growth Dietary intake and nutrition Zinc supplementation
	Micronutrient	48	116	58	
	Vitamin A	25	61	22	
	Anemia	25	53	23	
	Malnutrition	25	43	20	
	Diarrhea	20	43	19	
	Bangladesh	18	29	10	
	Phytate	25	45	15	
	Stunting	22	32	14	
	Zinc deficiency	5	5	10	
	Nutrient intake	8	9	10	
	Adolescents	17	24	12	
	Infant	13	19	9	
	Undernutrition	12	20	8	
	Micronutrient Deficiencies	19	24	8	
	Preschool children	12	13	8	
	Covid-19	6	12	9	
Cluster 4 (yellow)	Nutrition	41	94	45	
	Diet	38	94	44	
	Nutritional status	29	41	20	
	Dietary intake	20	38	18	
	Deficiency	36	72	26	
	Vitamins	9	25	11	
	Elderly	6	13	13	
	Bioavailability	22	39	16	
	Epidemiology	11	21	11	
Cluster 5 (green)	Zinc supplementation	22	56	31	
	Growth	29	56	26	
	Zinc status	26	27	26	
	Zinc intake	23	33	24	
	Zinc absorption	19	36	18	
	Complementary foods	9	17	18	
	Biofortification	25	63	27	
	Cognition	9	13	10	
	Absorption	14	27	11	
	Lactation	17	30	12	

Table 5 (continued)

Cluster (color)	Author's keyword	Links	Total link strengths	Occurrences	Remarks
Cluster 6 (light blue)	Iron	47	200	68	Elements related to zinc and health
	Copper	34	120	47	
	Selenium	35	96	29	
	Cadmium	22	47	19	
	Lead	14	25	9	
	Toxicity	14	21	8	
	Magnesium	20	42	14	
	Trace element	11	18	10	
	Calcium	17	46	15	

level in the mother. The amount of zinc in the human brain rises proportionately with growing and stays constant after reaching adulthood (Markesbery et al. 1984). Up to 90% of the total zinc in the brain comes from metalloproteins, which are proteins with zinc ions directly attached to the side chains of Cys, His, or other amino acids (Frederickson 1989; Anzellotti and Farrell 2008). DNA and RNA polymerases, respiratory enzymes, protein kinases (protein metabolism), alkaline phosphatases (blood protein breakdown), carbonate dehydratases (catalyzes carbon dioxide hydration), and lactate dehydrogenases (cell energy production) are additional non-brain zinc metalloproteins (Lewis et al. 2005; Kibiti and Afolayan 2015; Durrani and Parveen 2022). More than 300 enzymes in animals, plants, and microbes depend on zinc for their structure, catalysis, and co-catalysis (Vallee and Falchuk 1986; Takeda 2000). Additionally, this trace element's antimicrobial properties aid in the healing of skin wounds by preserving cellular viability, promoting fibroblast growth, and increasing ECM synthesis and secretion (Liu et al. 2023).

Cluster (2): biologically processes of zinc deficiency (purple) According to zinc bioavailability in the body, human zinc insufficiency is classified clinically as mild, moderate, or severe (Hambidge 2000). According to Hambidge and Walravens (1982), severe zinc deficiency will hurt vital organ systems such as the immunological, skeletal, and central neurological systems. This condition is frequently fatal, particularly in infants. However, a slight zinc deficit hinders growth and the body's ability to fight off harmful infections (Bates et al. 1993; Black 1998; Bhutta et al. 1999; Hambidge 2000). The human model of intentionally induced moderate zinc shortage has decreased thymulin activity, disturbs the balance between Th1 and Th2 cell function, and contributes to cell-mediated immune dysfunction (Prasad 2014). Additionally, Prasad (2014) noted the advantages of giving zinc supplementation to aged test volunteers, such as reducing oxidative stress and pathogenic infections.

Evidence for zinc deficiency-related oxidative injuries was found in animal model research, including hyperoxic lung injury, the creation of carbon-centered free radicals in the lung microsomes, conjugated dienes and malondialdehyde in the liver, and many other things (Powell 2000). Regarding that, taking dietary zinc supplements may be able to reduce oxidative damage by avoiding two processes: (1) oxidation of the proteins' sulfhydryl group and (2) other transition metals' formation of reactive oxygen species (ROS) (e.g., iron and copper). The dismutation of ROS into peroxide and oxygen molecules is another function of the zinc metalloprotein superoxide dismutase (Siddique et al. 2013). Additionally, sustained zinc shortage may increase sensitivity to pro-oxidants that are particular to the liver (Bray and Bettger 1990).

Cluster (3): unhealthy growth (red) Given that adequate food intake is required to sustain rapid development and growth, young children relate to an increasing prevalence of zinc deficiency and stunting (chronic malnutrition). This is especially true in environments with inadequate resources (Bhutta et al. 1999; Islam et al. 2022). At least 165 million children were stunted in 2011, with sub-Saharan Africa and south Asia having the highest prevalence of stunting in children under five (Horton and Lo 2013; Das et al. 2016). With 65 million or 37% of all children under five who are stunted, South Asia had the highest percentage (Shekar et al. 2016). Stunted children are more likely to join school late, drop out of school, or retake a subject because stunting creates anomalies in the brain maturation processes that result in cognitive impairment (Udani 1992; Mendez and Adair 1999; Daniels and Adair 2004; Kar et al. 2008).

Zinc undernutrition contributed to 1.2% of the disease burden, with 4% in children between the ages of 6 months and 5 years old, according to a comparative risk assessment conducted in Asia, Africa, and Latin America. Here, the estimated number of deaths from zinc deficiency was 453,207, or 4.4% of all child fatalities. Malnutrition caused 14%, 10%, and 7% of deaths from diarrhea, malaria, and pneumonia among children discussed earlier (Fischer Walker et al. 2009). It has been demonstrated that consuming zinc through conventional treatment can reduce the severity and persistence of diarrhea during the severe diarrheal phase, which has the potential to cause zinc losses in the intestine (Bhutta et al. 1999). Out of the 18.9 million children (about the population of New York) under five who live in Bangladesh, zinc therapy during diarrhea could avert the estimated 30,000 to 75,000 fatalities yearly (Jones et al. 2003; Ahmed et al. 2012).

Animal studies showed that fetal starvation resulted in congenital heart abnormalities (CHDs) and the infant's cardiac deformities (Lopez et al. 2008). CHDs are the most prevalent congenital impairments, with an estimated prevalence of 9.4% of births globally (Liu et al. 2019); 9% of live births were affected most frequently in China, where more than 150,000 instances are reported yearly (Zhao et al. 2019; Yang et al. 2022). In addition, malnourished children are more susceptible to dying from illnesses that commonly affect children, such as measles, malaria, HIV/AIDS, pneumonia, or diarrhea (Black et al. 2013).

Cluster (4): dietary intake and nutrition (yellow) Unquestionably, nutrition plays a key role in maintaining good health in people of all ages. Vitamins C, D, and E, zinc, selenium, and omega-3 fatty acids are crucial dietary components with immunomodulatory effects that have been proven effective in preventing infectious infections (Brown et al. 1998; Shakoor et al. 2021). The typical method of calculating zinc content uses dietary loads, such as 100 mL or 100 g of solid food, 100 kcal, and the reference amount typically consumed, or RACC. As a result, the relationship between zinc concentration and zinc-containing dietary intakes is linear. However, considering that the normal consumption of various foods typically comes in smaller serving sizes, Forouzesh and colleagues suggested that calculating zinc per 100 kcal per eating occasion is improper (Forouzesh et al. 2022).

High-risk COVID-19 patient populations, such as the elderly, have dietary deficiencies in vitamins and minerals, increasing morbidity and mortality risk (Grant et al. 2020). An estimated 17.3% of the world population is at risk of zinc deficiency each year (Wessells and Brown 2012), with zinc-associated mortality estimates varying from 453,207 in the Global and Regional Comparative Risk Assessment 2009 (Fischer Walker et al. 2009), to 97,330 in the Global Burden of Disease Study 2010 (Lim et al. 2012), to 116,000 in the Lancet 2013 Maternal and Child Nutrition series (Black et al. 2013). Many foods contain zinc, but high phytate or fiber levels can reduce zinc bioavailability. Foods high in zinc include meat, dairy products, nuts, and shellfish (Forouzesh et al. 2022).

With only 10 years left to advance toward the SDGs, the COVID-19 crisis has drawn attention to the necessity of addressing the unfinished undernutrition agenda midway through the UN Decade of Action on Nutrition (Heidkamp et al. 2021). In low- and middle-income (LMIC) countries, the %age of malnourished mothers and children is rapidly decreasing (Black et al. 2013). Therefore, fighting "malnutrition in all its forms" is crucial globally. When the United Nations declared 2016–2025 as the Nutrition Decade of Action (also known as the Nutrition Decade) and added nutrition as an objective to Sustainable Development Goal 2, it was clear that this desire existed (Target 2.2: Ending all kinds of malnutrition by 2030). These go beyond the six global targets—referred to as the "global targets"—that the World Health Assembly set for diet-related non-communicable diseases (NCDs) and the nutrition of expectant mothers, children, and newborns (World Public Health Nutrition Association 2021).

Cluster (5): zinc supplementation (green) Findings from numerous community-based intervention trials indicate that dietary zinc supplementation is an efficient treatment approach for treating pneumonia, diarrhea, and ageusia/dysgeusia in young children, which can further reduce child mortality. Therefore, the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) currently recommend adding zinc supplements to treatment plans for diarrhea (Hess et al. 2009; UNICEF 2009; Santos 2022). Zinc is essential for milk synthesis and release in the mammary gland during breastfeeding and its important roles in embryogenesis and the gestational period during pregnancy (Hess and King 2009; Donangelo and King 2012). Consequently, as zinc is released into milk during breastfeeding, maternal zinc loss rises by 50% or more (Rahmannia et al. 2019). Early postpartum weeks may be a good time to increase zinc consumption because low zinc levels can endanger the mother and harm the baby (Aoki et al. 2022). The additional RDA recommended for nursing moms is 7 mg d-1 during the first six months and 4 mg d-1 during the following six months (Moser-Veillon 1995).

When compared to high-income countries, underdeveloped countries have a significantly lower daily intake of zinc than those in animal-based meals (Wessells and Brown 2012). The daily energy consumption of an adult person is roughly 60%, derived from sources of wheat, grains, maize, and rice. Wheat and rice have lower zinc micronutrient contents and bioavailability than other grains. The next step in improving nutritional content is to establish a sustainable method of biofortification through crop breeding (Tilman et al. 2002; Cakmak and Kutman 2018).

Zinc supplementation is a low-cost and simple way to increase zinc intake, and zinc supplements also served as an essential intervention against mortality from pneumonia and diarrhea (Black 1998; Fischer Walker et al. 2009, 2013). Nonetheless, excessive zinc intake can lead to chronic effects, where supplementation with quantities of zinc above the suggested upper limit can result in copper deficiency, especially if the form of zinc in the supplement is readily bioavailable (Maret and Sandstead 2006). There were studies that showed adverse effects of excessive zinc supplementation (Chandra 1984; Salzman et al. 2002).

Cluster (6): elements related to zinc and health (light blue) Many metals that impact health have connections to zinc, which are extremely complex. Similar in their physical and chemical makeup, zinc and iron compete in different metabolic proteins, with zinc acting as an antioxidant and iron as a pro-oxidant (Kilari et al. 2010). However, zinc is also in charge of regulating the metabolism of iron via regulating the expression of ferroportin (FPN 1) and the divalent metal iron transporter-1 (DMT1) (Kondaiah et al. 2019). Iron builds up in cells and tissue due to induced zinc shortage in the animal model, which causes anemia (El Hendy et al. 2001; Niles et al. 2008; Geiser et al. 2012). In addition to iron, the relationship (or ratio) between zinc and copper is crucial for maintaining good health. The ratio of zinc to copper was maintained via a collective compensatory mechanism, which can be used to develop potential cancer biomarkers (Michalczyk and Cymbaluk-Poska 2020).

While zinc appears to be very healthy for us, there have also been reports of zinc toxicity, particularly when Zn is consumed in excess, which can deplete copper, calcium, and magnesium (Spencer et al. 1994; Michalczyk and Cymbaluk-Poska 2020). Children exposed to lead may develop intellectual disabilities, renal failure, and even pass away (Koller et al. 2004). On the other hand, exposure to toxic cadmium may cause cancer, emphysema, and hypertension (Ugwuja et al. 2015). Fortunately, supplemental zinc intake appears to mitigate the effects of lead exposure (by lowering blood lead levels) and cadmium exposure (by increasing metallothionein, a protein that can bind and "house" the metal) (Zhou et al. 2001; Cantoral et al. 2015; Ugwuja et al. 2015).

Full counting of bibliographic couplings among the documents

The total link strength, shown by a positive numerical value in the VOSviewer tool, indicates the number of bibliographic linkages between the related documents. When there is a stronger relationship, this value is higher. As a result, the publications are chosen based on their total strength of a relationship. While mapping Fig. 10, this analysis type sets the required minimum number of citations for a publication at 50; 380 publications out of 1730 were classified as visualization items. The overall connection strength of the 380 documents' bibliographic coupling relationships will then be calculated. In addition to the total link strength values, the network connecting those documents is specified by the set of colors.

The top three documents were "Global burden of childhood pneumonia and diarrhea" by Walker (year: 2013, 1309 citations; red node); "Zinc and immune function: The biological basis of altered resistance to infection" by Shankar (year: 1998; blue node; 1006 citations); and "Discovery of Human Zinc Deficiency: Its Impact on Human Health and Disease" by Waalkes (year: 1998; blue node; 1006 citations) (year: 2000, 677 citations, green node). Similar to this, various colors denote various clustered clusters. As a result, each of the top three citations came from a different cluster.

The top 10 documents with total links strength (TLS) were then determined. The top five articles were, in descending order, "Zinc and immune function: The biological basis of altered resistance to infection" by Shankar (year: 1998, TLS: 715, blue color, cluster 3), "Developmental zinc deficiency and behavior" by Golub (year: 1995, TLS: 447, light blue color, cluster 6), and "Discovery of human zinc deficiency: Its impact on human health and disease" by Prasad (year: 2013, T (year: 2001, TLS: 344, red color, cluster 1).

Sixth on the list was Caulfield's study, "Potential contribution of maternal zinc supplementation during pregnancy to maternal and child survival," followed by Hess' study, "Recent advances in knowledge of zinc nutrition and human health" and Caulfield's study, "Targeting of the mouse Slc39a2 (Zip2) gene highly reveals cell-specific patterns of expression, and unique functions in zinc, iron, and calcium homeostasis" (year: 2006, TLS: 304, green color, cluster 2).

Based on their different clusters, the top 10 documents might come together. Cluster 3 provided four papers, cluster 1 provided three, cluster 2 provided two, and cluster 6 provided one document. Cluster 1 primarily focuses on zinc supplementation and nutrition, whereas cluster 3's four publications show how zinc aids immunity to fend off diseases and infections. Meanwhile, two clusters 2 documents discussed gene expression, and a 1995 paper by Golub described how a zinc deficiency affects the deprivation of behavioral development. These findings give a broad overview of the research trends pertinent to those studying zinc status in public health.

Potential research and limitations

This study analyzed academic publications that are related to zinc status in public health. We noticed that ‘zinc deficiency’ seems to be a significant research topic that encourages publications with high citations. Researchers are interested in conducting experiments and clinical trials to explore the effects of zinc deficiency rather than to ascertain the effects of excessive zinc intake, particularly via zinc supplementation. Perhaps the concern of zinc supplementation is not a global concern, for example, not a concern in the least developed countries.

New researchers planning to begin a study in the field of zinc and public health may find the analysis of disciplines categories, times cited and publications over time, core journals, co-authorships of the authors, organizations, and countries, co-occurrence studies, and bibliographic couplings among documents useful as a reference for potential research. Additionally, by looking at many subject categories associated with zinc status-public health research, scholars may benefit from multidisciplinary topic investigation and inclusion. The top categories for more research are nutrition, dietetics, biochemistry, molecular biology, endocrinology metabolism, public environmental, occupational health, pediatrics, and multidisciplinary sciences.

In addition, choosing a high-impact journal for information discovery and publication will be easier for scholars in the field. The research community benefits most from the collection and bibliometric evaluation of the pertinent papers since it helps it comprehend the academic environment, including collaborations between authors, groups, and nations. The hot topics from the co-occurrence network mapping of the author’s keywords can then be used to determine potential research.

Based on the total link strengths of the full counting of bibliographic couplings among the documents, the emerging trends of zinc status-public health described the role of zinc in immunity against diseases and infections, supplementation and nutrition, gene expression, and deficiency which affects physical and behavioral development. The combined results of hot keyword and bibliographic couplings will help researchers address the issue of malnutrition, which will lead to “Target 2.2: Ending all kinds of malnutrition by 2030” in Sustainable Development Goal No.2.

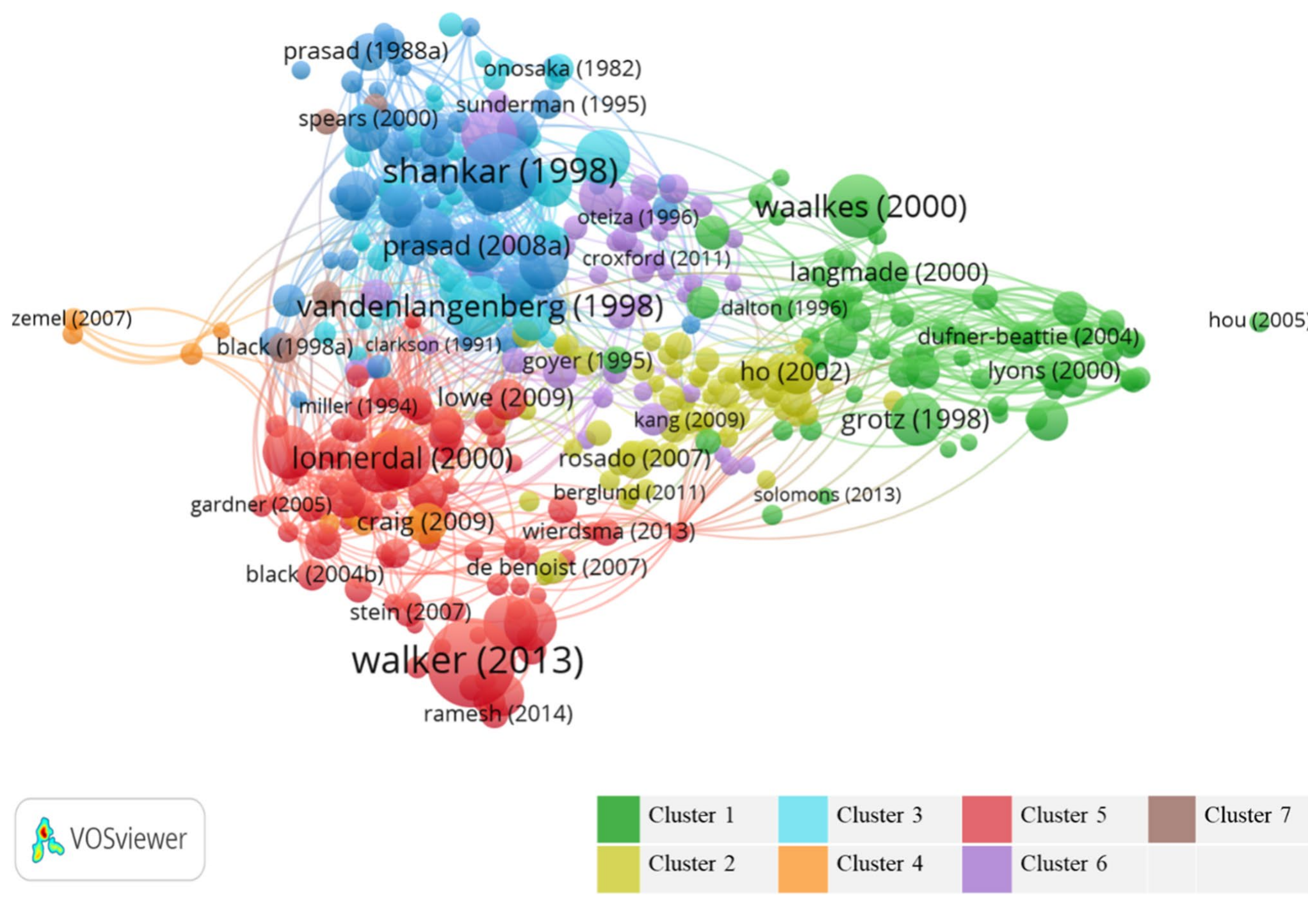

Fig. 10 Network mapping of bibliographic couplings among the documents related to zinc status in public health from 1978 to 2022

On the other hand, this study has several restrictions that should be considered in subsequent investigations. The electronic database was initially restricted to the WoS database, which would have left out several important papers. Furthermore, the WoS retrieval mechanism did not utilize a comprehensive text search. Thus, some relevant articles might have been missed while some irrelevant ones might have been added, thus resulting in a bias in the way selection databases are displayed. Second, we eliminated non-English literature from our research on the global trend of zinc status in public health, which could have led to selection bias.

Third, our conclusion may be biased because we excluded other unpublished research from our analysis. Fourth, because this work has so many authors, some may go by other names or share the same author from multiple institutions. Even though we carefully proofread the process, some mistakes are inevitable. Additionally, this work does not contain any upgrades after July 29, 2022. Nevertheless, we are certain that this is the first bibliometric examination of zinc status in public health. The research is unique as a result. Despite its flaws, the study offers a historical context for ongoing research and reveals areas that need further investigation and growth.

Conclusion

Journal articles in English were extracted from the Web of Science (WoS) database between 1978 and 2022 using the keywords "zinc status," "zinc deficiency," "zinc intake," "public health," "human health," and "health." The breadth of disciplinary categories is noteworthy; 108 distinct categories were available for use in studies on zinc and public health. Because most researchers believe that micronutrients zinc, which has an immune-boosting effect, and antiviral mechanisms may positively impact COVID-19 therapeutic interventions, 2019, 2020, and 2021 had the highest number of publications, with 90, 88, and 91, respectively. The Journal of Nutrition, American Journal of Clinical Nutrition Field, and Nutrients are the scientific journals with the greatest influence on zinc status in public health.

According to this study, researchers with a higher number of zinc publications are more experienced and knowledgeable about zinc status in public health than those who publish fewer papers on the subject. With an H-index of 83, Keen C.L. was the author of most publications on the public health status of zinc (922 publications). As a result, thirteen of the top fifteen most active institutes in public health research on zinc status are in North American regions, with the remaining two in Oceania and South America. Most of the documents were produced by the University of California, Davis, which also received the highest marks for overall link strength, and the University of Colorado was ranked second. Both institutions are in the USA. Furthermore, the USA collaborated with most countries, had the highest %age of papers with 964 publications (55.72%), and had the most citations (50,665 citations). As a result, the USA is the epicenter of research on the role of zinc in public health.

A keyword cluster analysis of zinc status in public health revealed (1) the importance of zinc, (2) the effects of zinc deficiency, (3) unhealthy growth, (4) dietary intake and nutrition, (5) zinc supplementation, and (6) components associated with zinc and health. These clusters corroborated the findings of the complete counting of bibliographic couplings and total link strengths among the manuscripts, indicating the growing trends in zinc status-public health. As a result, this bibliometric analysis can assist in identifying gaps in knowledge and zinc status skills, thereby improving public health outcomes. More research is needed to determine the effects of bibliometric analysis of each cluster linked to zinc status-public health outcomes to achieve the third Sustainable Development Goal (SDG no. 3) of good health and well-being by 2030.

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References

Ahmed T, Ireen S, Ahmed AS et al (2012) Nutrition of children and women in Bangladesh: trends and directions for the future. J Health Popul Nutr 30:1. https://doi.org/10.3329/jhpn.v30i1.11268

Ali NIM, Aiyub K, Lam KC, Abas A (2022) A bibliometric review on the inter-connection between climate change and rice farming. Environ Sci Pollut Res 29:30892–30907. https://doi.org/10.1007/s11356-022-18880-1

Aliev G, Li Y, Chubarev VN et al (2019) Application of acyzol in the context of zinc deficiency and perspectives. Int J Mol Sci 20:2104. https://doi.org/10.3390/ijms20092104

Andrade DF, Romanelli JP, Pereira-Filho ER (2019) Past and emerging topics related to electronic waste management: top countries, trends, and perspectives. Environ Sci Pollut Res 26:17135–17151. https://doi.org/10.1007/s11356-019-05089-y

Anzellotti AI, Farrell NP (2008) Zinc metalloproteins as therapeutic targets. Chem Soc Rev 37:1629–1651. https://doi.org/10.1039/b617121b

Aoki C, Imai K, Owaki T et al (2022) The possible effects of zinc supplementation on postpartum depression and anemia. Medicina (b Aires) 58:731. https://doi.org/10.3390/medicina58060731

Aslan NA, Klkitli E, Ozturk N (2021) Effect of zinc deficiency on cognitive function in females with iron deficiency anemia. J Exp Clin Med (Turk) 38:111–114. https://doi.org/10.52142/omujecm.38.2.10

Barnett JB, Hamer DH, Meydani SN (2010) Low zinc status: a new risk factor for pneumonia in the elderly? Nutr Rev 68:30–37. https://doi.org/10.1111/j.1753-4887.2009.00253.x

Basabe-Desmonts L, Müller TJJ, Crego-Calama M (2007) Design of fluorescent materials for chemical sensing. Chem Soc Rev 36:993–1017. https://doi.org/10.1039/b609548h

Basharat S, Ahsan F, Sikander S (2019) Role of ketogenic diet in pediatric epilepsy. J Psychol Clin Psychiatry 10(3):118–122

Bates CJ, Bates PH, Dardenne M et al (1993) A trial of zinc supplementation in young rural Gambian children. Br J Nutr 69:243–255. https://doi.org/10.1079/BJN19930026

Berg K, Bolt G, Andersen H, Owen TC (2001) Zinc potentiates the antiviral action of human IFN- α tenfold. J Interferon Cytokine Res 21:471–474. https://doi.org/10.1089/10799900152434330

Bhutta ZA, Black RE, Brown KH et al (1999) Prevention of diarrhea and pneumonia by zinc supplementation in children in developing countries: pooled analysis of randomized controlled trials. J Pediatr 135:689–697. https://doi.org/10.1016/S0022-3476(99)70086-7

Bick MJ, Carroll J-WN, Gao G et al (2003) Expression of the zinc-finger antiviral protein inhibits alphavirus replication. J Virol 77:11555–11562. https://doi.org/10.1128/JVI.77.21.11555-11562.2003

Black RE (1998) Therapeutic and preventive effects of zinc on serious childhood infectious diseases in developing countries. Am J Clin Nutr 68:476S-479S. https://doi.org/10.1093/ajcn/68.2.476S

Black RE, Victora CG, Walker SP et al (2013) Maternal and child undernutrition and overweight in low-income and middle-income countries. Lancet 382:427–451. https://doi.org/10.1016/S0140-6736(13)60937-X

Boretti A, Banik BK (2022) Zinc role in Covid-19 disease and prevention. Vacunas 23:147–150. https://doi.org/10.1016/j.vacun.2021.08.003

Bray TM, Bettger WJ (1990) The physiological role of zinc as an antioxidant. Free Radic Biol Med 8:281–291. https://doi.org/10.1016/0891-5849(90)90076-U

Brown NAP, Bron AJ, Harding JJ, Dewar HM (1998) Nutr Suppl Eye Eye 12:127–133. https://doi.org/10.1038/eye.1998.21

Cakmak I, Kutman UB (2018) Agronomic biofortification of cereals with zinc: a review. Eur J Soil Sci 69:172–180. https://doi.org/10.1111/ejss.12437

Cantoral A, Téllez-Rojo MM, Levy TS et al (2015) Differential association of lead on length by zinc status in two-year old Mexican children. Environ Health 14:95. https://doi.org/10.1186/s12940-015-0086-8

Chandra RK (1984) Excessive intake of zinc impairs immune responses. JAMA 252:1443–1446. https://doi.org/10.1001/jama.1984.03350110043027

Chasapis CT, Loutsidou AC, Spiliopoulou CA, Stefanidou ME (2012) Zinc and human health: an update. Arch Toxicol 86:521–534. https://doi.org/10.1007/s00204-011-0775-1

Chasapis CT, Ntoupa P-SA, Spiliopoulou CA, Stefanidou ME (2020) Recent aspects of the effects of zinc on human health. Arch Toxicol 94:1443–1460. https://doi.org/10.1007/s00204-020-02702-9

Chen YB, Tong XF, Ren J, et al (2019) Current research trends in traditional Chinese medicine formula: a bibliometric review from 2000 to 2016. Evid-Based Complement 2019. https://doi.org/10.1155/2019/3961395

Chinni V, El-Khoury J, Perera M et al (2021) Zinc supplementation as an adjunct therapy for COVID-19: challenges and opportunities. Br J Clin Pharmacol 87:3737–3746. https://doi.org/10.1111/bcp.14826

Daniels MC, Adair LS (2004) Growth in young Filipino children predicts schooling trajectories through high school. J Nutr 134:1439–1446. https://doi.org/10.1093/jn/134.6.1439

Das JK, Achakzai ABK, Bhutta ZA (2016) Stop stunting: Pakistan perspective on how this could be realized. Matern Child Nutr 12:253–256. https://doi.org/10.1111/mcn.12285

Doboszewska U, Wlaź P, Nowak G, Młyniec K (2020) Targeting zinc metalloenzymes in coronavirus disease 2019. Br J Pharmacol 177:4887–4898. https://doi.org/10.1111/bph.15199

Doerr TD, Marks SC, Shamsa FH et al (1998) Effects of zinc and nutritional status on clinical outcomes in head and neck cancer. Nutr 14:489–495. https://doi.org/10.1016/S0899-9007(98)00036-7

Donangelo CM, King JC (2012) Maternal zinc intakes and homeostatic adjustments during pregnancy and lactation. Nutrients 4:782–798. https://doi.org/10.3390/nu4070782

Durrani AM, Parveen H (2022) Zinc deficiency and its consequences during pregnancy. Microbial biofertilizers and micronutrient availability. Springer International Publishing, Cham, pp 69–82. https://doi.org/10.1007/978-3-030-76609-2_3

El Hendy HA, Yousef MI, El-Naga NIA (2001) Effect of dietary zinc deficiency on hematological and biochemical parameters and concentrations of zinc, copper, and iron in growing rats. Toxicology 167:163–170. https://doi.org/10.1016/S0300-483X(01)00373-0

Fenner R, Cernev T (2021) The implications of the Covid-19 pandemic for delivering the Sustainable Development Goals. Futures 128:102726. https://doi.org/10.1016/j.futures.2021.102726

Fischer Walker CL, Ezzati M, Black RE (2009) Global and regional child mortality and burden of disease attributable to zinc deficiency. Eur J Clin Nutr 63:591–597. https://doi.org/10.1038/ejcn.2008.9

Fischer Walker CL, Rudan I, Liu L et al (2013) Global burden of childhood pneumonia and diarrhoea. Lancet 381:1405–1416. https://doi.org/10.1016/S0140-6736(13)60222-6

Forouzesh A, Forouzesh F, Samadi Foroushani S, Forouzesh A (2022) A new method for calculating zinc content and determining appropriate zinc levels in foods. SSRN Electron J. https://doi.org/10.2139/ssrn.4133664

Fosmire GJ (1990) Zinc toxicity. Am J Clin Nutr 51:225–227. https://doi.org/10.1093/ajcn/51.2.225

Fraker GJ, FLeuke RW (1981) Effect of dietary zinc deficiency on lymphocyte function in the mouse. Diet and Resistance to Disease. Springer US, Boston, pp 107–119. https://doi.org/10.1007/978-1-4615-9200-6_6

Frassinetti S, Bronzetti GL, Caltavuturo L et al (2006) The role of zinc in life: a review. J Environ Pathol Toxicol Oncol 25:597–610. https://doi.org/10.1615/JEnvironPatholToxicolOncol.v25.i3.40

Freake HC, Sankavaram K (2013) Zinc: physiology, dietary sources, and requirements. In: Encyclopedia of human nutrition (Third

Edition). Elsevier, pp 437–443. https://doi.org/10.1016/B978-0-12-375083-9.00286-5

Frederickson CJ (1989) Neurobiology of zinc and zinc-containing neurons. Int Rev Neurobiol 31:145–238. https://doi.org/10.1016/S0074-7742(08)60279-2

Gao G, Guo X, Goff SP (2002) Inhibition of retroviral RNA production by ZAP, a CCCH-type zinc finger protein. Science 297:1703–1706. https://doi.org/10.1126/science.1074276

Geiser J, Venken KJT, De Lisle RC, Andrews GK (2012) A mouse model of acrodermatitis enteropathica: loss of intestine zinc transporter ZIP4 (Slc39a4) disrupts the stem cell niche and intestine integrity. PLoS Genet 8:e1002766. https://doi.org/10.1371/journal.pgen.1002766

Ghanei E, Baghani M, Moravvej H et al (2022) Low serum levels of zinc and 25-hydroxyvitmain D as potential risk factors for COVID-19 susceptibility: a pilot case-control study. Eur J Clin Nutr 23:1–6. https://doi.org/10.1038/s41430-022-01095-5

Grant W, Lahore H, McDonnell S et al (2020) Evidence that vitamin D supplementation could reduce risk of influenza and COVID-19 infections and deaths. Nutrients 12:988. https://doi.org/10.3390/nu12040988

Hambidge M (2000) Human zinc deficiency. J Nutr 130:1344S-1349S. https://doi.org/10.1093/jn/130.5.1344S

Hambidge KM, Walravens PA (1982) Disorders of mineral metabolism. Clin Gastroenterol 11:87–117. https://doi.org/10.1016/S0300-5089(21)00496-X

Hart JD, Chokephaibulkit K, Mayxay M et al (2022) COVID-19 vaccine boosters in the Asia-Pacific region in the context of Omicron. Lancet Reg Health West Pac 20:100404. https://doi.org/10.1016/j.lanwpc.2022.100404

Heersmink R, van den Hoven J, van Eck NJ, van Berg J, den, (2011) Bibliometric mapping of computer and information ethics. Ethics Inf Technol 13:241–249. https://doi.org/10.1007/s10676-011-9273-7

Heidkamp RA, Piwoz E, Gillespie S et al (2021) Mobilising evidence, data, and resources to achieve global maternal and child undernutrition targets and the Sustainable Development Goals: an agenda for action. Lancet 397:1400–1418. https://doi.org/10.1016/S0140-6736(21)00568-7

Hess SY, King JC (2009) Effects of maternal zinc supplementation on pregnancy and lactation outcomes. Food Nutr Bull 30:S60–S78. https://doi.org/10.1177/15648265090301S105

Hess SY, Lönnerdal B, Hotz C et al (2009) Recent advances in knowledge of zinc nutrition and human health. Food Nutr Bull 30:S5–S11. https://doi.org/10.1177/15648265090301S102

Horton R, Lo S (2013) Nutrition: a quintessential sustainable development goal. Lancet 382:371–372. https://doi.org/10.1016/S0140-6736(13)61100-9

Islam MM, Black RE, Krebs NF et al (2022) different doses, forms, and frequencies of zinc supplementation for the prevention of diarrhea and promotion of linear growth among young Bangladeshi children: a six-arm, randomized, community-based efficacy trial. J Nutr 152:1306–1315. https://doi.org/10.1093/jn/nxab439

Jan van Eck N, Waltman L (2018) Manual for VOSviewer version 1.6.8. CWTS meaningful metrics. Universiteit Leiden

Jayawardena R, Sooriyaarachchi P, Chourdakis M et al (2020) Enhancing immunity in viral infections, with special emphasis on COVID-19: a review. Diabetes Metab Syndr: Clin Res Rev 14:367–382. https://doi.org/10.1016/j.dsx.2020.04.015

Jones G, Steketee RW, Black RE et al (2003) How many child deaths can we prevent this year? Lancet 362:65–71. https://doi.org/10.1016/S0140-6736(03)13811-1

Jothimani D, Kailasam E, Danielraj S et al (2020) COVID-19: poor outcomes in patients with zinc deficiency. Int J Infect Dis 100:343–349. https://doi.org/10.1016/j.ijid.2020.09.014

Kar BR, Rao SL, Chandramouli BA (2008) Cognitive development in children with chronic protein energy malnutrition. Behav Brain Funct 4:31. https://doi.org/10.1186/1744-9081-4-31

Kasavan S, Yusoff S, Guan NC et al (2021a) Global trends of textile waste research from 2005 to 2020 using bibliometric analysis. Environ Sci Pollut Res 28:44780–44794. https://doi.org/10.1007/s11356-021-15303-5

Kasavan S, Yusoff S, Rahmat Fakri MF, Siron R (2021) Plastic pollution in water ecosystems: a bibliometric analysis 2000 to 2020. J Clean Prod 313:127946. https://doi.org/10.1016/j.jclepro.2021b.127946

Kawade R (2012) Zinc status and its association with the health of adolescents: a review of studies in India. Glob Health Action 5:7353. https://doi.org/10.3402/gha.v5i0.7353

Khalil GM, Gotway Crawford CA (2015) A bibliometric analysis of U.S.-based research on the behavioral risk factor surveillance system. Am J Prev Med 48:50–57. https://doi.org/10.1016/j.amepre.2014.08.021

Khan AS, Khan Narendra A AR et al (2016) Alzheimer's disease and autistic spectrum disorder: is there any association? CNS Neurol Disord Drug Targets 15:390–402. https://doi.org/10.2174/1871527315666160321104303

Kibiti C, Afolayan A (2015) Herbal therapy: a review of emerging pharmacological tools in the management of diabetes mellitus in Africa. Pharmacogn Mag 11:258. https://doi.org/10.4103/0973-1296.166046

Kilari S, Pullakhandam R, Nair KM (2010) Zinc inhibits oxidative stress-induced iron signaling and apoptosis in Caco-2 cells. Free Radic Biol Med 48:961–968. https://doi.org/10.1016/j.freeradbiomed.2010.01.019

King JC, Brown KH, Gibson RS et al (2015) Biomarkers of nutrition for development (BOND)—zinc review. J Nutr 146:858S-885S. https://doi.org/10.3945/jn.115.220079

Koller K, Brown T, Spurgeon A, Levy L (2004) Recent developments in low-level lead exposure and intellectual impairment in children. Environ Health Perspect 112:987–994

Kondaiah P, Yaduvanshi PS, Sharp PA, Pullakhandam R (2019) Iron and zinc homeostasis and interactions: does enteric zinc excretion cross-talk with intestinal iron absorption? Nutrients 11:1885. https://doi.org/10.3390/nu11081885

Krebs NF (2013) Update on zinc deficiency and excess in clinical pediatric practice. Ann Nutr Metab 62:19–29. https://doi.org/10.1159/000348261

Kumar A, Kubota Y, Chernov M, Kasuya H (2020) Potential role of zinc supplementation in prophylaxis and treatment of COVID-19. Med Hypotheses 144:109848. https://doi.org/10.1016/j.mehy.2020.109848

Lewis SM, Hotchkiss CE, Vllrey DE (2005) Nutrition and nutritional disease. In: The laboratory primate, handbook of experimental animals. pp 181–208. https://doi.org/10.1016/B978-012080261-6/50013-1

Lim SS, Vos T, Flaxman AD et al (2012) A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 380:2224–2260. https://doi.org/10.1016/S0140-6736(12)61766-8

Little PJ, Bhattacharya R, Moreyra AE, Korichneva IL (2010) Zinc and Cardiovascular Disease. Nutrition 26:1050–1057. https://doi.org/10.1016/j.nut.2010.03.007

Liu Y, Chen S, Zühlke L et al (2019) Global birth prevalence of congenital heart defects 1970–2017: updated systematic review and meta-analysis of 260 studies. Int J Epidemiol 48:455–463. https://doi.org/10.1093/ije/dyz009

Liu Z, Tang W, Liu J et al (2023) A novel sprayable thermosensitive hydrogel coupled with zinc modified metformin promotes the

healing of skin wound. Bioact Mater 20:610–626. https://doi.org/10.1016/j.bioactmat.2022.06.008
Lopez V, Keen CL, Lanoue L (2008) Prenatal zinc deficiency: influence on heart morphology and distribution of key heart proteins in a rat model. Biol Trace Elem Res 122:238–255. https://doi.org/10.1007/s12011-007-8079-2
Ma TJ, Lee GG, Liu J, Lae R (2022) Bibliographic coupling: a main path analysis from 1963 to 2020. Inf Res 27:918. https://doi.org/10.47989/irpaper918
Maggini S, Wenzlaff S, Hornig AD (2010) Essential role of vitamin C and zinc in child immunity and health. J Int Med Res 38:386–414. https://doi.org/10.1177/147323001003800203
Maret W, Sandstead HH (2006) Zinc requirements and the risks and benefits of zinc supplementation. J Trace Elem Med Biol 20:3–18. https://doi.org/10.1016/j.jtemb.2006.01.006
Markesbery WR, Ehmann WD, Alauddin M, Hossain TIM (1984) Brain trace element concentrations in aging. Neurobiol Aging 5:19–28. https://doi.org/10.1016/0197-4580(84)90081-2
Mendez MA, Adair LS (1999) Severity and timing of stunting in the first two years of life affect performance on cognitive tests in late childhood. J Nutr 129:1555–1562. https://doi.org/10.1093/jn/129.8.1555
Michalczyk K, Cymbaluk-Płoska A (2020) The role of zinc and copper in gynecological malignancies. Nutrients 12:3732. https://doi.org/10.3390/nu12123732
Moser-Veillon PB (1995) Zinc needs and homeostasis during lactation. Analyst 120:895. https://doi.org/10.1039/an9952000895
Mousa A, Naqash A, Lim S (2019) Macronutrient and micronutrient intake during pregnancy: an overview of recent evidence. Nutrients 11:443. https://doi.org/10.3390/nu11020443
Müller S, Möller P, Bick MJ et al (2007) Inhibition of filovirus replication by the zinc finger antiviral protein. J Virol 81:2391–2400. https://doi.org/10.1128/JVI.01601-06
Narváez-Caicedo C, Moreano G, Sandoval BA, Jara-Palacios M (2018) Zinc deficiency among lactating mothers from a peri-urban community of the Ecuadorian Andean region: an initial approach to the need of zinc supplementation. Nutrients 10:869. https://doi.org/10.3390/nu10070869
Niles BJ, Clegg MS, Hanna LA et al (2008) Zinc deficiency-induced iron accumulation, a consequence of alterations in iron regulatory protein-binding activity, iron transporters, and iron storage proteins. J Biol Chem 283:5168–5177. https://doi.org/10.1074/jbc.M709043200
Plum LM, Rink L, Hajo H (2010) The essential toxin: impact of zinc on human health. Int J Environ Res Public Health 7:1342–1365. https://doi.org/10.3390/ijerph7041342
Powell SR (2000) The antioxidant properties of zinc. J Nutr 130:1447S-1454S. https://doi.org/10.1093/jn/130.5.1447S
Prasad AS (2008) Zinc in human health: effect of zinc on immune cells. Mol Med 14:353–357. https://doi.org/10.2119/2008-00033
Prasad AS (2014) Impact of the discovery of human zinc deficiency on health. J Trace Elem Med Biol 28:357–363. https://doi.org/10.1016/j.jtemb.2014.09.002
Prasad AS, Miale A Jr, Farid Z et al (1963) Zinc metabolism in patients with the syndrome of iron deficiency anemia, hepatosplenomegaly, dwarfism, and hypogonadism. J Lab Clin Med 61:537–549
Rahmannia S, Diana A, Luftimas DE et al (2019) Poor dietary diversity and low adequacy of micronutrient intakes among rural Indonesian lactating women from Sumedang district, West Java. PLoS One 14:e0219675. https://doi.org/10.1371/journal.pone.0219675
Razzaque MS (2020) COVID-19 pandemic: can maintaining optimal zinc balance enhance host resistance? Tohoku J Exp Med 251:175–181. https://doi.org/10.1620/tjem.251.175
Read SA, Obeid S, Ahlenstiel C, Ahlenstiel G (2019) The role of zinc in antiviral immunity. Adv Nutr 10:696–710. https://doi.org/10.1093/advances/nmz013
Roohani N, Hurrell R, Kelishadi R, Schulin R (2013) Zinc and its importance for human health: an integrative review. J Res Med Sci: Off J Isfahan Univ Med Sci 18(2):144
Salzman MB, Smith EM, Koo C (2002) Excessive oral zinc supplementation. J Pediatr Hematol Oncol 24:582–584
Samad N, Sodunke TE, Abubakar AR et al (2021) The implications of zinc therapy in combating the COVID-19 global pandemic. J Inflamm Res 14:527–550. https://doi.org/10.2147/JIR.S295377
Santos HO (2022) Therapeutic supplementation with zinc in the management of COVID-19–related diarrhea and ageusia/dysgeusia: mechanisms and clues for a personalized dosage regimen. Nutr Rev 80:1086–1093. https://doi.org/10.1093/nutrit/nuab054
Shakoor H, Feehan J, al Dhaheri AS, et al (2021) Immune-boosting role of vitamins D, C, E, zinc, selenium and omega-3 fatty acids: could they help against COVID-19? Maturitas 143:1–9. https://doi.org/10.1016/j.maturitas.2020.08.003
Shekar M, Dayton Eberwein J, Kakietek J (2016) The costs of stunting in South Asia and the benefits of public investments in nutrition. Matern Child Nutr 12:186–195. https://doi.org/10.1111/mcn.12281
Shyamal M, Mazumdar P, Maity S et al (2016) Highly selective turn-on fluorogenic chemosensor for robust quantification of Zn(II) based on aggregation induced emission enhancement feature. ACS Sens 1:739–747. https://doi.org/10.1021/acssensors.6b00289
Siddique T, Deng HX, Ajroud-Driss S (2013) Motor neuron disease. Emery and Rimoin's principles and practice of medical genetics, pp 1–22. https://doi.org/10.1016/B978-0-12-383834-6.00141-5
Spencer H, Norris C, Williams D (1994) Inhibitory effects of zinc on magnesium balance and magnesium absorption in man. J Am Coll Nutr 13:479–484. https://doi.org/10.1080/07315724.1994.10718438
Suganya A, Saravanan A, Manivannan N (2020) Role of zinc nutrition for increasing zinc availability, uptake, yield, and quality of maize (*Zea Mays L.*) grains: an overview. Commun Soil Sci Plant Anal 51:2001–2021. https://doi.org/10.1080/00103624.2020.1820030
Takeda A (2000) Movement of zinc and its functional significance in the brain. Brain Res Rev 34:137–148. https://doi.org/10.1016/S0165-0173(00)00044-8
Tang Q, Wang X, Gao G (2017) The short form of the zinc finger antiviral protein inhibits influenza A virus protein expression and is antagonized by the virus-encoded NS1. J Virol 91:e01909–e01916. https://doi.org/10.1128/JVI.01909-16
te Velthuis AJW, van den Worm SHE, Sims AC et al (2010) Zn^{2+} Inhibits coronavirus and arterivirus RNA polymerase activity in vitro and zinc ionophores block the replication of these viruses in cell culture. PLoS Pathog 6:e1001176. https://doi.org/10.1371/journal.ppat.1001176
Tellinghuisen TL, Marcotrigiano J, Rice CM (2005) Structure of the zinc-binding domain of an essential component of the hepatitis C virus replicase. Nature 435:374–379. https://doi.org/10.1038/nature03580
Tilman D, Cassman KG, Matson PA et al (2002) Agricultural sustainability and intensive production practices. Nature 418:671–677. https://doi.org/10.1038/nature01014
Udani PM (1992) Protein energy malnutrition (PEM), brain and various facets of child development. Indian J Pediatr 59:165–186. https://doi.org/10.1007/BF02759978
Ugwuja EI, Ogbonnaya LU, Uro-Chukwu H et al (2015) Plasma cadmium and zinc and their interrelationship in adult Nigerians: potential health implications. Interdiscip Toxicol 8:77. https://doi.org/10.1515/intox-2015-0012

UNICEF. Division of Communication, UNICEF (2009) Tracking progress on child and maternal nutrition: a survival and development priority. UNICEF. https://data.unicef.org/resources/tracking-progress-child-maternal-nutritionsurvival-development-priority/
Vallee BL, Falchuk KH (1986) The biological basis of zinc physiology. NeuroSci 6:2950–2967
Walsh CT, Sandstead HH, Prasad AS et al (1994) Zinc: health effects and research priorities for the 1990s. Environ Health Perspect 102:5–46. https://doi.org/10.1289/ehp.941025
Wessells KR, Brown KH (2012) Estimating the global prevalence of zinc deficiency: results based on zinc availability in national food supplies and the prevalence of stunting. PLoS One 7:e50568. https://doi.org/10.1371/journal.pone.0050568
World Public Health Nutrition Association (2021) The UN Decade of Nutrition: WPHNA's position at mid-term. World Nutr 12:11–24. https://doi.org/10.26596/wn.202112311-24
Yang J, Kang Y, Chang Q et al (2022) Maternal zinc, copper, and selenium intakes during pregnancy and congenital heart defects. Nutrients 14:1055. https://doi.org/10.3390/nu14051055
Zhang Y, Liu Y, Qiu H (2018) Association between dietary zinc intake and hyperuricemia among adults in the United States. Nutrients 10:568. https://doi.org/10.3390/nu10050568
Zhang Y, Acton Steven et al (2020) Clinical, cytogenetic and survival characteristics of myelodysplastic syndrome patients with polycythaemia. Acta Medica Mediterr 36:3305–3309. https://doi.org/10.19193/0393-6384_2020_6_512
Zhao Q-M, Liu F, Wu L et al (2019) Prevalence of congenital heart disease at live birth in China. J Pediatr 204:53–58. https://doi.org/10.1016/j.jpeds.2018.08.040
Zhou Z, Zheng J, He Y (2001) Approach to the relationship between the expression of metallothionein-III mRNA and free zinccontents. Chinese J Neurol 34(2):107–110