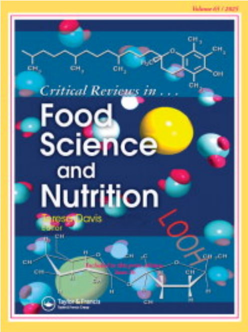

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REVIEW ARTICLE

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Trends in micronutrient research since the SDGs: a global perspective

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ABSTRACT
Sustainable food systems have become a central focus in efforts to combat micronutrient malnutrition, with increasing recognition of their role in achieving the Sustainable Development Goals (SDGs). This article presents a bibliometric analysis of micronutrient research from 2015 to 2023, examining trends and thematic clusters within the SDGs framework. Using data from the Web of Science and science mapping techniques, the study identifies key trends and thematic clusters that highlight evolving research priorities. Four major trends emerge: the application of machine learning, the exploration of macroalgae for their micronutrient potential, the use of CRISPR/Cas9 technology in biofortification, and concerns about heavy metal contamination in food. Research clusters show a strong focus on bone health, particularly osteoporosis and vitamin D, which align with SDG 3 (Good Health and Well-being). Yet research on micronutrient deficiencies, such as those in iron, zinc, and vitamin A, remains underrepresented despite their high global impact on malnutrition, especially in low- and middle-income countries, raising concerns about whether research priorities sufficiently address the SDGs. This study highlights the need for more targeted research to align with SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production). The article concludes by stressing the importance to balance cutting-edge technological advances with a renewed emphasis to address critical micronutrient gaps to improve global nutrition and align with sustainable food system goals.

KEYWORDS
food and nutrition security; environmental pollutants; biofortification; genomics; food safety

Introduction

Concerns about food production and its adequacy for a growing global population have deep historical roots. Early thinkers like Tertullian and later economists such as Thomas Malthus, with his 1798 work *An Essay on the Principle of Population*, raised alarms about potential food shortages as the human population grows exponentially while food production increases arithmetically (Peacock 1954; Spengler 1971). Although these fears persisted into the twentieth century with works like Paul Ehrlich's *The Population Bomb* (Ehrlich 1968) and the Brundtland Report (Keeble 1988), advances in science and technology have largely dispelled the notion of imminent global food crises. Agricultural productivity has surged, outpacing both population growth and per capita food supply (Mason-D'Croz et al. 2019). For instance, from 1961 to 2013, significant increases in macronutrient consumption were observed in developed and developing countries (Ritchie, Rosado, and Roser 2017).

However, despite these gains, improvements in dietary quality have not been uniform. While increased protein and calorie supplies have alleviated hunger to some extent (Alexander et al. 2015; Tilman and Clark 2015), disparities persist, especially in the distribution of essential micronutrients (Pingali 2012, 2023). The geopolitical landscape further complicates these issues, as developing economies, where many nutrient-rich crops are grown, often struggle with inadequate resources and infrastructure. This has hindered efforts to improve agricultural practices and enhance the production and distribution of micronutrient-rich foods (Grote et al. 2021; Pardey, Alston, and Piggott 2006; United Nations n.d.). Moreover, the focus on starchy cereals and livestock production, driven by political and economic pressures, has sometimes led to a decline in the cultivation of nutrient-dense crops (Awika 2011; Delgado 2003; FAO 2004). This emphasis on macronutrients at the expense of micronutrient-rich crops has contributed to global inadequate supply of essential vitamins and minerals (Chen, Chaudhary, and Mathys 2021; Damerau, Waha, and Herrero 2019; Kumar, Sharma, et al. 2022; Smith et al. 2021).

For example, Smith et al. (2021) found that the 2018 global food system provided only 64% of the required calcium and 69% of vitamin E, despite adequate macronutrient levels. Their scenarios including waste reduction, scaling up production for 2030, plant-based systems, and removing sugar crops still failed to meet micronutrient requirements. The decline in the production of nutrient-dense crops is a major part of this issue (Welch, Graham, and Cakmak 2013). For instance, while rice production has increased dramatically, the production of iron rich legumes such as beans has

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declined, coinciding with rising iron deficiency (Beal and Ortenzi 2022; CDC 2021; Safiri et al. 2021). Vitamin A and calcium deficiencies, along with iron-deficiency anemia, remain critical global health issues (Fanzo 2023; Shlisky et al. 2022; Stevens et al. 2022). These deficiencies, often termed "hidden hunger," affect over 2 billion people globally, particularly women, adolescents, and children (Darnton-Hill 2018; Ray et al. 2022).

This issue has driven international efforts to eradicate deficiencies and their health impacts. Starting with the 1943 United Nations declaration of zero hunger and continuing with the Sustainable Development Goals (SDGs) adopted in 2015, there has been a global commitment to ending malnutrition in all its forms and ensuring access to nutritious food by 2030 (Branca et al. 2020; Fanzo 2023). The 2021 Food Systems Summit further emphasized the need for a holistic food system approach to address malnutrition, including micronutrient deficiencies – moving beyond traditional short-term strategies such as food fortification (e.g., iodine in salt, vitamin A in sugar), micronutrient supplementation (e.g., iron and folic acid tablets for pregnant women), and emergency food aid programs (Covic et al. 2021; Fanzo 2023; HLPE 2017). This approach prioritizes both nutritional security and environmental health, framing sustainable food systems as central to combating micronutrient malnutrition (Smith et al. 2021; West et al. 2014; Willett et al. 2019). Despite the growing literature on these issues, there remains a lack of focused reviews on micronutrient research in the context of sustainable food systems. This article addresses this gap through a bibliometric analysis of peer-reviewed publications since the adoption of the Sustainable Development Goals (SDGs) in 2015.

The article addresses two main questions: 1) What are the trends in research on sustainable food systems with a focus on micronutrients since the SDGs? and 2) What major themes can be identified to guide future research? The article is organized as follows: the next section outlines the bibliometric review methods, followed by results and discussion in Section 3. The final section summarizes the findings, discusses limitations, and suggests future research directions.

Methods

Bibliometric review methodology

Bibliometric analysis, pioneered by Garfield and Sher (1963), uses statistical, mathematical, and data mapping techniques to examine research trends and contributions within a specific thematic domain by analyzing bibliographic data from scientific publication databases (Aznar-Sánchez et al. 2019). This approach is valuable to understand accumulated scientific knowledge and conceptual developments within established fields by methodically interpreting large volumes of unstructured data (Donthu et al. 2021). This review follows guidelines similar to those outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) extension for scoping reviews (PRISMA-ScR, Tricco et al. 2018) and employs the five-stage methodological framework proposed by Zupic and Čater (2015): (1) formulating the research question, (2) identifying relevant studies, (3) analyzing the data, (4) visualizing the findings, and (5) interpreting the results. The research questions are designed to assess the progress of research and content related to sustainable food systems, with a primary focus on micronutrient studies since the adoption of the Sustainable Development Goals (SDGs).

Databases and search methods

The Web of Science (WoS) Core Collection was selected for its high data quality, including standardized reference items, availability of Keywords Plus, and minimal missing data – features that are essential for bibliometric analysis (Zupic and Čater 2015). Using a single, reliable database like WoS also mitigates potential errors or inconsistencies during data consolidation and cleaning, which can arise from using multiple sources (Donthu et al. 2021). Thus, WoS was deemed sufficient for the scope of this study.

A structured search strategy was developed and validated by the authors in the WoS Core Collection to identify relevant literature on micronutrients in the context of a sustainable global food system. The strategy involved defining key concepts, selecting appropriate search terms, and applying Boolean operators (AND, OR) to refine results. Given the variability in journal indexing practices, the search extended beyond keywords to include article titles and abstracts. The search terms encompassed multiple permutations of key concepts, which includes micronutrients, sustainability, global food system, vitamins, and minerals. Wildcard searches were applied within WoS to ensure comprehensive coverage. To maintain focus, the term "malnutrition" was intentionally excluded, and key search terms included "sustain*," "food system," "global" or "worldwide," "micronutrient*," and "vitamins and minerals."

Eligibility and study selection criteria

The initial search retrieved 16,692 records, which were reduced to 14,453 after eliminating duplicates and screening for relevance. Eligibility criteria for inclusion in the bibliometric analysis were: (1) peer-reviewed original research articles and review papers published in English between January 2015 and December 2023, and (2) relevance to the research question, assessed based on the focus on micronutrient research. This included various study types, such as observational studies, randomized controlled trials (RCTs), and experimental research, as well as review articles that synthesized existing knowledge. Other document types, such as conference papers, book chapters, and editorials, were excluded to maintain consistency in publication types and ensure the inclusion of high-quality, academically rigorous sources.

Bibliometric data analysis

Bibliometric studies use two primary techniques for analyzing metadata: performance analysis and science mapping (Abafe, Bahta, and Jordaan 2022; Zupic and Čater 2015). Performance analysis examines contributions from research entities such as individuals and institutions, while science mapping explores the relationships between these entities, revealing the structure of scientific domains (Cobo et al. 2011; Donthu et al. 2021). This study focuses on science mapping, capturing a snapshot of the field over the SDGs era.

Key techniques employed within science mapping include content analysis (word analysis), co-occurrence network analysis, thematic map analysis, and trend topic analysis (Zupic and Čater 2015). Content analysis, in particular, was used to identify and analyze the frequency and context of key terms and phrases in the literature, including both Author Keywords and Keywords Plus (Zupic and Čater 2015). This approach facilitated the identification of emerging trends, dominant research themes, and shifts in research focus. Co-occurrence network analysis was used to examine how frequently terms or keywords appeared together in the literature (Cobo et al. 2011), while thematic map analysis categorizes research themes based on their centrality (importance) and density (development) (Cobo et al. 2015). Themes were classified into four quadrants: (1) Motor themes (high centrality, high density) represent well-developed and influential topics driving the field. (2) Niche themes (low centrality, high density) are specialized areas with strong internal development but limited influence on broader research. (3) Basic themes (high centrality, low density) form the foundational concepts of the field. (4) Emerging or declining themes (low centrality, low density) include new or fading topics. This classification helps visualize the structure and evolution of research within the field. And finally, trend topic analysis was performed to identify the evolution of research themes over time. This tracks the frequency of keywords across different periods, highlighting emerging, stable, and declining topics within the field (Büyükkıdık 2022).

All analysis was conducted using Microsoft® Excel® for Microsoft 365 MSO (version 2311) and the RStudio software environment (version 2023.06.1 + 524, RStudio 2020), along with the Bibliometrix R package (Aria and Cuccurullo 2017), to process and visualize the bibliometric data.

Results and discussion

Descriptive information on publication output

Table 1 presents the key metadata statistics after screening and cleaning. The dataset, spanning from January 2015 to December 2023, comprises 14,453 documents from 2,883 journals, reflecting a consistent annual growth rate of 7.47%. Notably, 27.2% of these documents involve international co-authorship, highlighting strong global collaboration within the research field. Most of the documents are research articles (10,538), with reviews accounting for the remaining 3,915. Figure 1 illustrates the annual publication numbers for both articles and reviews included in the analyzed sample, visually demonstrating the growth in publication output over this period.

Word analysis (content analysis)

To explore the conceptual foundations of the field, a keyword analysis was performed using both Author Keywords and Keywords Plus. Author Keywords reflect research priorities and community interests, extracted directly from the metadata field assigned by the authors, while Keywords Plus, an automated indexing system in Web of Science, identifies additional relevant terms that frequently appear in the titles of cited references but may not be present in the article's title or Author Keywords (Abafe, Bahta, and Jordaan 2022).

Table 2 presents the top 10 most frequent terms identified in both keyword analyses. These results reveal a strong research focus on vitamin D (1,520 occurrences), osteoporosis (1,515 occurrences), and bone mineral density (935 occurrences). Together, these three terms account for 29% of the total frequency of Author Keywords, highlighting the centrality of these themes in micronutrient and sustainable food systems research.

Co-occurrence network analysis

Co-occurrence network analysis was used to explore relationships between paired data within the dataset. In bibliometric studies, this method examines how frequently two bibliographic items related to a specific research topic appear together in the same documents (Zhou et al. 2022). Applying this approach to author keywords provided insights into primary research areas and thematic associations. Figure 2a illustrates the co-occurrence network, revealing two distinct clusters (red and blue). Vitamin D emerges as the most frequently occurring keyword, which demonstrated strong connections with bone mineral density, osteoporosis, and calcium (blue cluster). Osteoporosis, in particular, maintains a notable link with bone mineral density, reinforcing the well-established research focus on bone health. In the red cluster, a strong association is observed between minerals and vitamins, which underscores their interconnected roles in nutrition and health. Within this cluster, frequently occurring micronutrients such as zinc, iron, and vitamin C appear in relation to health topics like immune function, anemia,

Table 1. Summary statistics of the metadata.

Description	Results
Timespan	2015:2023
Sources (Journals)	2882
Documents	14453
Annual growth rate %	7.47
Document average age	4.37
Average citations per doc	18.2
References	590907
Document contents	
Keywords plus (ID)	22429
Author's Keywords (DE)	24141
Authors	
Authors	58769
Authors of single-authored docs	409
Authors collaboration	
Single-authored docs	458
Co-Authors per Doc	5.8
International co-authorships %	27.21
Document types	
Article	10538
Review	3915

Note: Summary statistics of the metadata, including the number of sources, documents, citations, keywords, authors, and collaboration metrics for the analyzed period (2015–2023).

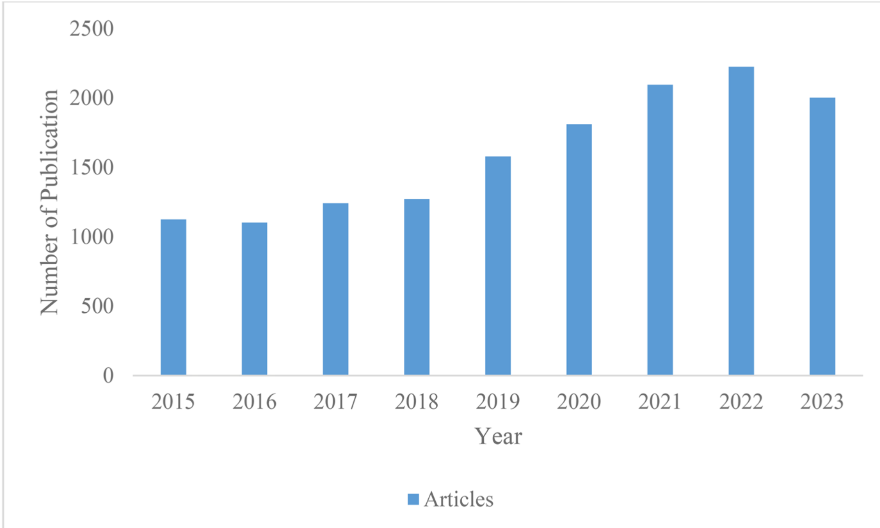

Figure 1. Annual publication numbers (articles and reviews) included in the analyzed sample.

Table 2. 10 Most frequent words based on authors Keywords and keyword plus, identified using biblioshiny.

Authors keywords	Occurrences	Keyword plus	Occurrences
Vitamin D	1520	Bone-mineral density	1905
Osteoporosis	1515	Vitamin D	1591
bone mineral density	935	Risk	1235
Minerals	641	Mineral density	1022
Nutrition	636	Osteoporosis	996
Vitamins	608	Health	906
Bone	496	Supplementation	784
Calcium	466	Calcium	779
Micronutrients	411	Postmenopausal women	779
Diet	286	Women	770

and metabolic health. The strong interconnectivity in the co-occurrence network suggests the prominence of bone health in micronutrient research, particularly around vitamin D and calcium. However, the presence of zinc and iron in the network also implies a secondary focus on immune and metabolic health, possibly in the context of deficiency-related conditions like anemia. The observed clustering indicates that while vitamin D research remains dominant, there may be opportunities to further integrate micronutrient studies into broader public health and sustainability frameworks.

Thematic map analysis

The thematic map provides a structured overview of research efforts within sustainable food systems and micronutrient research. By categorizing research topics based on their development and relevance, it highlights established areas, emerging trends, and potential research gaps. Figure 2b presents five clusters, each representing different stages of research progression:

Motor themes – osteoporosis, vitamin D, bone mineral density

Motor themes are well-developed and highly relevant areas of research. Their strong interconnectivity with other topics suggests they are central to the field. The prominence of osteoporosis, vitamin D, and bone mineral density indicates a sustained research focus on micronutrients' roles in bone health, particularly in preventing age-related conditions and calcium metabolism.

Niche themes – food security

Niche themes are specialized topics that may have lower connectivity to broader research trends but remain important for specific subfields. Food security appears in this category, which suggest that while it is a major global concern, its direct integration with micronutrient-focused research is still developing. This positioning highlights an opportunity to further explore how micronutrient interventions can enhance food security outcomes.

Basic themes – phytochemicals

Basic themes represent foundational and well-established areas of research that form the building blocks for further investigation. Phytochemicals, known for their bioactive properties and potential health benefits, are widely studied in relation to nutrition and disease prevention. Their placement as a basic theme indicates their essential role in the discourse on sustainable food systems and micronutrient research.

Nutritional values – transitioning between basic and emerging or declining. Topics in this category exist between fundamental and evolving research areas. Nutritional values, as a theme, suggests a stable yet potentially shifting research focus. This placement may reflect ongoing discussions about nutrient bioavailability, dietary guidelines, or shifting priorities within food system sustainability, indicating either renewed interest or a gradual decline in emphasis.

Emerging or declining themes – health benefits. Emerging or declining themes represent areas that are either gaining

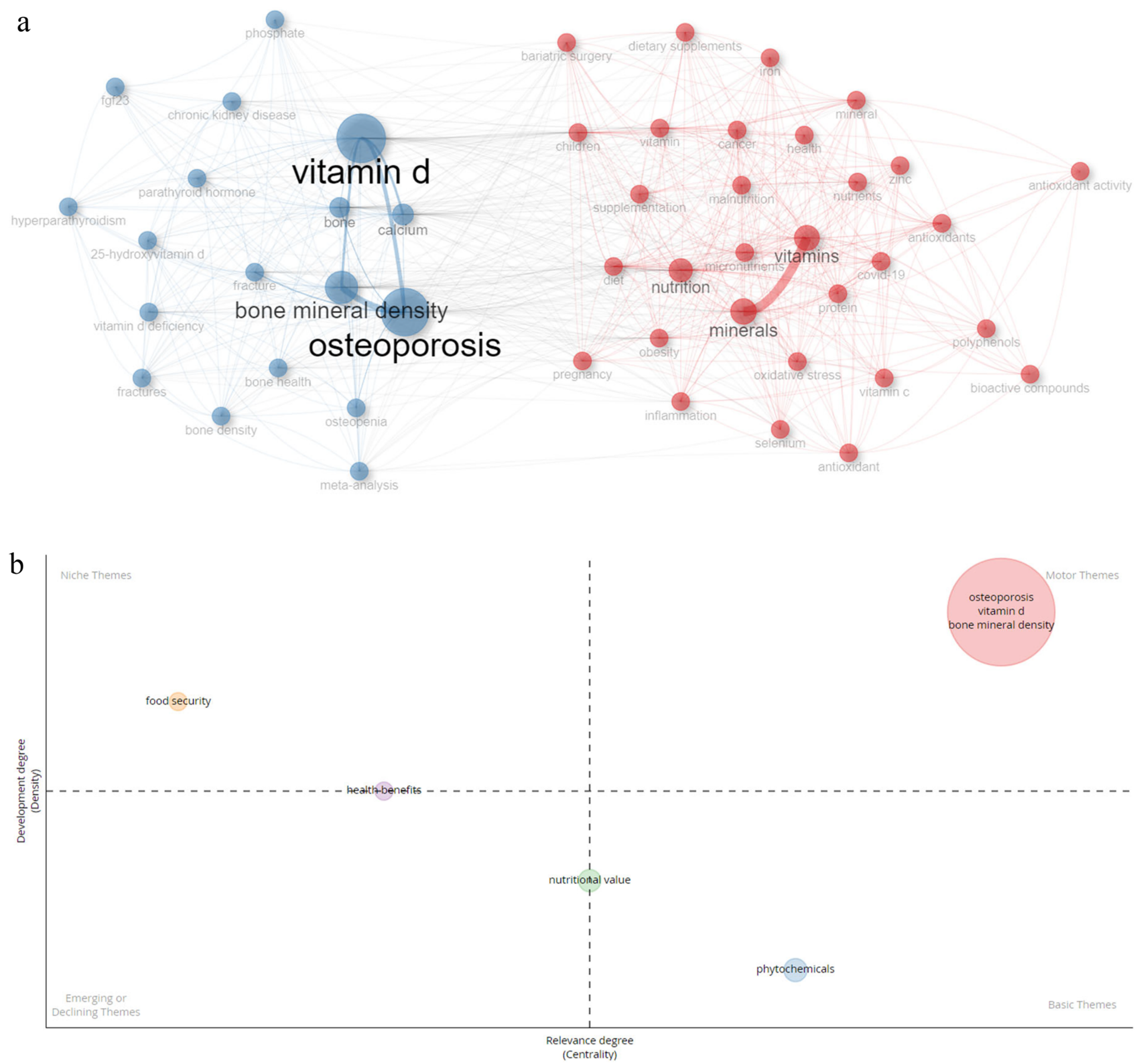

Figure 2. **(a)** Co-occurrence network analysis of Author's Keywords showing the relationships between frequently co-occurring author keywords in the dataset, grouped into two distinct clusters. Vitamin D is the most central keyword (blue cluster), demonstrating strong connections with bone mineral density, osteoporosis, and calcium, indicating a dominant research focus on bone health. The red cluster highlights broader nutritional themes, with vitamins and minerals as central nodes. This cluster connects micronutrients like zinc, iron, selenium, and vitamin C with research areas including malnutrition, obesity, antioxidants, and oxidative stress. **Note**: Larger node size indicates keywords with higher occurrence and edge thickness depicts strength of connection, while color indicates clustering. (**b**) Thematic map of Author's Keywords showing the development and centrality of research themes based on the frequency and recency of publications. The development degree (vertical axis) reflects how established or emerging a theme is, while the centrality (horizontal axis) indicates its prominence in the broader field. Circle size represents volume of publications associated with each theme, with larger circles indicating more frequently researched topics.

research traction or losing relevance over time. Health benefits fall into this category, positioned between niche and emerging/declining themes. This suggests that while research on the health benefits of micronutrients remains relevant, it may be undergoing shifts in focus – either toward novel micronutrient sources, personalized nutrition, or broader public health applications.

Trend (hot) topics

An analysis of author keywords was conducted, focusing on those with at least five occurrences, to identify emerging trends and shifting research priorities. This emphasizes recent years to capture current developments in the field. Figure 3 highlights 42 keywords that meet this criterion, showing notable increases in attention to macroalgae and heavy metals since 2020, as well as a rise in the prominence of machine learning and Cas9 since 2022.

Macroalgae

The global food system faces numerous challenges, including rising food insecurity, climate change, and widespread micronutrient deficiencies (Galanakis 2024). Traditional

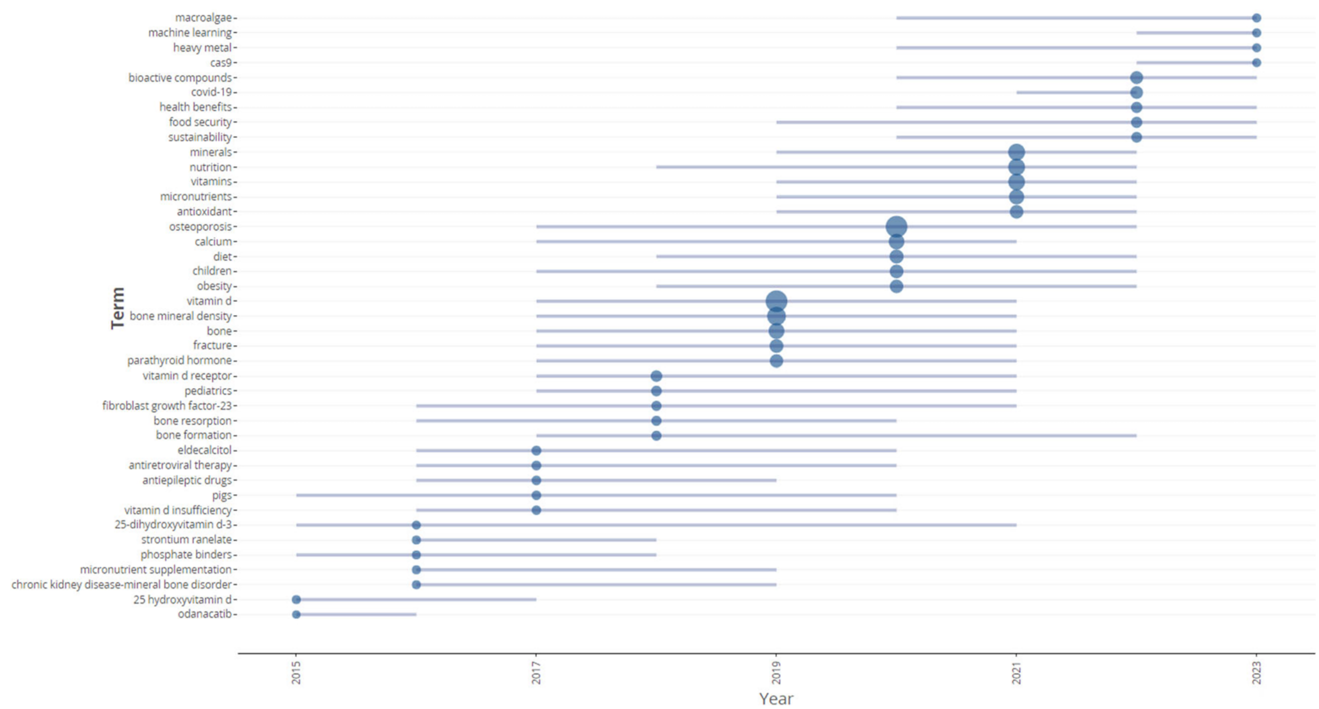

Figure 3. Trending topics from 2015 to 2023. Trends are based on keywords appearing at least five times per year. The length of the wicks represents the duration of each trend, while node size corresponds to keyword frequency, with larger nodes indicating greater prominence.

agricultural systems often struggle to meet the increasing demand for nutritious food, particularly in regions where malnutrition is prevalent (Galanakis 2024). In response, sustainable solutions, such as biofortification and innovative agricultural practices, are gaining importance to address these challenges.

One such solution is macroalgae (seaweeds), which have garnered significant attention for their rich nutritional profile and environmental benefits (Ali, Ramsubhag, and Jayaraman 2021; Cherry et al. 2019). Macroalgae are categorized into brown, red, and green algae and contribute to over 50% of global marine and coastal aquaculture production (Xie et al. 2024). Their protein content is noteworthy, with some red varieties, like *Porphyra spp*., having protein levels comparable to soybean meal (Øverland, Mydland, and Skrede 2019). This positions macroalgae as a potential protein alternative to address global protein demand and environmental concerns (Galanakis 2024).

Macroalgae are also rich in vitamins (A, C, E, B-complex) and minerals (Na, Mg, P, K, I, Fe, Zn), with some of their micronutrient content often compared to or exceeding that of other commonly consumed foods (Biris-Dorhoi et al. 2020; Circuncisão et al. 2018). Their rapid growth, high biomass yield, and nutrient profile make them an option to improve food production systems and addressing micronutrient deficiencies, such as iodine, a critical concern in many regions (Costa et al. 2021; Milinovic 2020; Mota et al. 2023; Tullberg, Nguyen, and Wang 2022).

In addition to their nutritional benefits, macroalgae contain bioactive compounds such as flavonoids, antioxidants, and fucoxanthin, which may help alleviate oxidative stress, cardiovascular diseases, and inflammation (Choudhary, Chauhan, and Mishra 2021; Peñalver et al. 2020; Tanna and Mishra 2019). Fucoxanthin, in particular, has shown anti-obesity, anti-inflammatory, and anti-cancer properties (Cunningham et al. 2023; Peng et al. 2011). Polysaccharides from macroalgae also have diverse bioactive effects, that includes antioxidant and antimicrobial properties (Abdelrhman et al. 2022; Xie et al. 2024). Despite these benefits, there is limited knowledge about the bioavailability of macroalgae nutrients and potential toxic metal accumulation, highlighting the need for further in studies (Choudhary, Chauhan, and Mishra 2021; Circuncisão et al. 2018).

Beyond their nutritional potential, macroalgae offer significant environmental and economic benefits. They can contribute to carbon sequestration, reduce nutrient loads in coastal waters, and offer a sustainable alternative to land-based crops, reducing the pressure on terrestrial agriculture (Buschmann et al. 2017; Duarte et al. 2017). Economically, the global seaweed industry is valued at billions of dollars, with applications ranging from food and feed to biofuels and pharmaceuticals (Nayar and K 2014; Zhang et al. 2022). However, sustainable scaling of macroalgae production requires addressing challenges such as habitat impact, energy use, and regulatory frameworks (Duarte et al. 2017; Zhang et al. 2022). These aspects are critical to ensure that macroalgae fulfill their potential as a sustainable and nutritious resource for the future.

Machine learning

The rapid advance in technologies such as robotics, nanotechnology, gene editing, and artificial intelligence (AI) has ushered in the era of Agriculture 4.0, marking the fourth agricultural revolution (Klerkx and Rose 2020; Xu, Xu, and Li 2018; Zambon et al. 2019). Among these technologies, machine learning (ML), a subset of AI, is transforming the global food system by enabling systems to analyze food system data, identify patterns, and make predictions without explicit programming (Thomas et al. 2022). It encompasses supervised, unsupervised, semi-supervised, and reinforcement learning techniques, each serving distinct purposes (Ennaji, Vergütz, and El Allali 2023; Kirk et al. 2022).

Supervised learning maps inputs to outputs based on training data, while unsupervised learning identifies patterns and clustering (De Rainville et al. 2014; Venkataraju et al. 2023). ML can facilitate evidence-based decision-making across various fields, including nutrition, healthcare, agriculture, and environmental applications by rapidly uncovering important information in complex datasets (Côté and Lamarche 2021; Ding et al. 2023). In nutrition science, ML algorithms are revolutionizing fields like nutrigenomics, which examines how human genetic variations influence nutrient responses. ML algorithms can help analyze extensive genetic and nutritional data to create personalized nutrition frameworks (Ferrario and Gedrich 2024; Ordovas et al. 2018), integrating omics data (genomics, proteomics, metabolomics, and transcriptomics) to tailor dietary recommendations based on individual genetic profiles (Chaudhary et al. 2021; Ferrario and Gedrich 2024; Ramos-Lopez, Martinez, and Milagro 2022). This approach enhances precision in preventive and therapeutic interventions, including managing conditions like irritable bowel syndrome and colorectal cancer through dietary adjustments and probiotics (Legesse Bedada et al. 2020; Sanders et al. 2013).

ML models also enhance predictive analytics for micronutrient deficiencies, accommodating individual variations in diet, genetics, and microbiome (Galanakis 2024; Matusheski et al. 2021). For example, ML algorithms have helped manage deficiencies related to bariatric surgeries and supported obesity and metabolic disorder interventions (Kirk et al. 2022; Shang et al. 2020). In particular, random forest models and neural networks are used for personalized nutrition recommendations, analyzing factors such as weight loss progress and energy intake (Galanakis 2024; Sempionatto et al. 2021). Moreover, ML has aided in the prediction of micronutrient content in food, including unreported nutrients and spatial distribution of soil micronutrients. These approaches have been used to predict micronutrient profiles in cooked food from raw ingredients, reducing error rates and guiding future data generation (Naravane and Tagkopoulos 2023; Razavi and Xue 2023). These models could be integrated into mobile applications to provide consumers with detailed micronutrient information, aiding informed dietary choices (Ennaji, Vergütz, and El Allali 2023). Additionally, ML algorithms like random forest and support vector regression are effective to predict spatial micronutrient distribution, guiding targeted fertilizer application and enhancing micronutrient-rich crop cultivation (Ennaji, Vergütz, and El Allali 2023; Folorunso et al. 2023; Keshavarzi et al. 2023; Welch, Graham, and Cakmak 2013).

While machine learning (ML) shows promise in nutrition research, notable limitations persist (Kirk et al. 2022). As the authors noted, overoptimism often arises from non-rigorous methodologies, such as insufficient data sets and improper validation techniques like simple data splits, leading to inconsistent results. The infrequent use of nested cross-validation further compromises generalizability, particularly across diverse populations and data collection methods. Flawed feature selection and misestimation of feature importance by algorithms like random forest and XGBoost can distort findings. Additionally, practical drawbacks include among others, high costs for data collection, hardware, and maintenance, along with challenges in integrating diverse data sources (Kirk et al. 2022). Despite its potential, ML must overcome these issues to significantly impact nutrition-related health outcomes.

Cas9

Meeting the growing global demand for nutritious and sustainable food requires innovative crop improvement strategies that enhance both productivity and nutritional quality (Galanakis 2024). Climate change, soil degradation, and shifting dietary patterns further necessitate resilient agricultural systems that can provide essential nutrients while minimizing environmental impacts (Kaur, Awasthi, and Tiwari 2020; Shaheen et al. 2023). In this context, genome-editing technologies, particularly CRISPR/Cas9, are transforming food systems which enables precise genetic modifications to improve crop yield, resistance to biotic and abiotic stressors, and nutritional value (Dong et al. 2020; Young et al. 2019).

Traditional breeding methods such as selective breeding, hybridization, and mutagenesis have played a fundamental role in shaping modern agriculture (Ahmar et al. 2020; Kumar, Sharma, et al. 2022). However, these approaches are time-consuming, constrained by genetic variability, and often result in unintended genetic changes (Ahmar et al. 2020; Breseghello and Coelho 2013; Zhu, Li, and Gao 2020). Additionally, conventional breeding may not always align with the most pressing nutritional needs, limiting its effectiveness in addressing global micronutrient deficiencies. The growing demand for biofortified crops necessitates more precise and efficient tools, such as CRISPR/Cas9, to accelerate improvements in food quality and availability.

Since its introduction in plants in 2013 (Miao et al. 2013; Nekrasov et al. 2013), CRISPR/Cas9 has been widely applied to enhance traits relevant to food systems, such as disease resistance, drought tolerance, and crop nutrient composition (Ahmar et al. 2020; Young et al. 2019). Unlike conventional breeding, CRISPR/Cas9 allows targeted gene modifications without incorporating foreign DNA, making it a highly specific and efficient tool for crop improvement (Anders and Jinek 2014). This has been particularly impactful in biofortification efforts, where CRISPR has been used to increase essential micronutrients in staple crops.

For instance, CRISPR-mediated genome editing has enhanced the vitamin A content in golden rice, a critical intervention for vitamin A deficiency in regions where rice is a dietary staple (Dong et al. 2020). Similarly, iron and zinc concentrations have been improved in wheat and maize to combat widespread micronutrient deficiencies (Ibrahim et al. 2022). This technology has also been applied to increase vitamin E levels in barley, supporting improved dietary intake and consumer health (Zeng et al. 2020). Beyond staple crops, CRISPR/Cas9 has been successfully used to enhance nutrient profiles in apple, kiwifruit, orange, and banana, demonstrating its versatility in improving food quality across diverse agricultural products (Ahmad et al. 2021; Kaur, Awasthi, and Tiwari 2020; Zhu, Li, and Gao 2020).

Despite its potential, the integration of CRISPR/Cas9 into food systems is not without challenges. Regulatory frameworks vary widely across countries, with some nations imposing stringent restrictions on genome-edited crops, slowing their commercialization and adoption (Ahmad et al. 2021). Technical hurdles also persist, including the efficient delivery of CRISPR components into plant cells and mitigating off-target effects to ensure precise modifications (Kumar, Sharma, et al. 2022). Ethical considerations further complicate widespread implementation, as concerns about unintended genetic consequences, ecological impacts, and public perception continue to shape policy discussions (Young et al. 2019). Addressing these regulatory, technical, and ethical barriers will be crucial for realizing CRISPR's full potential in building resilient and nutritionally robust food systems.

Heavy metals

The launch of the United Nations' Global Soil Partnership and the declaration of 2015 as the International Year of Soils highlighted the critical role of soil health in sustaining life. The then UN Secretary-General Ban Ki-moon's remark, "*A healthy life is not possible without healthy soils,*" underscores the interdependence between soil vitality and human well-being (United Nations, n.d.). This recognition has driven research efforts to improve soil health for nutritional quality of food, ensuring food systems deliver essential nutrients while mitigating risks from harmful elements like heavy metals and pesticides.

Soil contamination with heavy metals poses significant threats to human health, ecosystem stability, and agricultural productivity (Mariana et al. 2021). Metals such as lead (Pb), cadmium (Cd), mercury (Hg), zinc (Zn), iron (Fe), copper (Cu), chromium (Cr), and arsenic (As) accumulate in soils due to activities like mining, industrial emissions, and the use of agrochemicals (Gaur et al. 2021; Singh et al. 2024). These metals, often carcinogenic and neurotoxic, are hazardous even in trace amounts (Gaur et al. 2021; Jiang et al. 2020). Their persistence in the soil, due to low mobility and limited degradation, threatens agricultural productivity and contaminates water sources (Bi et al. 2018; Chen et al. 2022; Mariana et al. 2021; Supriatin 2016).

The global concern over heavy metal contamination is compounded by the inadequacy of traditional treatment methods, which often fail to offer cost-effective and eco-friendly solutions (Gaur et al. 2021). Moreover, contamination exacerbates micronutrient deficiencies by hindering nutrient uptake in plants. Heavy metals like cadmium and lead can displace essential micronutrients, such as zinc and iron, from the soil, reducing their bioavailability to crops and ultimately affecting the nutritional intake of human populations dependent on those crops (Duffner et al. 2014). This issue is particularly critical in regions already struggling with high levels of malnutrition (Duffner et al. 2014). Therefore, addressing heavy metal contamination is critical to ensure food safety and improving public health and micronutrient deficiencies.

Recent advances in agricultural science offer promising solutions to these challenges. Nano-scale remediation technologies, for example, have shown potential in effectively removing or neutralizing contaminants at the molecular level, enhancing soil quality and crop safety (Abd Elnabi et al. 2023). Bioremediation, which uses microorganisms or plants to detoxify polluted soils, is another innovative approach that can restore soil health and reduce contamination (Abd Elnabi et al. 2023). Omics technologies, including genomics, proteomics, and metabolomics, offer valuable insights into soil and plant interactions, enabling more targeted and effective remediation strategies (Jamla et al. 2021). Integrated approaches that combine these technologies with traditional soil management practices provide a comprehensive solution to mitigate contamination and improve crop nutrient content. These emerging trends underscore the need for continued research and innovation to address soil contamination and its impact on micronutrient deficiencies, paving the way for more sustainable and resilient food production systems.

Conclusion

This bibliometric analysis of micronutrient research from 2015 to 2023, framed by the Sustainable Development Goals (SDGs), identifies key trends and thematic clusters that highlight evolving relationship between research priorities and global nutritional challenges. Content analysis, co-occurrence network analysis, and thematic map analysis all revealed that osteoporosis, vitamin D, and bone mineral density were the dominant research themes, which align with SDG 3 (Good Health and Well-being) and its targets on reducing non-communicable diseases and ensuring adequate nutrition. These themes reflect the growing emphasis on bone health, likely driven by aging populations, public health campaigns on osteoporosis prevention, and increasing interest in vitamin D's role in immunity, especially in high-income countries.

While these themes are critical, the dominance of bone health research contrasts with the continued global burden of hidden hunger, particularly deficiencies in iron, zinc, and vitamin A that disproportionately affect low- and middle-income countries. These deficiencies remain underrepresented in the literature, which raises concerns about whether research efforts are sufficiently aligned with SDG 2 (Zero Hunger), particularly Target 2.2, which aims to eliminate malnutrition and address micronutrient deficiencies in vulnerable populations. A broader cross-examination of the 169 SDG targets suggests that much of the research aligns with SDG 3 (Good Health and Well-being), particularly Target 3.1 on maternal health and Target 3.2 on child mortality, both of which are impacted by micronutrient deficiencies. However, there is limited focus on SDG 12 (Responsible Consumption and Production), which relates to sustainable food systems and micronutrient-rich diets.

Beyond bone health, the analysis also identified research trends, including machine learning applications, macroalgae, CRISPR/Cas9 technology, and heavy metal contamination. While these are well-established fields, their intersection with micronutrient research has grown due to evolving nutritional challenges. For example, macroalgae have long been studied for their role in omega-3 fatty acid production, but recent research has expanded to their micronutrient potential, particularly iodine and bioactive compounds relevant to functional foods. Similarly, machine learning is increasingly applied to food composition analysis and dietary assessments, while CRISPR/Cas9 has seen growing use in biofortification efforts aimed at enhancing disease resistance, drought tolerance, and the nutrient composition of crops.

To bridge the gap between research focus and global nutritional needs, future studies must balance cutting-edge developments with a renewed emphasis on addressing the most pressing micronutrient deficiencies. Strengthening the alignment of research priorities with SDG 2.2 (ending all forms of malnutrition), SDG 3 (Good Health and Well-being), and SDG 12 (sustainable food systems) will be crucial to ensure that scientific advances contribute meaningfully to reducing hidden hunger and improving nutrition outcomes globally.

Several limitations of this study should be noted. The reliance on data from the Web of Science database may exclude relevant studies from other sources, potentially missing important contributions to the field. Additionally, the focus on the period from 2015 to 2023 may not capture longer-term trends, and limiting the scope to micronutrient might overlook broader developments within nutrition and food systems. Nevertheless, this review provides valuable insights into emerging research trends and underscores the need for a more comprehensive, SDG-aligned approach to addressing micronutrient deficiencies – ensuring that research efforts are targeted where they are most needed.

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Author contributions

EAA conceptualized and designed the study, analyzed and interpreted the data, and drafted the manuscript. NWS, TMRM, and WCM contributed to the design and methodology, provided critical revisions for intellectual content, and reviewed the manuscript. All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Data availability

Data will be made available upon reasonable request.

Disclosure statement

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