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A DECADE OF IRON BIOFORTIFICATION IN CROPS: BIBLIOMETRIC ANALYSIS OF SCIENTIFIC PUBLICATIONS AND FUTURE PERSPECTIVES

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Abstract
Iron (Fe) deficiency disorders are one of the major challenges faced by global nutritional security even after more than six decades of the green revolution in the 1960s. Numerous advancements in medical science and healthcare infrastructure have helped bear the brunt of severe ailments like Fe-deficiency anaemia. However, nutritional enhancement of the food consumed by people remains the primary approach to tackle hidden hunger in the long run. Biofortification of crops is one of the most practically suitable methods to ensure this nutritional enrichment. Several methodologies have been used over the years to achieve this aim including agronomic biofortification, breeding-based crop improvement and genetic-engineering for enhancing the accumulation of Fe in economically important parts of the crop. This review aims to provide a bibliometric overview of the research and development that happened in this field in the last decade. The current work utilized Scopus database as a standard source for collecting authentic documents and shed some light on the trends in the Fe-biofortification research such as the research output, relevant authors, collaborations, countries leading this research domain and the projected future trend for the field of Fe-biofortification. All the analyses were performed with the help of bibliometrix integrated with biblioshiny, a R-code based online platform for easy bibliometric analysis. The PRISMA framework was prepared for the study and finally 822 documents were used for the analysis which revealed a promising future for Fe-biofortification research. Projected trends show an increase in research output till 2030 while the growth in publications eventually saturate in the coming decade.

Keywords: Iron, biofortification, Scopus, bibliometric analysis, biblioshiny, PRISMA

1. Introduction

The global population is expected to exceed 8.5 billion by 2030. There is a huge pressure on the global agricultural system to keep producing sufficient food to feed the population from the same available land (Rahman & Zhang, 2022). Therefore, traditionally the focus was always on enhancing yield which eventually led to the green revolution. The extensive use of high-yielding varieties and agricultural inputs ensured a massive increase in the yield of major crops like rice and wheat with countries in the Indian subcontinent being the major beneficiaries. The green revolution helped the world achieve food security (Nelson et al., 2019). However, over the years the focus has gradually shifted towards nutritional security. There is enough agricultural production to feed the population, yet the dietary patterns and production practices expose specific regions in the world to 'hidden hunger', a condition where the minimum nutritional requirements are not fulfilled even though sufficient volume of food is available. Among the various types of micronutrient deficiencies characteristic of hidden hunger, Fe-deficiency disorders are one of the most prevalent especially in Africa and South-East Asia, the regions which are primarily dependent on rice as their major diet. Rice is inherently deficient in Fe and Zn while the preference towards milled rice further aggravates this problem by stripping the grains of their bran, the storehouse of all the micronutrients (Yao et al., 2020). Amongst the disorders caused by the ensuing Fe-deficiency, anaemia is the most common with children and pregnant women being the worst affected sections of the society. Therefore, concentrated efforts for the alleviation of its negative effects on human health and socio-economic stability of affected communities, are the need of the hour.

Biofortification of major food crops, such as rice, is one of the most popular methods for a long-term alleviation of Fe-deficiency disorders in rice-eating populations. Instead of changing the dietary patterns that communities have built over centuries, this approach aims to enrich what is already consumed to ensure that the health benefits of biofortification reach every stratum of the society (Dhaliwal et al., 2022). Crop biofortification can be carried out by multiple methods falling under three broad categories – agronomic biofortification, plant-breeding for

nutritionally enhanced varieties and genetic engineering for modified accumulation of essential micronutrients (Garg et al., 2018). Agronomic methods deal with crop production practices which are manipulated to force higher accumulation of Fe in the plants (Bhardwaj et al., 2022). Plant-breeding is concerned with the identification of genes and quantitative trait loci (QTLs) within the naturally available variation in crops and deploy precise crossing and selection pressure to develop lines with the intended biofortification. Advancements in this field such as molecular markers and speed breeding have significantly improved the efficiency of breeding-based workflows for Fe-biofortification of crops (Virk et al., 2021). Genetic engineering eases this process even further with CRISPR/Cas9-based toolkits allowing precise nucleotide level manipulations of genes to regulate or shut down the function of target proteins involved in Fe uptake, homeostasis and distribution. This technique allows the enhancement of Fe accumulation in edible parts of crops, such as grains in cereals, at rates impossible with the sole use of its predecessors (Shohael et al., 2025). All these techniques have cumulatively contributed immensely towards finding viable solutions for dealing with dietary deficiency of Fe and its ill-effects. However, there is still a lot of scope for further exploration and practical utilization of the results obtained from Fe-biofortification related research.

The current work provides a bibliometric analysis of the last decade of research related to Fe-biofortification of crops. The authors have mapped the research trends starting from the volume of research output to the global collaborative and citation networks along with the growing popularity of specific authors and journals. The analysis was performed with the documents obtained specifically from the Scopus database to ensure the dependability of the sources and limit the analysis to the most relevant works in the field while avoiding a meaninglessly large volume of documents with redundancies (Baas et al., 2020). The tool used for this analysis is Bibliometrix (Aria & Cuccurullo, 2017; Aria et al., 2024; Aria, D'Aniello, et al., 2026), an open-source free-to-use package operating on the R-programming language. It is integrated with Biblioshiny (Aria & Cuccurullo, 2026), an interactive online user-friendly interface for easy bibliometric analysis without any prior knowledge of programming languages or other complex softwares built for the purpose. Using the tool, not only a mere overview of the available literature but a statistical evaluation of the same was also performed to determine the trends in the impact of the published research. The tool deploys the SAAS workflow which stands for Search, Appraisal, Analysis and Synthesis. It mimics the actual structure of scientific research involving the search for relevant documents, validation and filtration of metadata, statistical analysis of the metadata and the visualization or mapping of results for insights (Aria et al., 2026). The methodology and metrics used in the current work, the results obtained and their interpretations have been described at length in the following sections.

2. Materials and Methods

2.1 Collection of data

A PRISMA framework (Fig.1) was prepared for shortlisting the documents (Page et al., 2021). The Scopus database was searched with the query statement: TITLE-ABS-KEY(rice) OR TITLE-ABS-KEY(crop) AND TITLE-ABS-KEY-AUTH(iron) AND TITLE-ABS-KEY(biofortification). The initial search resulted in 1,398 documents which were excluded with the help of many filters as mentioned in the PRISMA diagram. The date range was set from 2016 to 2026. The document type filter was set to exclude 'erratum' and 'retracted' documents. The subject category filter was set to 'Agricultural and Biological Sciences' and 'Biochemistry, Genetics and Molecular Biology' to limit the documents to these two categories. The language filter was set to 'English' to ensure that the documents which are more widely understood globally are included in the analysis. Finally, 'keywords' filter was set to limit the document search to key terms such as 'iron', 'biofortification', 'zinc', 'micronutrients', 'crops' and 'deficiency'.

2.2 Bibliometric summary

The list of documents with all its metadata was downloaded as .csv file from Scopus. The biblioshiny interface was accessed by installing and loading the bibliometrix library on R-studio which opens the web interface as a local server. The .csv file with the metadata was loaded onto the interface which automatically converted it into bibliometrix format for downstream analysis. The first report generated was a bibliometric summary (Fig 2.) of the metadata revealing salient features such as the number of documents, sources, authors and citations (Zupic & Čater, 2014).

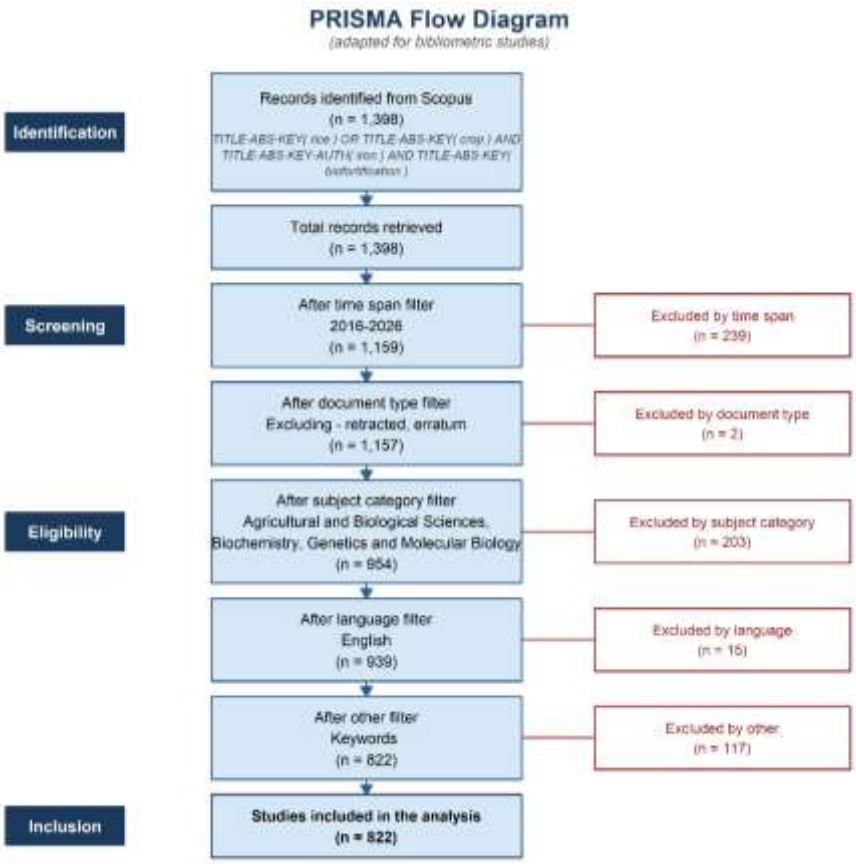


Figure 1 PRISMA framework used for the bibliometric analysis. This framework is a standard workflow design for the collection of documents used in bibliometric analyses and systematic reviews.

2.2 Analysis of authors and affiliations

The interface was used to list out the top 10 authors based on several parameters including their volume research output, impact of their publications measured by h-index, annual research output trend and number of citations (Aria, Le, et al., 2024; Hirsch, 2005). The specific statistical analysis applied for authors' impact was based on the Lotka's law which mathematically describes the frequency at which authors in a given field are expected to produce scientific publications (Pao, 1985; Nicholls, 1986). The citations were first categorised, for the analysis, into 'global' and 'local' where the former refers to the citations received across the entire catalogue of documents available online while the later refers to the citations occurring within the list of documents used for the present study. The affiliations were analysed in a similar manner to present an overview of the research output from the top individual institutions ranked on the basis of their volume of research and publications. To get a complete picture, the collaborations in this field were also analysed to visualize the degree of independent and collaborative research not only between institutions but also between countries based on a world map of collaborations generated from the information regarding the country to which the affiliated institution of the authors belonged to, from within the metadata.

2.3 Keyword, journal and thematic analysis

The keywords were analysed using the same interface to reveal several details such as the most important keywords used in the field of Fe biofortification research, the frequency of usage of keywords over time, the proportion of individual keywords within all the keywords used in the documents used for this analysis, co-occurrence of the keywords in publications and a dendrogram mapping the pattern of keywords used in groups (Callon et al., 1983; (Cobo et al., 2010). The analysis of journals was coupled with this to reveal the sources of documents contributing or publishing the highest volume of research in this field. Bradford's law was specifically used for analysing the relevance of the journals in this field based on how scientific publications are scattered across sources (Brookes, 1969). This helped understand additional thematic and factorial analyses (Greenacre, 2007; Cuccurullo et al., 2016) which explored the common concepts often explained together in scientific papers in order to make thematic clusters of the core aspects in the field of Fe biofortification.

2.4 Combination of results and projection of future trends

After all the analyses involving all the metadata, the results from the analyses of keywords, authors and journals were viewed combinedly to reveal the connection between the three and sum up the bibliometry (Chen, 2017). Additionally, the future trends were also projected based on statistical analyses to estimate the volume of research

output expected from this field in the following decade with an eventual saturation in the increase in the number of publications observed in the last decade (Aria et al., 2020; Bettencourt et al., 2009; Small & Upham, 2008; Wang, 2017).

3.0 Results and Discussion

3.1 Salient features of metadata and publication trend

The filters applied to the list of documents related to Fe biofortification obtained for a time span of 2016 to 2026 resulted in a final list of 822 documents spread 310 different sources (Fig. 2a) which reflects a wide range of journals publishing scientific literature related to the topic. The annual rate of increase in the volume of publication output is well over 11 percent which is impressive for concept which has been tossed around for more than a decade. More 3500 authors have published literature in this field with a significant amount of international co-authorship indicative of a strong collaborative network in the field of Fe biofortification. Individual documents are almost around four years old and get more than 20 citations on average. The publication trend shows peaks in the volume of output during 2017, 2020 and 2023 with the bar still going up in 2026. This shows that the interest of the scientific community in this topic has been dynamic and is currently still increasing.

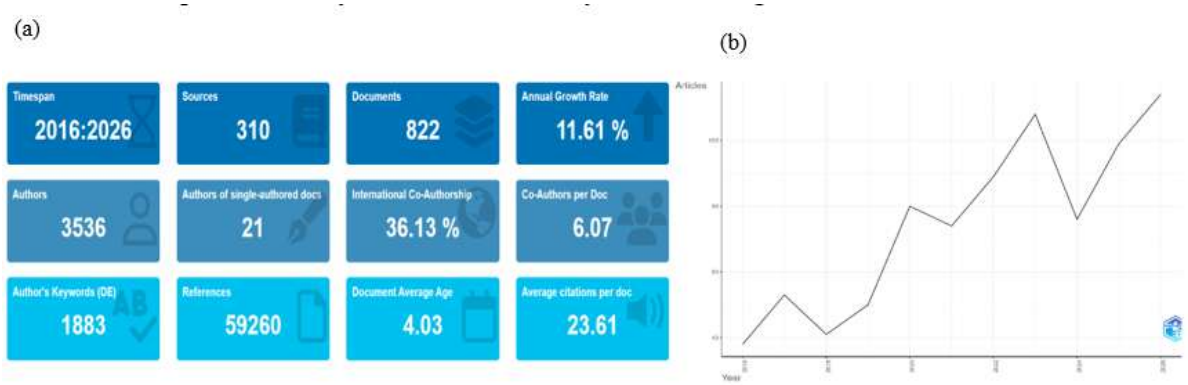


Figure 2 Brief overview of the metadata (a) The salient features reveal information about the time span, documents, sources, authors, keywords and other relevant insights into the gross numbers attached to these aspects. (b) The annual growth curve shows an increase in the output of publications over time with the numbers waxing and waning throughout the decade.

3.2 Key authors, collaborations, countries and institutes in the field of Fe biofortification

The relevant authors in the field were evaluated based on their volume of scientific publications within the 10-year period under consideration (Fig. 3a). S. Kumar occupies the top spot with more than 25 publications during this period and a high h-index of 16 (Fig. 3b). The graph of average scientific output of the authors shows that Kumar S. produced the major chunk of his contributions during 2022-2023 with 2023 being a year of high scientific output for a majority of the top 10 most relevant authors (Fig 3c.). However, citations within the list of documents used in the study reveal N. K. Bhullar to be the most cited author with more than 200 citations (Fig. 3d). The pattern in authors' contributions is revealed by the statistical approach of Lotka's law. In this case too, the typical pattern is observed where roughly 80 percent of the authors published about one or two papers with only the very prolific authors constituting less than 10 percent of the total number of authors identified across the papers contributing 10 or more publications in the last decade (Fig. 4a). The co-citation network (Small, 1973; Kessler, 1963) sheds more light on the connection in the publications of the influential authors S. Kumar, A. Kumar and M. Govindaraj appearing more frequently across citations within their publications based on the size of the circles representing the respective clusters (Fig. 4b). The historiograph (Garfield et al., 2003; Garfield, 2004; Lucio-Arias & Leydesdorff, 2008) takes this even further by representing the lineage of these citations over the years. The lines converge towards 2023 revealing a stabilization in the understanding of Fe-biofortification with P. Senguttuvel and his publications in 2023 being the converging point (Fig. 4c).

Analysis of the countries to which the relevant authors of this field belong revealed that India leads the world in terms of the volume of scientific output related to Fe biofortification with more than 4500 articles involving Indian authors (Fig. 5a). The rise in the volume of scientific publications over time is also the steepest for India reflecting a growing

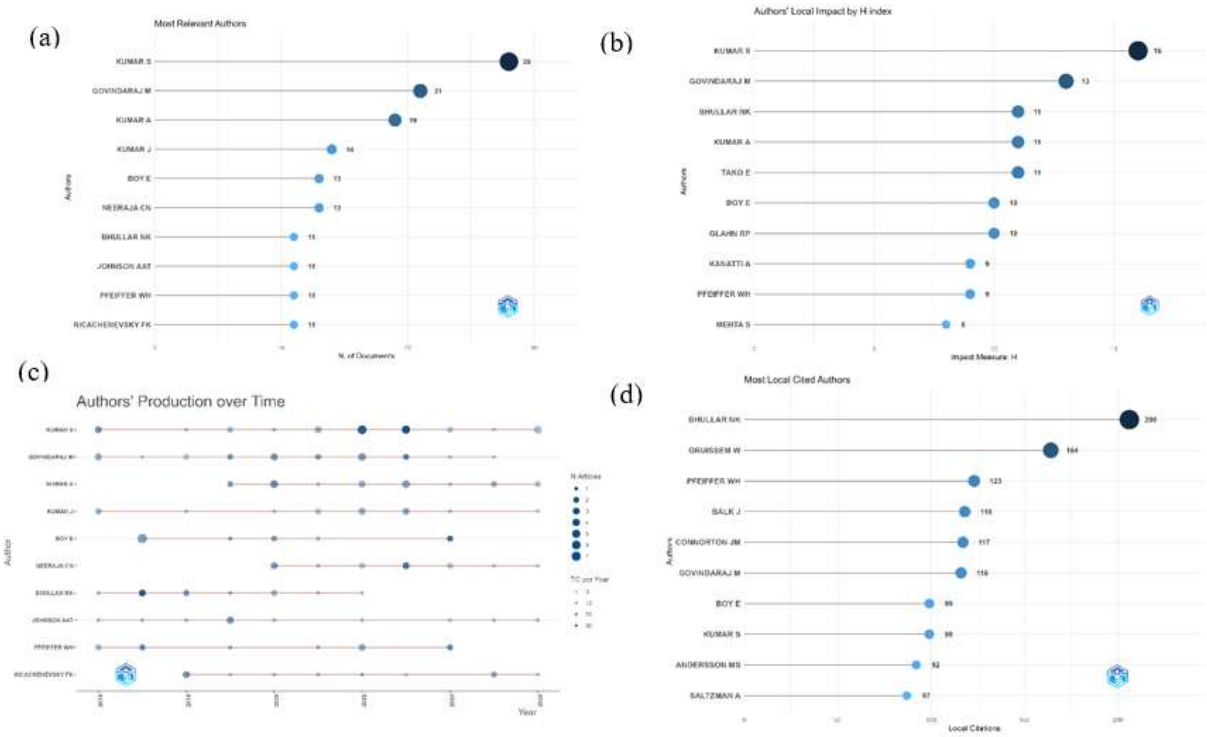


Figure 3 Graphical representations of relevant authors and their publication statistics. (a) Top 10 relevant authors based on their number of publications (b) Impact of the authors' publications based on h-index (c) Annual production trend of the top authors in the field (d) Top authors based on the number of citations received by the authors within the documents used for analysis

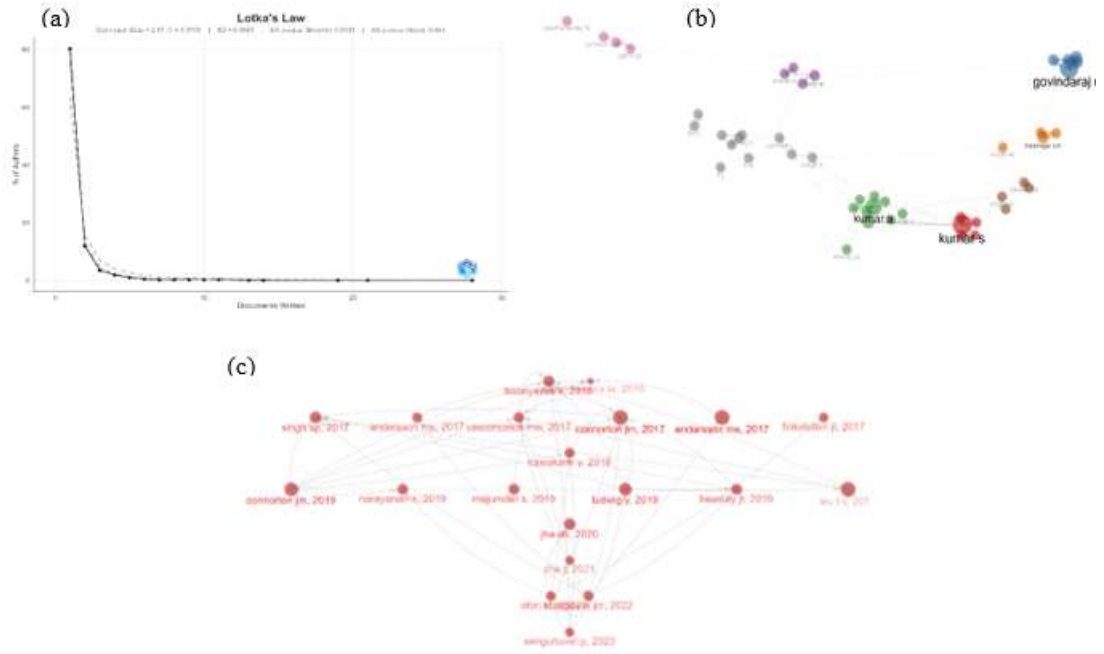


Figure 4 Analysis of the pattern of authors' contributions and citation patterns (a) Statistical analysis of the pattern of contribution of authors (b) Co-citation network of the authors (c) Historiograph of the author citation networks showing a lineage of the citations with respect to the changing trend of conceptual relevance of publications in the field

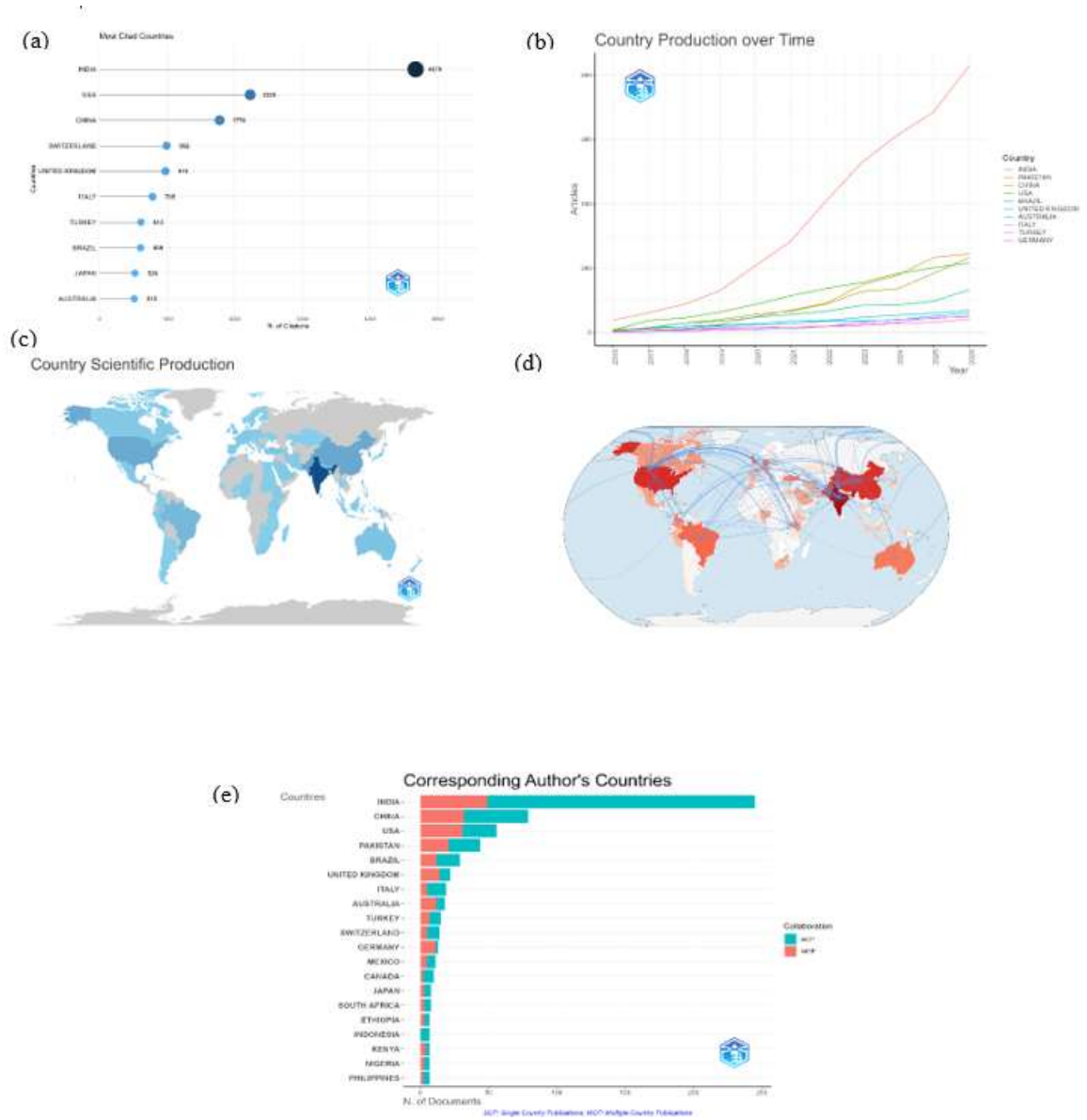


Figure 5. Analysis of the countries' contribution to Fe-biofortification research. (a) List of top 10 countries contributing to this field based on number of citations received (b) Trend of scientific production volume of countries over time (c) World map showing countries with their volume of publications depicted by the intensity of blue (d) World map of cross-country citationss with the magnitude depicted by the intensity of red (e) Graphical depiction of single country publications (SCP) and multi country publications (MCP) highlighting the scientific collaboration between countries

interest of the Indian scientific community in this field (Fig.5b). The high volume of publications is also reflected in the world-map depicting the number of global publications from countries (Fig. 5c) as well as the one depicting cross-country citations (Fig. 5d) where India tops the list again. This citation pattern can be understood from the number of single country publications (SCPs) and multi country publications (MCPs) where India again shows a very high proportion of MCPs in its volume of publications indicating the growing international collaborations at the global level (Fig. 5e).

The institutional affiliations of the authors publishing the highest number of scientific articles in the field of Fe biofortification naturally follows a similar trend as shown by the countries. Punjab Agricultural University (PAU) from India takes the top spot for the most relevant affiliations in this field followed by Indian Agricultural Research Institute (IARI) and Cornell University (Fig. 6a). However, the trend of publications over time shows a reduction in the rate of increase in the publication output for PAU and Cornell University while IARI still maintains a steep rise in the same even for 2026 (Fig. 6b).

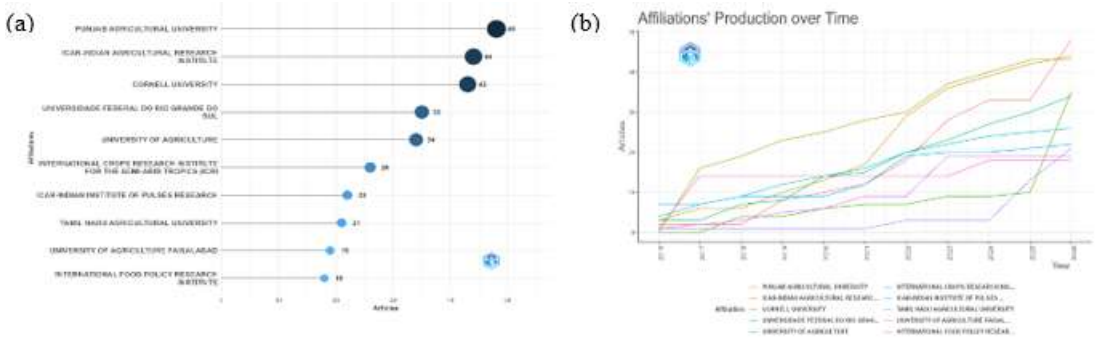
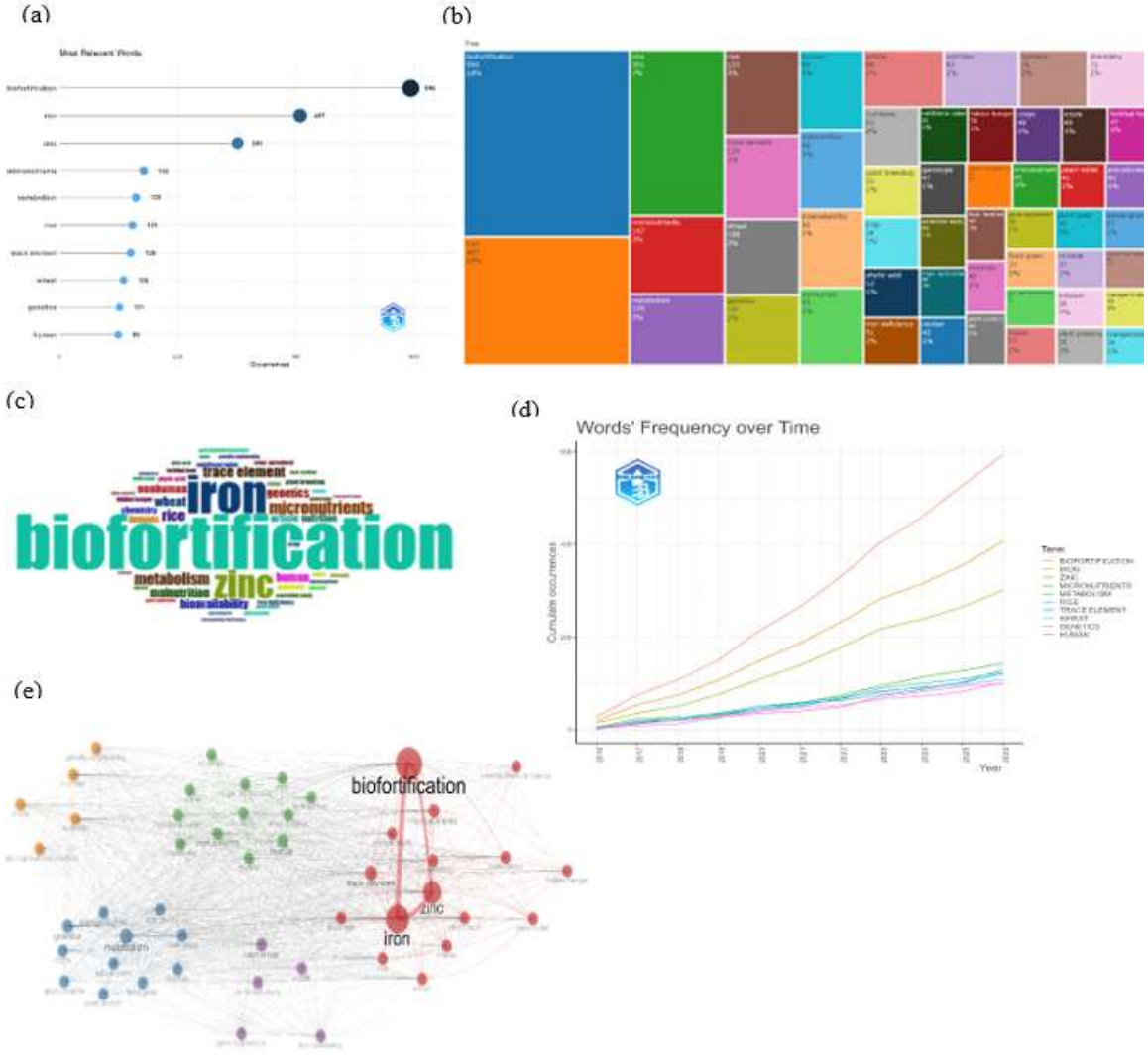


Figure 6 Analysis of affiliations of the authors publishing in the field of Fe biofortification. (a) Most relevant affiliations based on the number of articles featuring authors affiliated to the respective institutions. (b) Trend of publication output from the relevant affiliations in the last decade (2016-2026)

3.3 Major keywords in publications related to Fe-biofortification

Analysis of the keywords reveals an obvious result. 'Biofortification' is the most relevant keywords found across papers in this field with 'Iron' and 'Zinc' (Zn) occupying the next two spots. However, few other words such as micronutrients, rice, wheat and genetics reveal that the field of Fe-biofortification is actually focussing on these aspects of research in terms of the crop and the approach gaining popularity within the scientific community (Fig. 7a). The word-tree (Fig. 7b) and the word-cloud (Fig. 7c) confirm the same pattern with biofortification appearing in at least 14 percent of all the documents used in this study followed by Fe and Zn 10 percent and 7 percent respectively. The large number of keywords though, in the word-tree,



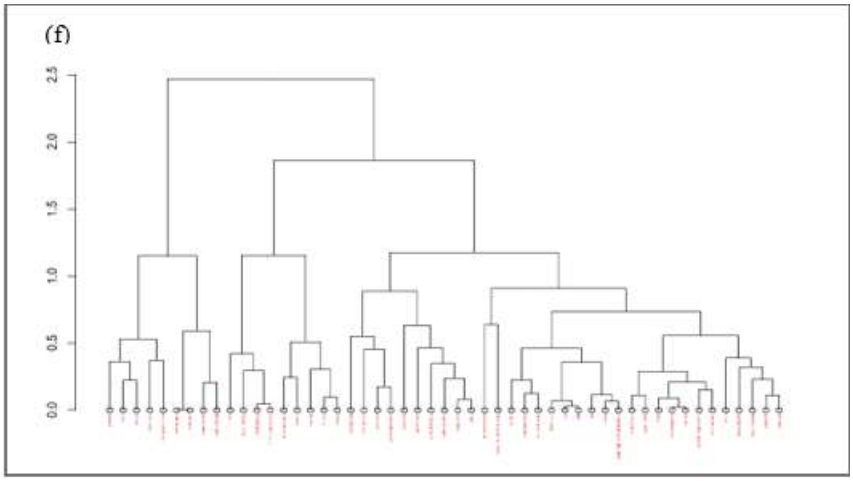


Figure 7 Analysis of relevant keywords in the field of Fe-biofortification. (a) Graphical representation of the most relevant keywords based on their occurrence across publications. (b) Word-tree of keywords with each colour representing a distinct keyword and the size of the rectangles showing their relevance in the field. (c) Word-cloud of keywords showing the more relevant keywords in larger font and vice versa. (d) Trend of usage of keywords over the last decade (e) Co-occurrence network of keywords with circles representing the keywords, their size representing relative relevance and the thickness of the connecting lines showing the degree of co-occurrence. (e) Dendrogram of keywords against an imaginary time scale revealing the lineage of co-occurrence of the keywords over the years in scientific publications

show that there are many other aspects covered by scholarly work on Fe-biofortification ranging from different crops to bioavailability and Fe-deficiency disorders.

The graph of use of keywords over time reflects the same growing use of the top three keywords with the others still being used a lot lesser comparatively (Fig. 7d). The co-occurrence network reveals an additional layer of information and shows that the top three keywords are not only used more frequently but also together in most papers as shown by the size of the circles thus forming a major cluster to which other nodes representing the lesser used keywords are connected (Fig. 7e). The dendrogram gives another angle to the same information by mapping out the pattern or lineage of the keywords in relation to each other with respect to the groupings occurring across an imaginary time scale (Fig. 7f). This visualization reveals more interesting patterns. Biofortification initially occurred more with Fe-deficiency while Fe and Zn often appeared together in scientific works. The micronutrients are further observed to be grouped with phytic acid which hints at publications concerning bioavailability of the nutrients in crops while the crops themselves like rice and wheat must have obviously appeared together in publications talking about important target plants for Fe-biofortification considering their importance in global agriculture.

3.4 Important documents, their sources and citation trends

The analysis of the publications related to Fe-biofortification in terms of the citations they receive in other scientific works in this field revealed two top publications. The paper titled - 'Wheat vacuolar iron Transporter *TaVIT2* transports Fe and Mn and is effective for biofortification' published by Connorton et al in 2017 in the journal 'Plant Physiology' is the most cited document within the list of documents used for this study while the paper – 'Vitamin C in plants: From functions to biofortification' published by Paciolla et al in 2019 in the journal 'Antioxidants' remains the most cited document, globally, in the field of nutrient biofortification. This reveals that Fe-biofortification is not the most sought-after topic in scientific publications considering the pattern of citations. However, the number of citations per year have been steadily dropping since 2019, possibly hinting at the increasing specialisation within this field with scientists and scholars working on particular aspects of biofortification and citing works within the boundaries of their work thus reducing cross-citations and the magnitude of total number of citations in the field. Analysing the same aspect from a different angle revealed different results. The repeated recurrence of specific publications across the other papers in the field revealed that the specific publication – 'Enrichment of Cereal Grains with Zinc: Agronomic or Genetic Biofortification?' – published by I. Cakmak in the journal 'Plant Soil' in 2008 – is the most recurring reference across the documents used for this study thus hinting that this was possibly a foundational paper which later authors still refer to for understanding or explaining concepts pertaining to crop biofortification.

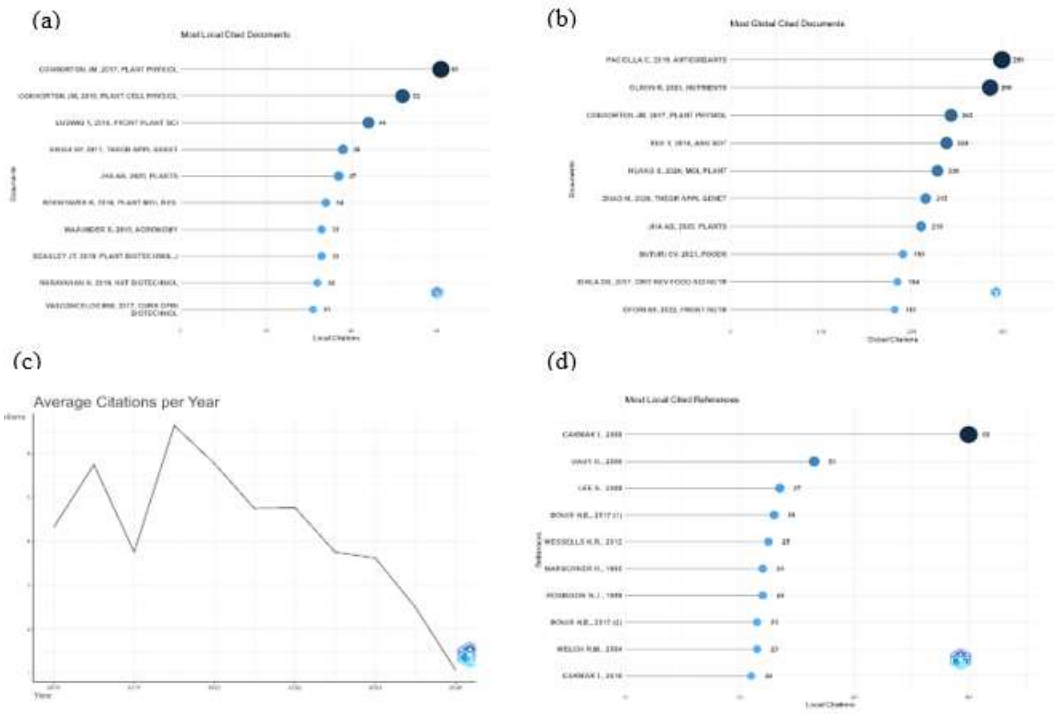


Figure 8 Analysis of citations across the documents (a) Documents with the highest citation within the local list of documents. (b) Documents within the list with the highest overall number of citations (c) Trend of annual number of citations (d) Documents recurring for the maximum number of times in references within the local list of documents

Shifting from the documents that talk about biofortification to the journals which publish them also revealed new patterns. ‘Frontiers in Plant Science’ tops the list of journals in terms of the

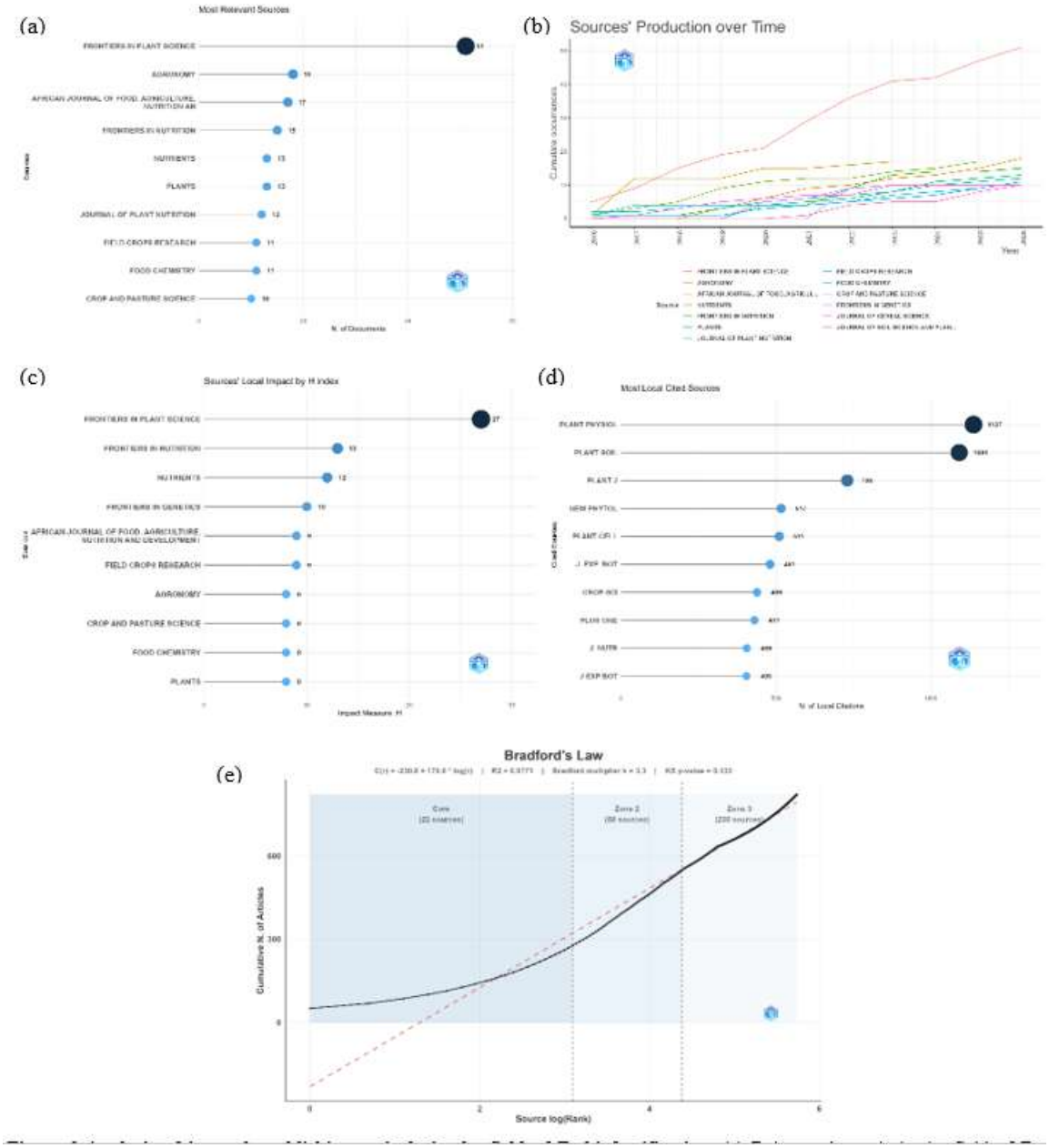


Figure 9 Analysis of journals publishing actively in the field of Fe-biofortification. (a) Relevant journals in the field of Fe-biofortification (b) Trend of volume of publications from the relevant journals. (c) Journals ranked based on their h-index (d) Journals recurring across the references within the local list of documents (e) Analysis of the pattern of scattering of documents across journals based on Bradford's law

volume of publication output in the last decade, the increasing rate of publications related to this field and overall h-index. However, in terms of citations received, 'Plant Physiology' and 'Plant Soil' are the top two journals. This reveals that the citations can help in understanding the foundational impact of specific journals in the field of crop biofortification. This differs from the dynamics of the relevance of the journals in the field which is measured, more often, in terms of the volume of their publication output and not the tangible impact they have on the field itself. The pattern in which papers are spread across journals can be understood by Bradford's law which divides the sources of publications into three zones. The core zone representing the influential papers consists of 22 sources while the zone 2 consists of nearly 60 sources. Majority of the journals are not as influential as others hence the zone 3 consists of more than 200 articles.

3.5 Thematic clusters and three-way relations

The analysis of the thematic clusters was again based on keywords as they essentially represent the relevant topics addressed in the scientific publications in a given field. The graphical representation of the trending topics confirms the previous trends while revealing new patterns too. Biofortification, Fe and Zn have been important throughout 2019 to 2024 with the highest frequency of occurrence across papers. Older topics like 'pearl millet'

and ‘fortified food’ have maintained their relevance from 2017 till 2024 and represent the undercurrent of the trend which is not very evident in terms of the occurrence in papers but is scientifically relevant. The conceptual structure map takes this further by giving a direction to the pattern in which the topics have converged. Diverse themes including, but not limited to, agriculture, crops, food grains, chemistry, genetics, transgenics and metabolism have concentrated towards core topics like biofortification and hidden hunger. Thematic clustering of these topics provides an easily understandable visualization of the overall situation of scientific literature in this field (Cobo et al., 2012). The most relevant keywords like biofortification, Fe and Zn are the basic themes which keep recurring throughout scientific literature while genetics and metabolism represent more niche themes which are very well-developed in terms of their relevant publications and research but not as prevalent across papers like other themes. Terms like micronutrients and trace elements are the motor themes which essentially drive the research in this field even though there are not explicitly mentioned in a large volume of publications.

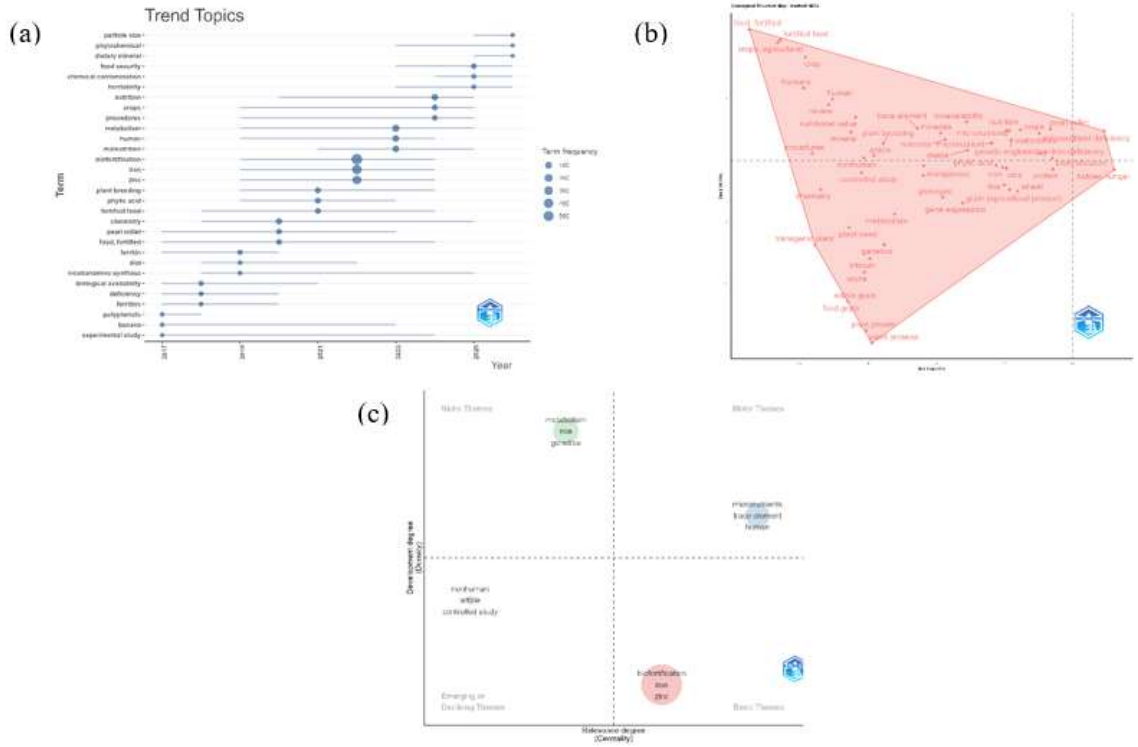


Figure 10 Thematic analysis of the core aspects of Fe-biofortification research. (a) Trending topics in the field of Fe-biofortification based on their frequency of recurrence across papers. (b) Conceptual structure map of the important concepts with a directional clustering based on factorial analysis. (c) Thematic map of the topics with clusters of important terms differentiated into basic, niche, motor and emerging or declining themes based in degree of relevance vs degree of development in the topic

3.6 Future trends of scientific publication in Fe-biofortification

Summing up the analyses performed in this study, the overall connections between three important pillars of the scientific publication industry authors, journals and the topics addressed in papers. The three-field plot visually represents this inter-connectedness. The number of lines connecting the individual authors journals and keywords depict their overall impact and relevance in this field. Statistical analyses considering scientific publications like a product predicted the life cycle just like any other industry. The cumulative growth curve projecting the number of cumulative publications in every year revealed that the gross numbers would cross 2000 by 2040 and stagnate by 2050 after a steady growth throughout the next two decades. The life cycle curve calculated at a R^2 value of 0.817 projects the number of publications per year to peak in 2027 with more than 100 papers published in the year following which the numbers are expected to drop steeply through the next two decades.

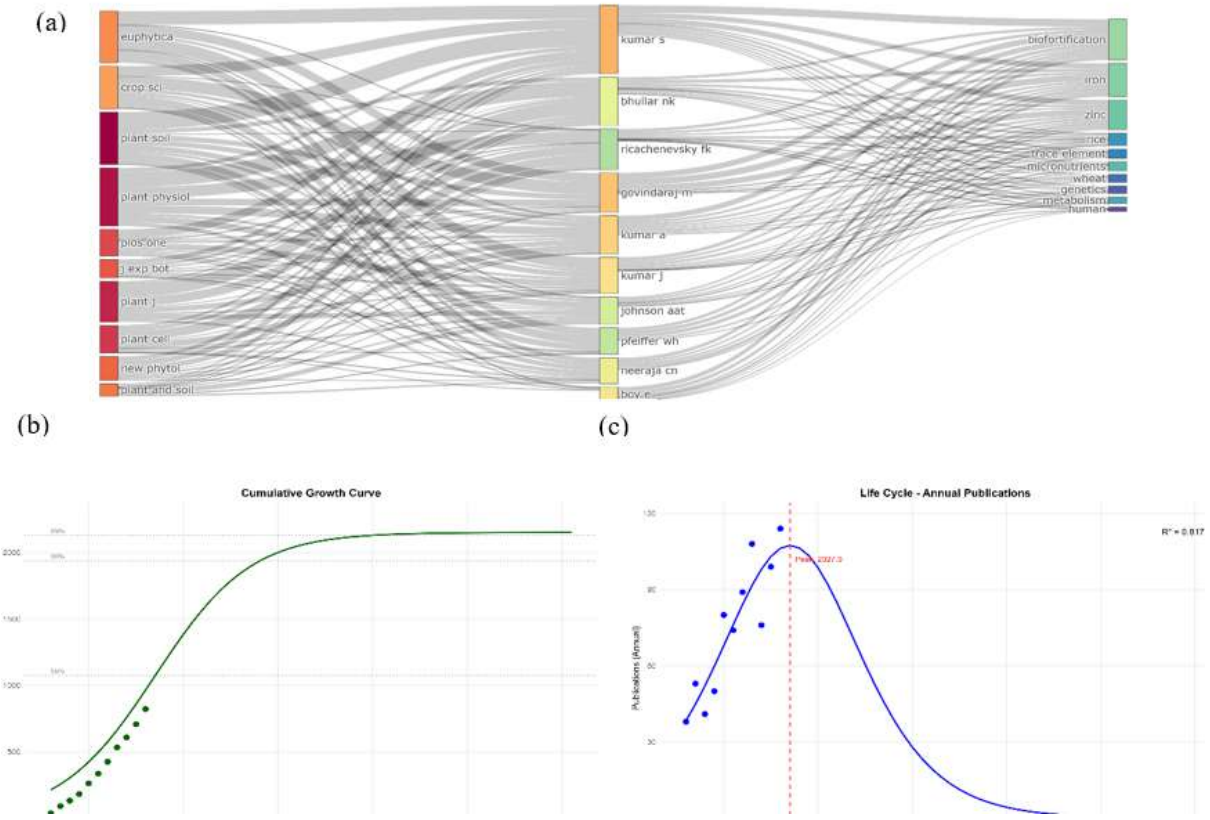


Figure 11 Overall summary and prediction of future trends. (a) Three-way field plot of authors, journals and keywords. The concentration of the lines near individual elements in the plot depict their relevance in the field. (b) Projected cumulative growth in the publications with every year's annual publication output added to the sum of all the publications in the previous years. (c) Life cycle of annual number of publications projected for the following decades calculated at $R^2 = 0.817$

4.0 Conclusion

Crop biofortification is a very important topic for the scientific community of plant biologists trying their best to ensure not only food security but also nutritional status of the population. Among the different possible nutrient biofortifications, Fe-biofortification is one of the critical areas of research to tackle Fe-deficiency disorders which are still quite prevalent in the global population and especially the regions with heavily cereal-dependent diets such as rice or wheat. The scientific publications in this field are a promising reminder of the concerted efforts of scientists and scholars to alleviate the burden of hidden hunger since decades. The present study delved into the bibliometric aspects of the publications pertaining to Fe-biofortification. Overall, there is a positive trend in this area of research with a high volume of relevant publications generated in the last decade. India stands out as the leading contributor in this area in terms of the gross number of papers being published as well as the importance of Indian authors and Indian institutions in the field. The high degree of collaborative publications in the field of crop biofortification is another positive hint towards the collective efforts in advancing the scientific understanding of the topic and disseminating the same.

The future predictions project a cumulative growth in the publications in this field for the coming decade. However, annual publications are expected to drop which could be a result of extensive specialisation in the field leading to a reduction in the overall numbers while scientific output is still generated in niche domains such as genetic engineering for crop improvement. Ultimately, the success of all scientific publications can be realised only when deliverables from research are translated into finalized products for deployment in the farmer's field. There is still a lot of scope for improvement in this regard. Concerted efforts in scientific research and publication need to be translated in terms of agricultural production and the public policies surrounding it to ensure that the generation of biofortified crops truly fulfils the aim of achieving global nutritional security.

Acknowledgement

All the analysis and figure preparation were done with the help of bibliometrix and biblioshiny.

Author contributions

Sougat Satapathy and Varanavasiappan Shanmugam have contributed equally to this study. Kokiladevi Eswaran, Jayakanthan Mannu, Djanaguiraman Maduraimuthu, Arul Loganathan and Krish K. Kumar have contributed to the supervision and validation of the study.

Data availability
No novel datasets were created for the current study. Data already available on Scopus database was used for the analysis.

Declaration of conflict of interest
There is no conflict of interest amongst the contributing authors.

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