sustainability

Review

Biofortification—Present Scenario, Possibilities and Challenges: A Scientometric Approach

Pooja Srivastav [1], Mahesh Vutukuru [2], Gobinath Ravindran [2,*] and Mohamed M. Awad [3,*]

1 School of Agriculture, SR University, Warangal 506371, Telangana, India
2 School of Engineering, SR University, Warangal 506371, Telangana, India
3 Mechanical Power Engineering Department, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt
* Correspondence: gobinathdpi@gmail.com (G.R.); m_m_awad@mans.edu.eg (M.M.A.)

Abstract: Biofortification refers to the process by which food crops are improved by the application of biotechnology, conventional plant breeding, and agronomic practices to increase the bioavailability of their nutritious components to human consumers. The biofortification of staple crops is a long-term, sustainable solution to address nutritional inadequacies. Thus, it is a practical and cost-effective way to provide micronutrients to communities that have limited access to various meals and other micronutrient therapies. Existing therapies, such as supplementation and industrial food fortification, which are insufficient to eliminate micronutrient deficiencies on their own, are complemented by biofortification. However, biofortification offers two substantial competitive advantages: the capacity to reach underserved rural communities and long-term cost-effectiveness. Biofortified crops can also be used to target rural populations with limited access to various dietary options or other micronutrient therapies. Hence, an attempt is made herein to provide an overview of the biofortification literature by employing scientometric and network analysis tools to examine records extracted from the Scopus database that were published between 2010 and 2021. This study investigates the most influential authors and journals, top-contributing institutions and countries, variations across publication years, co-occurrence analysis of keywords, and bibliographic coupling of sources. The results obtained through this study describe the real impact of the research published to date and its usage.

Keywords: biofortification; scientometric approach; iron deficiency

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1. Introduction

Ending all forms of hunger by 2030, as outlined in the United Nations' second Sustainable Development Goal (UN-SDG2), is a difficult but necessary endeavor, considering the short time remaining, the poor global health status, and the socioeconomic effects of hunger. Malnutrition is a grave issue on a global scale. About one-third of the world's population is affected by malnutrition or concealed hunger owing to micronutrient deficiencies, which significantly threaten economic growth [1]. Although the 1994 image of a dying child alongside a vulture waiting for food at a distance won the New York Times the Pulitzer Prize for Feature Photography, it also exposed the shocking reality of widespread global poverty, hunger, and unmet food needs. According to United Nations estimates, 821 million people worldwide were undernourished in 2018. Women and children are disproportionately affected by micronutrient deficiencies, which affect more than two-thirds of the world's population overall. There are 2 billion iron-deficient individuals [2], 2 billion iodine-deficient people, 150 million vitamin A-deficient people, and up to 3 million people in the world who are in danger of zinc insufficiency [3–5]. Thus, providing sufficient quantities of nutritious food is one of the 17 sustainable development goals outlined by the United Nations. The lack of essential nutrients, notably minerals such as iron (Fe), zinc (Zn), and vitamin A, is one of the main causes of "hidden hunger", especially in underdeveloped nations [6].

Nutritional insecurity is a huge hazard to the world's population, which is mostly dependent on a micronutrient-deficient cereal-based diet. Because of the poor overall quality of their diets, people often have several dietary deficiencies since these nutrient deficits are not mutually exclusive. The socioeconomic groups who are least able to achieve adequate dietary micronutrient intake are those who suffer the most. More than 1.3 billion people worldwide are estimated to rely on an income of less than USD 1 per day to exist [7]. These mineral deficiencies are more common in underdeveloped nations for this reason. By closely relating agriculture to nutrition and health, as well as by developing agricultural and nutritional practices and health policies that take this requirement into account, we can find sustainable answers to the problem of hidden hunger [8]. For healthy and productive lifestyles, humans need at least 49 recognized nutrients at regular and sufficient levels [9].

Until now, the primary goals of our agricultural system have been to boost crop productivity and grain yield, not to address human health. This strategy has caused a sharp increase in the lack of some micronutrients in dietary grains, which has increased nutrient deficiencies among consumers. Agriculture research in developing countries has increased calorically dense staple crop production and availability during the past 50 years, but not the production of non-staples high in micronutrients, such as vegetables, pulses, and animal products. It has become harder for the poor to afford a healthful diet due to the rising costs of non-essential goods [10]. Biofortification has been developed as a new technique for combating the widespread scourge of hidden hunger, whose root cause is the exclusive reliance on staple foods for nutrition. Biofortification promises improved nutritional accessibility to the public by overcoming many obstacles and meeting this need. This introduction outlines the various biofortification processes and their advantages and disadvantages [11,12].

1.1. Biofortification

Biofortification is the process of increasing the number of vitamins and minerals in a crop; it can be carried out via agronomic techniques, transgenic technology, or plant breeding. The most practical and sustainable method for addressing the nutritional issue is biofortification, which involves enhancing the nutrients in common foods. This method is likely to reach rural residents who have limited access to a range of dietary options or other micronutrient therapies by the use of biofortified crops. Around the world, initiatives to biofortify foods are concentrated on iron, zinc, selenium, and vitamin A in particular. These efforts attempt to supplement and, in some cases, replace chemical fortification or dietary supplements. Since 2003, many researchers and their collaborators have proven that this plant-breeding-based approach to alleviating vitamin deficits in agriculture is effective. More than twenty million farm households in developing nations already cultivate and consume biofortified foods. The main beneficiaries of biofortification are women and children, whose needs are particularly high and frequently unmet [13]. Farmers offer a solution via biofortification, which combines the micronutrient trait with other desired agronomic and consumer features. After meeting the family's dietary needs, surplus biofortified crops can be sold to rural and urban retail businesses.

1.2. Need and Demand for Biological Fortification

With regard to specific biofortification techniques, plant breeding can raise the micronutrient levels of plants. Micronutrients are another category of essential nutrients that the human body requires in very minute amounts. These consist of vitamin A, iron, zinc, copper, copper, manganese, iodine, selenium, molybdenum, cobalt, and selenium [14,15]. Numerous micronutrients control vital bodily and metabolic processes by working as cofactors for several enzymes in the human body [16]. The main source of nutrients for people is agriculture; cereals, which are a staple of the human diet, fall short of providing all the nutrients that are needed daily. Therefore, nutrient-poor agricultural goods cannot support healthy lives and may instead cause illness, an increase in the risk of morbidity and death, a fall in the socioeconomic development of a nation, impaired development, stunted mental and physical growth, and diminished livelihoods [17].

According to the United Nations' Food and Agriculture Organization, 780 million of the world's estimated 792.5 million malnourished people reside in developing nations [18,19]. As can be seen in Table 1, although most regions are on course or making progress toward reducing childhood stunting, far too many remain behind in meeting the other global nutrition targets, highlighting the need for increased urgency. While progress has been made in reducing wasting in Central and South America and the Caribbean, much more must be done in other regions where children continue to be at risk of this disease. Still a severe issue, the prevalence of child stunting has decreased in only a few places, despite widespread efforts to do so. The prevalence of childhood obesity is stagnating or even increasing in most places. The deterioration tendencies in East and Southeast Asia, as well as in Australia and New Zealand, are of particular concern. If we want to reduce the percentage of overweight children to below 3 percent, we must make real progress in this area. This would also help slow the worrying increase in adult obesity, which is a problem in every area of the world. Trends have either remained stable or deteriorated in every region except Central and South America or the Caribbean, making it clear that no region is on course to meet the targets for lowering anemia in women of reproductive age. Similarly, no region is on track to reduce the percentage of infants born with a low birth weight, according to the most recent estimates.

Table 1. Various forms of malnutrition and their progress in various regions [20].

	(Percent)								
	The Child Stunting		Child Overweight		Child Wasting	Low Birthweight		Anemia in Women of Reproductive Age	
	2012	2020	2012	2020	2020	2012	2020	2012	2020
World	26.2	22.0	5.6	5.7	6.7	15.0	14.6	28.5	29.9
Asia	28.1	21.8	4.9	5.2	8.9	17.8	17.3	31.1	32.7
Central and Southern Asia	39.2	29.8	3.1	2.7	13.6	26.4	25.5	47.5	47.5
Eastern Asia and Southeast Asia	16.0	13.4	6.5	7.7	4.1	8.0	8.0	18.2	19.5
Western Asia	17.8	13.9	9.0	8.3	3.5	10.0	9.9	31.7	32.5
Africa	34.5	30.7	5.0	5.3	6.0	14.1	13.7	39.2	38.9
Northern Africa	22.7	21.4	12.0	13.0	6.6	12.4	12.2	31.9	31.1
Eastern Africa	38.9	32.6	4.0	4.0	5.2	13.8	13.4	31.4	31.9
Middle Africa	38.0	36.8	4.4	4.8	6.2	12.8	12.5	46.1	43.2
Southern Africa	24.3	23.3	12.1	12.1	3.2	14.3	14.2	28.5	30.3
Western Africa	34.9	30.9	2.3	2.7	6.9	15.6	15.2	52.9	51.8
Caribbean	13.2	11.8	6.4	6.6	2.8	10.1	9.9	28.7	29.2
Central America	17.9	16.6	6.6	6.3	0.9	8.8	8.7	15.2	14.6
South America	10.2	8.6	7.7	8.2	1.4	8.6	8.6	18.4	17.3
Oceania	40.3	41.4	7.3	8.0	9.0	10.0	9.9	32.9	33.9
Australia and New Zealand	2.4	2.3	12.9	16.9	n.a.	6.2	6.4	7.6	8.8
Europe	5.3	4.5	9.6	8.3	n.a.	6.6	6.5	14.5	16.0
North America	2.8	3.2	8.8	9.1	0.2	7.9	7.9	9.9	11.7

n.a. indicates that the population coverage is under 50%.

Figure 1 states the need for biofortification for various reasons. Around 2 billion individuals worldwide experience "hidden hunger", which is brought on by a daily diet that is insufficient in vital micronutrients [21], despite increased food crop production. Half of all cases of anemia, which affects more than one-third of people worldwide, are brought on by nutritional deficiencies [22,23]. The lack of iron negatively impacts pregnancies, work ability, productivity, disease resistance, and cognitive development [24]. Women of reproductive age are among those most vulnerable to iron deficiency, with an estimated 44 percent of women in developing countries at risk or affected by iron deficiency anemia [25]. The children of mothers with anemia have low iron reserves, which causes them to need more iron than is provided by breast milk and stunts their growth [22]. The lack of zinc causes problems with learning, the immune system, and physical growth. It also results in poor DNA repair, which can increase the risk of developing cancer [3,26], as well as being directly related to the severity and frequency of diarrheal episodes, a major cause of child death [27].

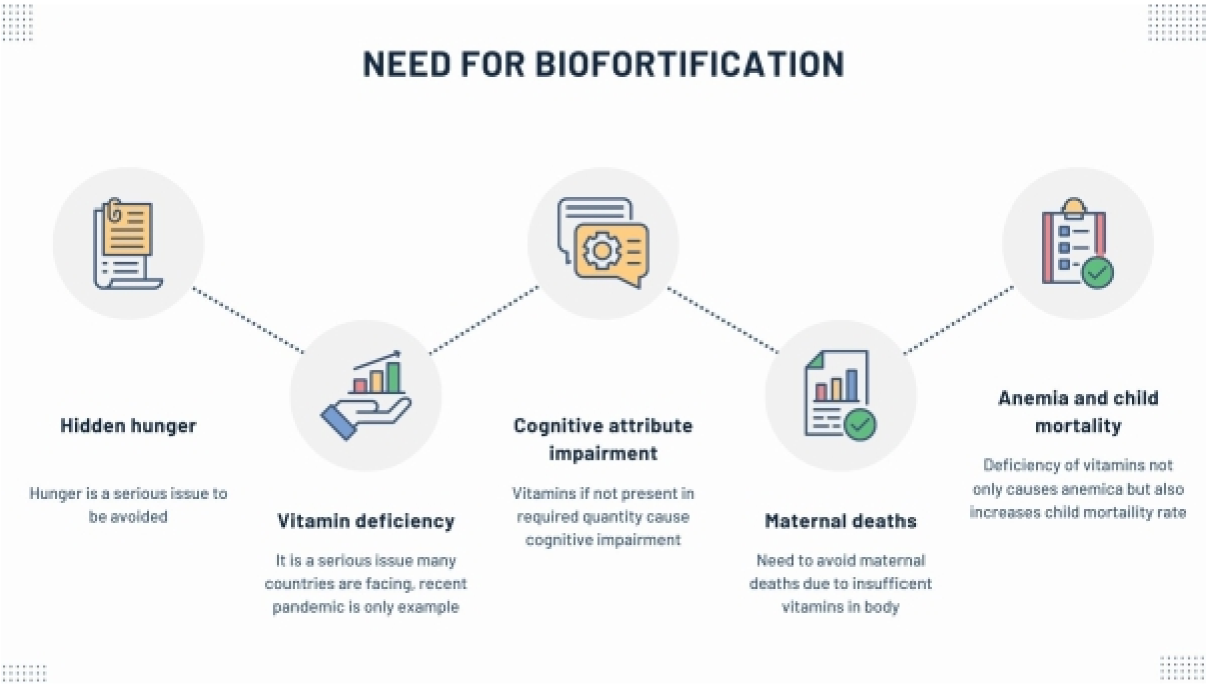

Figure 1. The need for biofortification.

Among the various vitamins and minerals that are considered essential for human health, the deficiencies of iodine (I), Fe, Zn, and vitamin A are the most widespread forms of micronutrient malnutrition (28). The deficiency symptoms and management of these four elements are mentioned in Table 2. The ability of erythrocytes to carry oxygen depends on iron, the core ion of hemoglobin. It also comprises the muscle protein myoglobin and several enzymes. Anemia, or a drop in hemoglobin levels in the blood, is caused by an iron shortage and impacts cognitive development, growth, and physical fitness. Worldwide, 38% of pregnant women and 43% of children under 5 have anemia. Additionally, low hemoglobin levels raise the risk of low birth weight and maternal death. Genetic predispositions, blood loss during menstruation, and illnesses such as malaria and other parasites all contribute to this effect [28].

A healthy immune system and good eyesight depend on vitamin A, the lack of which raises the risk of blindness, contributes to anemia development and is linked to higher rates of infection and infant death. Around 190 million preschoolers worldwide suffer from vitamin A insufficiency [28,29]. Iodine is necessary for the synthesis of thyroid hormones, and this requirement rises significantly during pregnancy and during childhood physical and cognitive development. Approximately 1.8 billion individuals globally do not consume enough iron in their diets. The insufficiency of iron is pervasive worldwide, except in nations where food is artificially enhanced with iodine [28,29]. The body requires about 300 enzymes that contain zinc for metabolic functions, RNA and DNA synthesis, and immune system function. Zn deficiency poses a serious threat to more than 17.3% of the world's population. A lack of Zn impairs the immune system, raises the chance of contracting infectious diseases and can harm a developing child, both during pregnancy and after birth [28,29].

Table 2. Reasons, symptoms, management, and prevention of the major micronutrient deficiencies, based on [28].

Nutrient	Specific Function	Reasons for Deficiency	Symptoms	Management and Prevention
Iron	Hemoglobin, various enzymes, myoglobin	Poor diet and elevated needs (e.g., while pregnant and in early childhood); chronic loss from parasitic infections (e.g., hookworms, schistosomiasis, whipworms)	Anemia and fatigue, impaired cognitive development, reduced growth, and physical strength	Foods richer in iron and with fewer absorption inhibitors, iron-fortified weaning foods, low-dose supplements in childhood and pregnancy, and cooking in iron pots
Iodine	Thyroid hormone	Except where seafood or salt fortified with iodine is readily available, most diets worldwide are deficient	Goitre, hypothyroidism, constipation, growth retardation, and endemic cretinism	Iodine supplements, fortified salt, and seafood
Vitamin A	Eyes, immune system	Diet poor in vegetables and animal products	Night blindness, xerophthalmia, immune deficiency, increased childhood illness, and early death, contributing to the development of anemia	More dark green leafy vegetables, animal products, fortification of oils and fats, and regular supplementation
Zinc	Many enzymes, immune system	Diets poor in animal products, and diets based on refined cereals (e.g., white bread, pasta, and polished rice)	Immune deficiency, acrodermatitis, increased childhood illness, early death, complications in pregnancy, and childbirth	Zinc treatment for diarrhea and severe malnutrition, and improved diet

Biofortification offers two substantial competitive advantages: the capacity to reach underserved rural communities and long-term cost-effectiveness. Compared with the ongoing costs associated with supplement and commercial fortification programs, plant breeding produces biofortified planting material, rich in micronutrients, that farmers can cultivate at nearly no marginal cost. Once created, nutritionally enhanced crops can be tested in different environments and areas and tweaked, increasing the initial investment's return. Once the micronutrient trait has been included in the fundamental breeding objectives of national and international crop development programs, agricultural research institutes incur few ongoing costs in terms of monitoring and maintenance.

Biofortified crops can also be used to reach rural people with limited access to diverse diets or other micronutrient therapies. Using the eating habits of women and children as a guide, target micronutrient values for biofortified crops can be determined. Biofortification provides farmers with a solution by merging the micronutrient features with other beneficial agronomic and consumer traits. After providing for the household's nutritional needs, extra biofortified crops can be sold at retail establishments in both rural and urban areas. Crops that are biofortified can enhance human nutrition. Nutritionists can study the preservation of micronutrients in crops under typical processing, storage, and cooking circumstances to show proof of nutritional value. This practice ensures that the target group's meals will still contain the right levels of vitamins and minerals [30]. Genetic variations in terms of retention and chemical concentrations that impede or enhance micronutrient bioavailability can be considered. Nutritionists also study how much of the nutrients inserted into crops are absorbed, but they must start with models before undertaking controlled human studies. The ability of biofortified crops to improve micronutrient status must be demonstrated by absorption, but the regular use of biofortified meals must directly quantify the status change. To determine the effects of biofortified crops on micronutrient status and the functional markers of micronutrient status, such as tests of physical activity and cognition for iron crops, and tests of visual adaptation to darkness for vitamin A crops, etc., randomized controlled effectiveness trials are conducted [31].

Biofortification breeding has necessitated the development or adaptation of cost-effective and rapid high-throughput analytical techniques for micronutrients, such as testing the mineral or vitamin contents of thousands of samples per season. Examples of these trait diagnostics include near-infrared spectroscopy (NIRS) and colorimetric carotenoid analysis methods. X-ray fluorescence spectroscopy (XRF) has become the method of choice for mineral analysis since it requires less pre-analytical preparation and permits non-destructive inspection [32,33].

1.3. Biofortification Approach

Current treatments, including supplementation and industrial food fortification, are not sufficient to fully correct vitamin deficits. Biofortification fills this gap. Three basic methods—transgenic, conventional, and agronomic—involve the use of biotechnology, crop breeding, and fertilization techniques, respectively, to biologically fortify vital micronutrients into agricultural plants, as shown in Figure 2. Plant breeding can raise the nutritional content of staple crops to the levels required for enhancing human nutrition without compromising yield or farmer-preferred agronomic features. The crop development process includes several steps, such as screening the germplasm for accessible genetic diversity, pre-breeding parental genotypes, creating and testing micronutrient-dense germplasm, undertaking genetic studies, and constructing molecular markers to lower costs and speed up the breeding process. Following the generation of promising lines, the resulting crops are tested under numerous target settings to determine the genotype x environment interaction (GxE), or the impact of the growing environment on micronutrient expression. The time that it takes for biofortified cultivars to reach the market has been sped up by robust localized testing. Based on the target populations' food consumption habits, anticipated nutrient losses during storage and processing, and estimated nutrient bioavailability, a team of nutritionists, food technologists, and plant breeders can define nutritional breeding goals by crop [34].

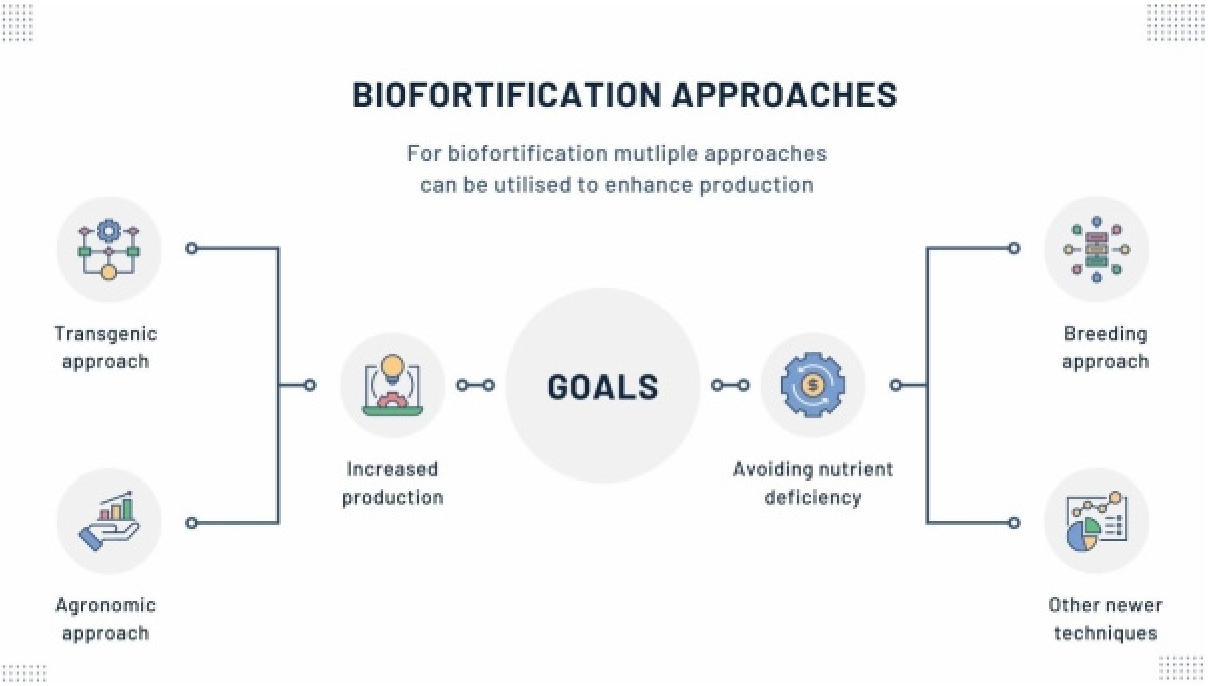

Figure 2. Different biofortification approaches to correcting nutrient deficiencies and improving yields.

Through improved fertilization in productive regions, agronomic biofortification can temporarily raise micronutrient levels. The most economical and straightforward method of biofortification is the application of fortified fertilizers enriched with micronutrients. However, the effectiveness of agronomical biofortification is largely dependent on soil composition, mineral mobility, and accumulation at specific places. Cost-effective but time-consuming, agronomic biofortification requires constant micronutrient administration to the soil or plants. The iron concentration in rice grains can be increased through biofortification by applying Fe foliar spray to rice crops [35]. Fertilization is one method of agronomic biofortification that can raise the food's levels of Fe, Zn, I, and Se. While deficiencies in Fe and Zn can be advantageous for both crops and consumers, deficiencies in I and Se have no negative effects on crop growth. The timing of foliar micronutrient treatment is found to be critical, in addition to the need to follow agronomic principles to maximize the micronutrient accumulation of Zn and Fe. Plant growth-promoting microbes can encourage plant growth as well as help to increase the movement of nutrients from the soil to the plant's edible parts. *Bacillus*, *Pseudomonas*, *Rhizobium*, and other species of soil bacteria can be employed to increase the phytoavailability of mineral elements [36].

The transgenic approach can be a viable option for developing biofortified crops when there is little to no genetic diversity in the number of nutrients available in different plant types [37]. It requires access to an endless genetic pool for the transfer and expression of desired genes from one plant species to another, regardless of their evolutionary and taxonomic status. Additionally, the only practical method for fortifying crops with a specific micronutrient when it does not naturally occur in them is through transgenic methods [38]. The creation of transgenic crops has depended heavily on the capacity to recognize and explain gene function and then use these genes to change plant metabolism [39]. High-lysine corn, soybeans with high levels of unsaturated fatty acids, cassava with high rates of provitamin A and iron content, and high-provitamin A golden rice are all successful instances of transgenic methods.

1.4. Compared Benefits of Biofortification

In comparison to many other methods for enhancing a person's nutritional condition, biofortification has an advantage because it targets the whole populace via staple foods. Many processed and fortified foods are out of the reach of the poor, and incorporating them into daily meals through alternative channels, such as free distribution, involves a number of challenges, including raising knowledge of nutrition, presenting the manufactured product, and putting it into practice (which might be a difficult undertaking if the community is uneducated, as it is in the majority of such cases). As opposed to other techniques of fortification or supplementation, the cycle will continue without much ongoing expenditure after the crop is introduced with a new genome. Once this occurs, the new genotype will also be present in its products and seeds. The yield is unaffected by fortified seed. As shown in Figure 3, it also offers major indirect benefits, such as disease-resistant plants and increased farm output. Combating the issue of malnutrition can be achieved by improving the nutritious content of daily foods, the quality of plants or crops, and the genetic variety.

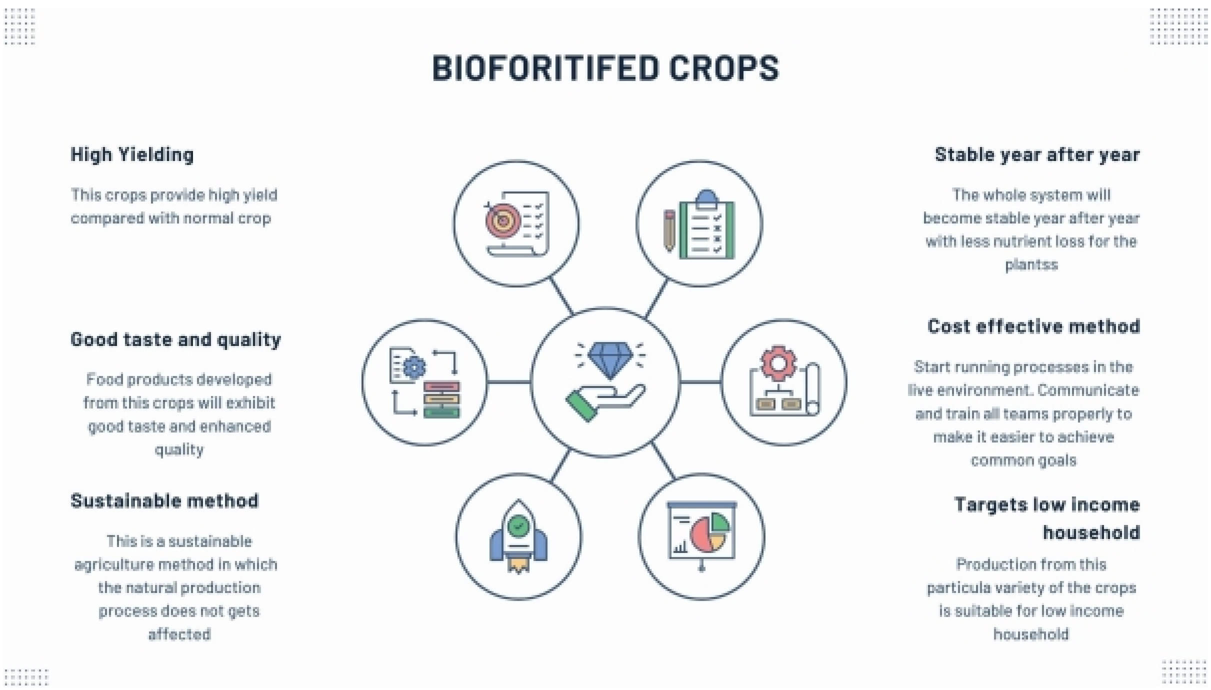

Figure 3. The benefits of biofortification.

1.5. Limitations

Although acceptability among the public is a common concern, the transgenic technique has outgrown the constraints of genetic variation in crops, a significant barrier in traditional breeding efforts. In order for farmers and the community to adopt biofortified crops, which may offer better quality, it is crucial that they do so. We take the Bt Brinjal as an example, which was created by the Indian seed business Mahyco but was not released in India because of safety concerns. The transgenic technique requires more work than breeding programs, and it has a very poor success rate in terms of cultivar release. This may be because it takes time to identify, modify, and express a particular target gene to understand its effects.

Agronomic biofortification is a widespread strategy; however, its rate of success is very unpredictable due to variances in the flow and storage of minerals in plants. It also changes depending on the varied soil types found in the various geographic regions [40]. This method is costly since it necessitates greater soil/plant input. Furthermore, there is no guarantee that the micronutrients will be concentrated in the plant's edible parts because this is not always the case. Therefore, the rate of success only applies to specific species of plants with particular minerals.

Long-term biofortification through conventional breeding is clearly successful, sustainable, and economical; however, there are drawbacks due to diversity in the plant gene pool for certain micronutrients. The lengthy process and labor-intensive effort required can be overstated. Other restrictions relate to managing crops after harvest and enhancing biofortification techniques. For instance, immediately after milling or polishing, the seeds of various cereal crops are typically ingested. Some minerals, including selenium and sulfur, are more abundant in the embryo, whereas iron, zinc, and copper are discovered to be more abundant in the bran portion [41,42]. As a result, grinding or polishing cereal grains significantly depletes a meal of minerals; the degree to which this depletion occurs depends on the genotypes of the cereal grains [41].

2. Methodology

2.1. Methods

The authors of this article employed scientometric analysis to study the publishing trends, research output, and publishing patterns related to biofortification. Scientometrics, a subfield of bibliometrics called scientific publication output analysis, analyzes the state of science and technology.

This tool can be used to place a country within a global context, an institution within a country, or a scientist within their professional community. Micro-studies (such as a specific institute's participation in publishing articles in a particular subject or field of science) and macro-analyses (such as a given country's proportion of contributions to the global output of scientific literature during a given period) can both use scientometric indicators [43]. Additionally, it is a technique that offers a scientific overview of the authors, countries, organizations, and collaborations that add to the body of knowledge on a worldwide scale [44]. A study was also conducted regarding the conceptual (co-occurrences of authors/keywords, theme progression), intellectual (co-citation network), and social (collaboration network) structures of the acquired data.

2.2. Database Selection

There are various databases that index and cite sources, and these databases span journals, books, reviews, and conference proceedings on a global and regional scale. Every database has its own approach, primary emphasis, and primary focus area. Because of its vast coverage of interdisciplinary domains, excellent coverage of citation reports, and availability of various analysis tools, Scopus was used to retrieve the current data [45,46]. With more than 80 million indexed items, Scopus is the most comprehensive data collection of peer-reviewed scientific literature in the world. Scopus is the most widely used database for bibliometric or scientometric research; hence, it is often used instead of various other databases (such as

Dimensions, Web of Science, PubMed, etc.). Additionally, Scopus has earned a reputation as a reliable and comprehensive bibliometric database for scholarly studies. It has been widely utilized by the academic community as a scientometric data source [47–49].

2.3. Search Query

To retrieve the scientometric data on biofortification, a search query was run in the main search interface of the Scopus database in the search field type: "Article Title, Abstract, Keywords." The search term was "biofortification" and was limited to these subject areas: agricultural and biological sciences, biochemistry, environmental science, chemistry, multidisciplinary, immunology, and microbiology. The search was conducted in July 2022, using the following search query:

TITLE-ABS-KEY ("*biofortification*") AND (LIMIT-TO (PUBSTAGE, "*final*")) AND (LIMIT-TO (AFFILCOUNTRY, "*India*" OR LIMIT-TO (AFFILCOUNTRY, "*United States*") OR LIMIT-TO (AFFILCOUNTRY, "*China*") OR LIMIT-TO (AFFILCOUNTRY, "*Brazil*") OR LIMIT-TO (AFFILCOUNTRY, "*Australia*") OR LIMIT-TO (AFFILCOUNTRY, "*Pakistan*") OR LIMIT-TO (AFFILCOUNTRY, "*United Kingdom*") OR LIMIT-TO (AFFILCOUNTRY, "*Italy*") OR LIMIT-TO (AFFILCOUNTRY, "*Germany*")) AND (LIMIT-TO (SUBJAREA, "*AGRI*") OR LIMIT-TO (SUBJAREA, "*BIOC*") OR LIMIT-TO (SUBJAREA, "*ENVI*") OR LIMIT-TO (SUBJAREA, "*CHEM*") OR LIMIT-TO (SUBJAREA, "*MULT*") OR LIMIT-TO (SUBJAREA, "*IMMU*")) AND (LIMIT-TO (DOCTYPE, "*ar*") OR LIMIT-TO (DOCTYPE, "*re*") OR LIMIT-TO (DOCTYPE, "*cp*")) AND (LIMIT-TO (PUBYEAR, *2021*) OR LIMIT-TO (PUBYEAR, *2020*) OR LIMIT-TO (PUBYEAR, *2019*) OR LIMIT-TO (PUBYEAR, *2018*) OR LIMIT-TO (PUBYEAR, *2017*) OR LIMIT-TO (PUBYEAR, *2016*) OR LIMIT-TO (PUBYEAR, *2015*) OR LIMIT-TO (PUBYEAR, *2014*) OR LIMIT-TO (PUBYEAR, *2013*) OR LIMIT-TO (PUBYEAR, *2012*) OR LIMIT-TO (PUBYEAR, *2011*) OR LIMIT-TO (PUBYEAR, *2010*)) AND (EXCLUDE (LANGUAGE, "*Chinese*") OR EXCLUDE (LANGUAGE, "*Portuguese*") OR EXCLUDE (LANGUAGE, "*German*") OR EXCLUDE (LANGUAGE, "*Spanish*")) AND (EXCLUDE (SRCTYPE, "*k*")).

2.4. Inclusion/Exclusion Criteria

The initial search retrieved 3864 documents. Limiting the search to the six subject areas mentioned in section below resulted in 3474 documents, representing 89.9% of the overall contribution in the field of biofortification. Limiting the publication period from 2010 to 2021, the publication stage to "final", and the publishing area to the top ten countries publishing articles in the field of biofortification retrieved 2149 documents. Finally, the search was restricted to using journal articles, review papers, and conference papers as sources. The language selected for the documents was English. After individually checking the titles, abstracts, and keywords of all admissible documents, 2065 records were removed from the initial search results of 4864 documents. The final 1799 records, which included 1471 articles, 299 reviews, and 29 conference papers, were all published between 2010 and 2021.

This paper presents a hybrid approach to systematically reviewing research on biofortification by integrating scientometric and complex network analyses. A description of the research process and the integration of analytical tools is shown in Figure 4.

2.5. Data Analysis

VOSviewer (version 1.6.15) was used to analyze the meaningful data from the 1799 documents yielded by the search, which were exported in the form of a (.)csv file from the Scopus database. Some fundamental tasks, such as learning about the publications and citation patterns, were carried out using the Scopus database itself. The relationships of co-authorship, bibliographic coupling, and co-citation were identified using the VOSviewer.

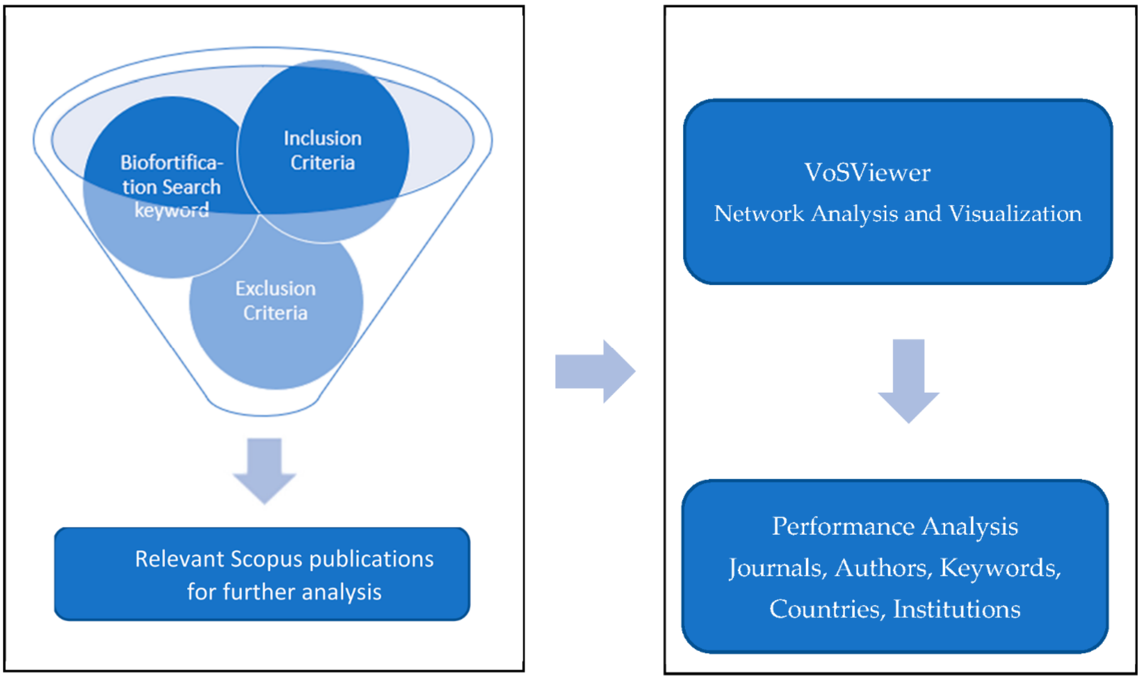

Figure 4. The general flowchart of literature analysis.

3. Results and Discussion

3.1. Research Productivity

The annual research output in the field of biofortification is shown in Figure 5, in terms of publications and citations. In 2010, the number of publications in the field of biofortification was only 38, and the corresponding citations numbered 56. Before 2010, only one citation appeared on this topic. The productivity of biofortification research gradually increased after 2010. The biggest rise was seen in the period from 2017 to 2021, when 70% of the publications were released. The year 2021 showed the most publications (N = 317) and the most citations (10,706).

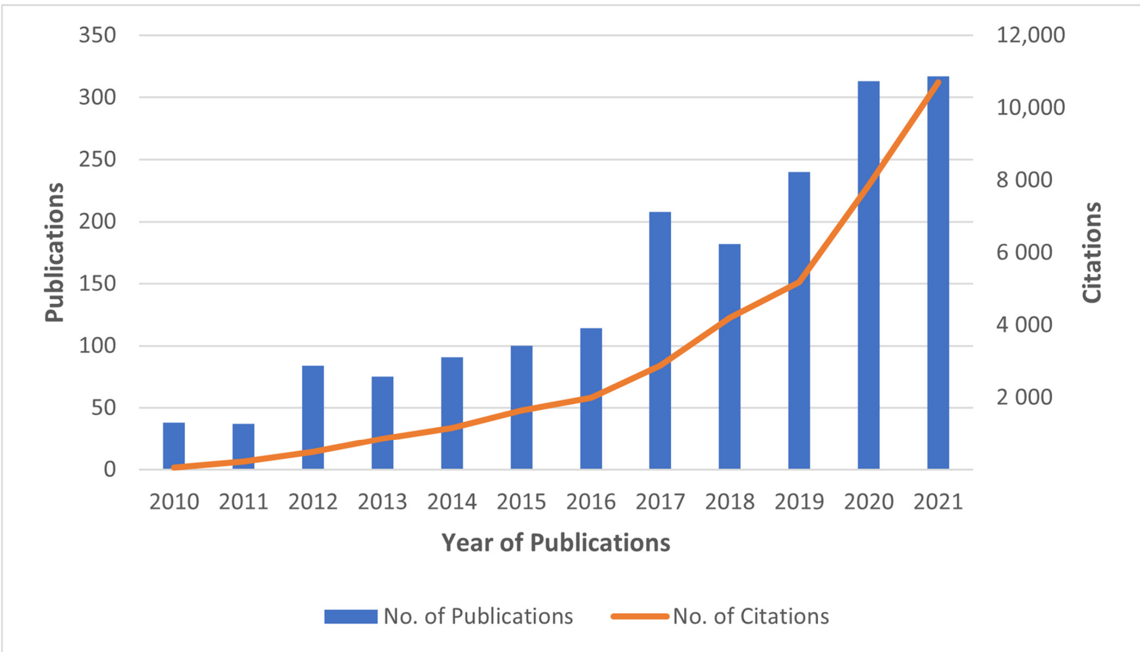

Figure 5. Publications and citation trends in biofortification from 2010 to 2021.

3.2. Leading Countries and Organizations

During the period from 2010 to 2021, 40 countries each published more than 10 research articles in the field of biofortification. Figure 6 shows the global geographic distribution of biofortification publications. India is ranked at the top, with 464 publications, closely followed by the United States, with 447 publications. China also contributed 328 articles during the above period. Together, these three countries accounted for 68.8% of all publications on biofortification in the world, showing that the three countries enjoy great research strength in the biofortification domain. Brazil, Australia, Pakistan, the United Kingdom, Italy, and Germany rank fourth to ninth, respectively, with publication numbers of between 100 and 200, indicating that these countries are relatively active in biofortification research. The attention paid to biofortification research in these locations needs to increase since 31 other countries from various regions of the world produced fewer than 50 or even fewer than 10 articles. Figure 7 shows the top ten countries in biofortification research productivity in terms of the number of publications.

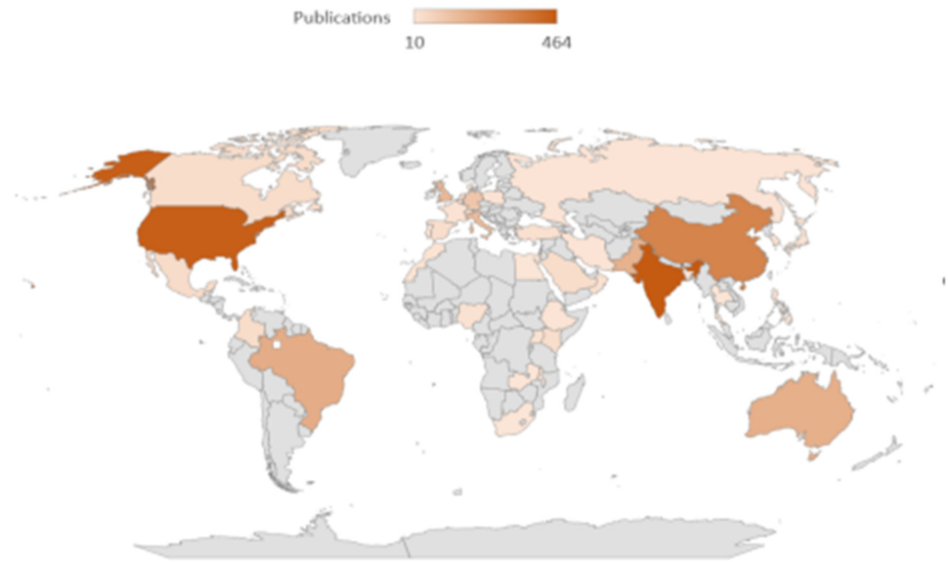

Figure 6. Global geographic distribution of biofortification publications.

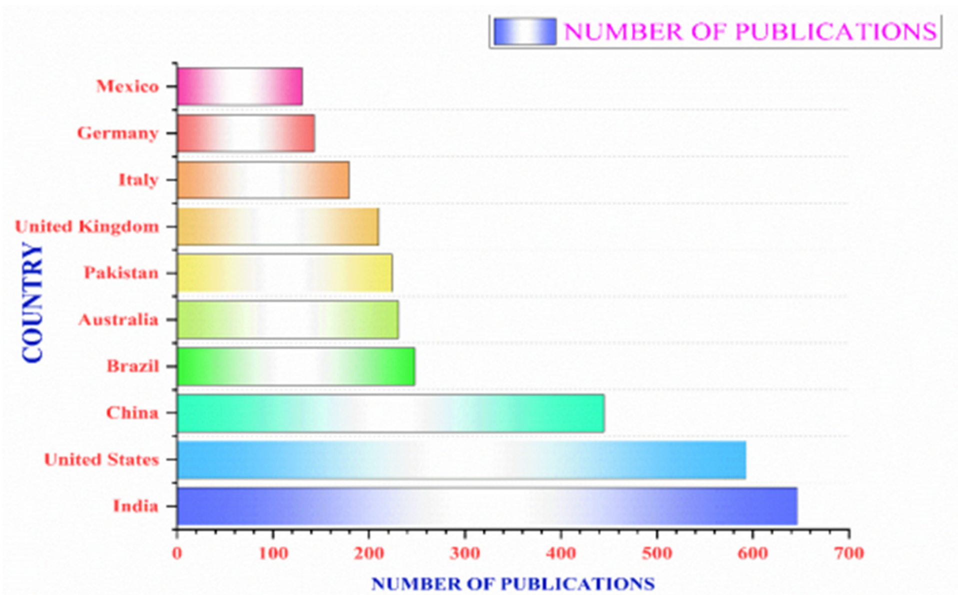

Figure 7. The leading countries in biofortification research.

In terms of the top 10 organizations publishing on biofortification, ICAR—the Indian Agricultural Research Institute, New Delhi—comes out on top, with 105 publications, closely followed by the University of Agriculture, Faisalabad, with 102 publications. The USDA Agricultural Research Service and the Indian Council of Agricultural Research are at rankings three and four, with 80 and 68 publications, respectively. The remaining six organizations contributed 321 publications in total. Of the 1799 publications in total during the period from 2010 to 2021, the top ten organizations contributed nearly 38%. Figure 8 shows the top ten contributing organizations in terms of biofortification research.

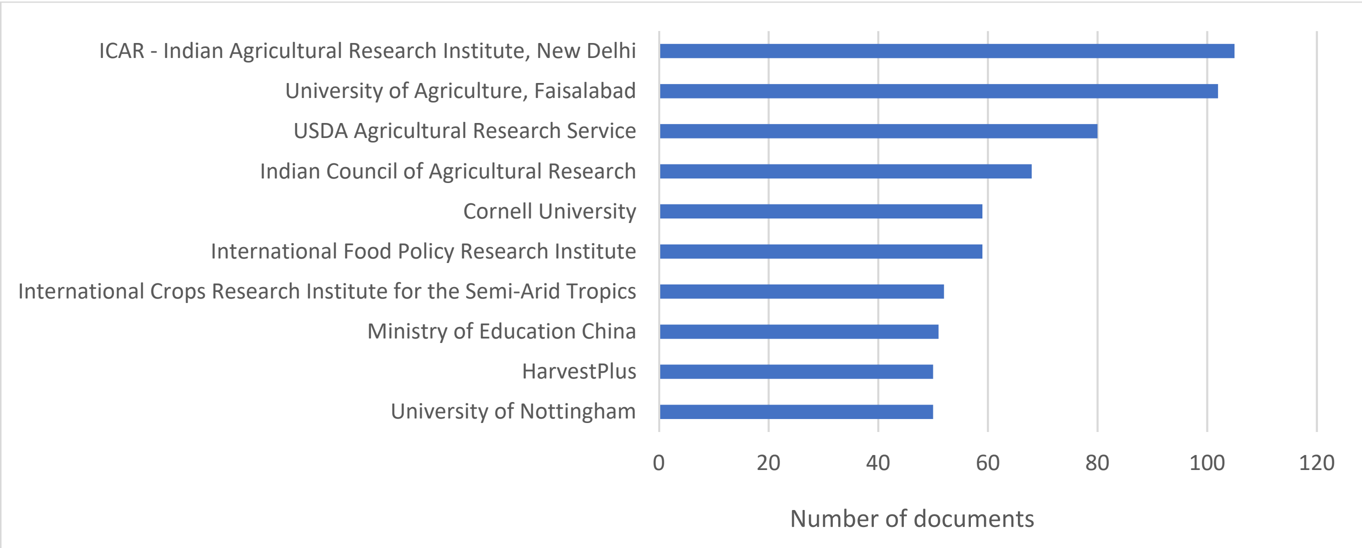

Figure 8. The leading organizations in biofortification research.

3.3. Most Productive Authors

Figure 9, below, shows the most productive authors in terms of biofortification research. The author, F. Hossain, affiliated with the Indian Agricultural Research Institute, India, produced 47 publications, with an h-index of 24. Three authors (M.R. Broadly, V. Muthusamy, and M. Farooq) produced 34, 33, and 31 publications, respectively. The other six authors comprising the top ten produced more than 20 publications each. The findings of the numerous authors as a whole indicate that this is a developing topic with the potential for major future investigation.

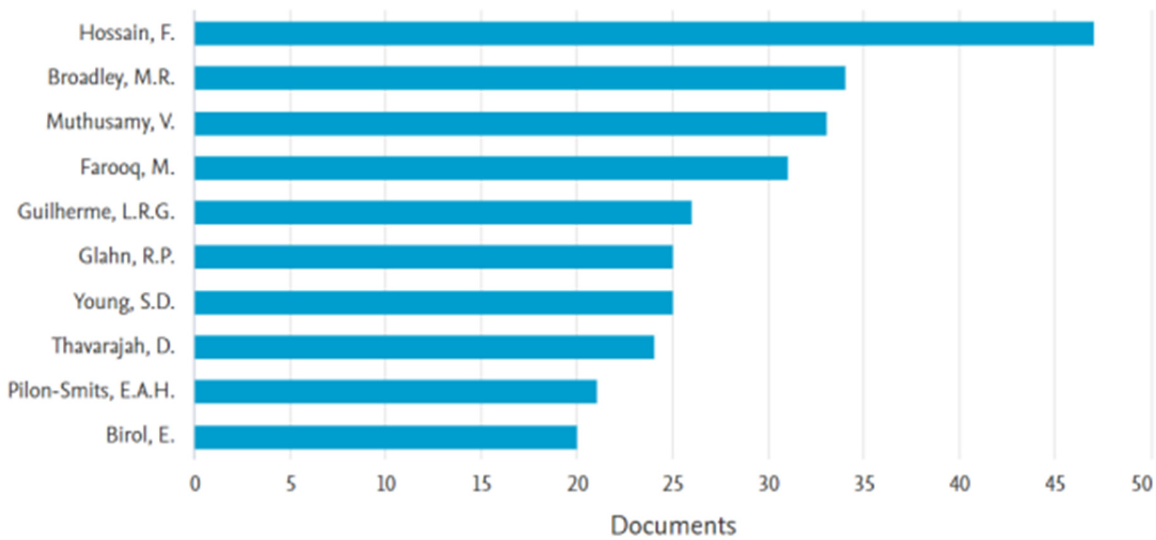

Figure 9. The most productive authors in biofortification research.

3.4. Most Influential Journals

Figure 10 shows the top ten scientific journals wherein articles on biofortification have been published. These ten journals generated 475 publications (26.4%), of which 272 were produced by four of those journals. *Frontiers in Plant Science* emerged as a top source with 98 publications, followed by *Nutrients* (68 publications), the *Journal of Agricultural and Food Chemistry* (54 publications), and *Plos One* (52 publications). Figure 11 shows high-productivity subject areas in which biofortification research was carried out. It can be seen that agricultural and biological sciences make the highest contribution, with 44%, followed by biochemistry, genetics, and molecular biology with 18% of articles, while environmental science occupies the third position, with 8% of articles.

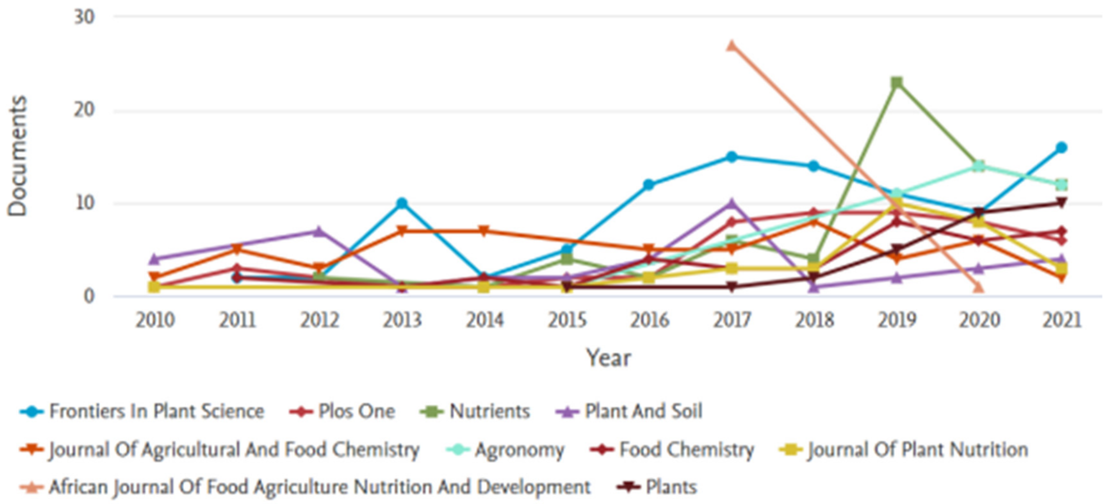

Figure 10. The top ten most influential journals in the field of biofortification.

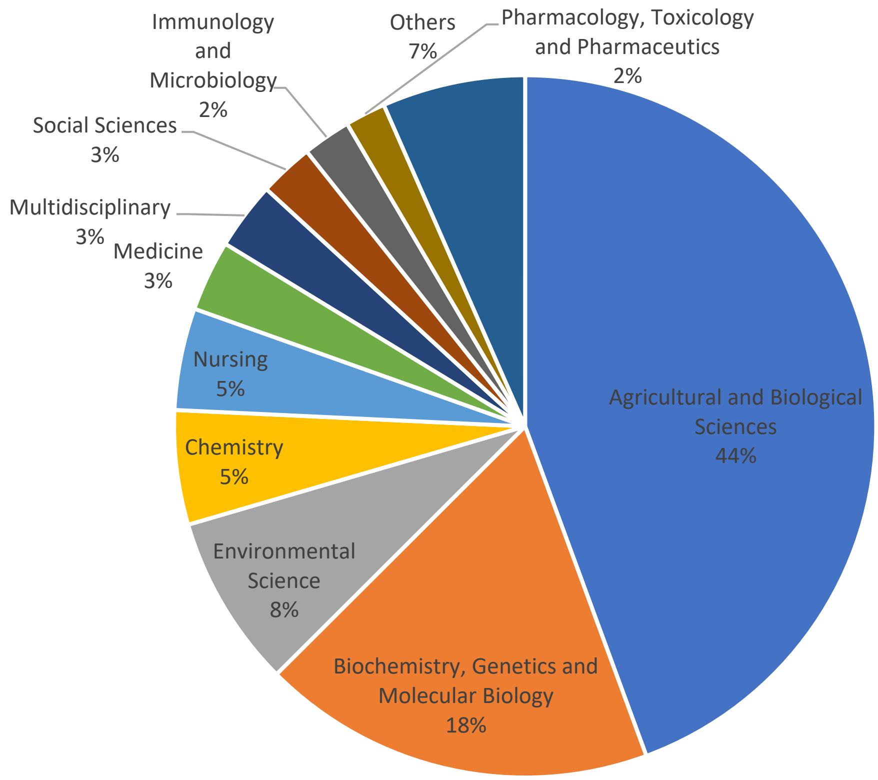

Figure 11. High-productivity subject areas in the field of biofortification.

Figure 12 shows the CiteScore of the top ten journals in the field of biofortification. Food chemistry consistently maintains a higher CiteScore compared to other journals since 2011 and had the highest CiteScore of 13.1 in 2021. The *African Journal of Food Agriculture Nutrition and Development* consistently maintained a lower CiteScore compared to other journals and had the lowest CiteScore of 0.7 in 2021. These results reveal the most prolific biofortification-related publication sources. Researchers and practitioners are hereby informed of the journals that they may wish to prioritize when retrieving the relevant information and publishing their findings.

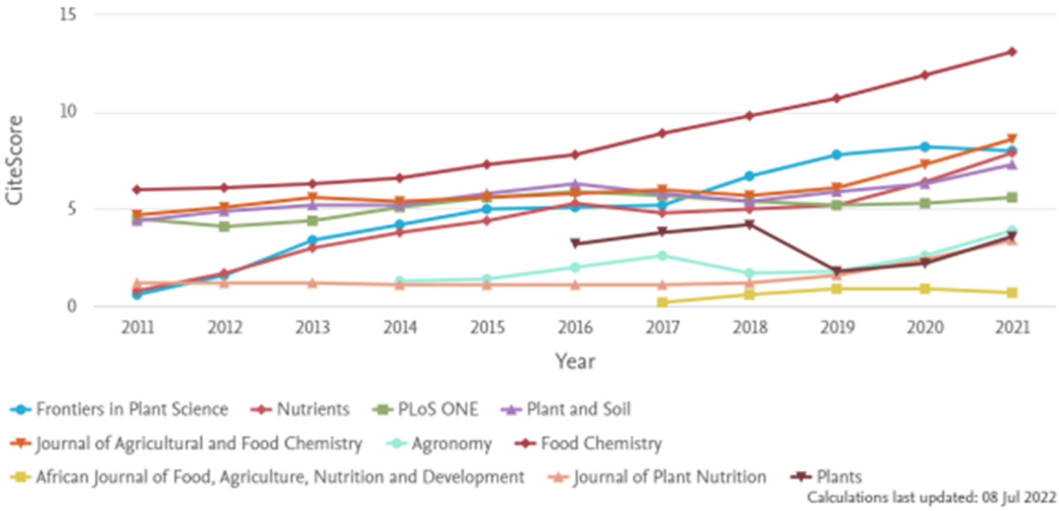

Figure 12. Year-wise CiteScore of the top 10 journals.

3.5. Keyword Co-Occurrences in Biofortification

The occurrences attributed in VOSviewer provide information regarding the total number of documents that include a certain keyword's frequency. Graphs that are referred to as co-occurrence networks are used to illustrate the frequency with which two keywords appear together. In the construction of a co-occurrence network, nodes or points are used to stand in for each variable. When two nodes are connected by a link, it indicates that each of those nodes contains the same keyword. A keyword network provides a distinct picture of a domain of research, making it easy to understand the topics that are discussed, as well as the ways in which they are connected to one another.

Table 3 and Figure 13 present the authors' keyword co-occurrences in the field of research on biofortification. Included were those keywords having at least 20 co-occurrences. Of the 3906 keywords, 34 met the threshold. The frequency with which nodes appear is proportional to their size. The lines connecting the nodes represent instances of these keywords appearing together in the same publication. The closer together the two nodes are, the more frequently those terms occur together.

Table 3. The top 20 keywords in biofortification research with a minimum of 20 co-occurrences.

Keyword	Frequency	Total Link Strength (TLS)	Keyword	Frequency	Total Link Strength (TLS)
Biofortification	755	868	Micronutrient	49	85
Zinc	187	421	Nutrition	50	81
Iron	137	326	Micronutrient deficiency	29	70
Wheat	99	181	Provitamin A	32	69
Rice	77	145	Phytic acid	37	65
Selenium	120	144	Carotenoids	44	55
Bioavailability	66	141	Vitamin A	23	51
Maize	76	140	Agronomic biofortification	47	48
Micronutrients	85	125	Pearl millet	22	47
Malnutrition	50	85	Phytate	23	47

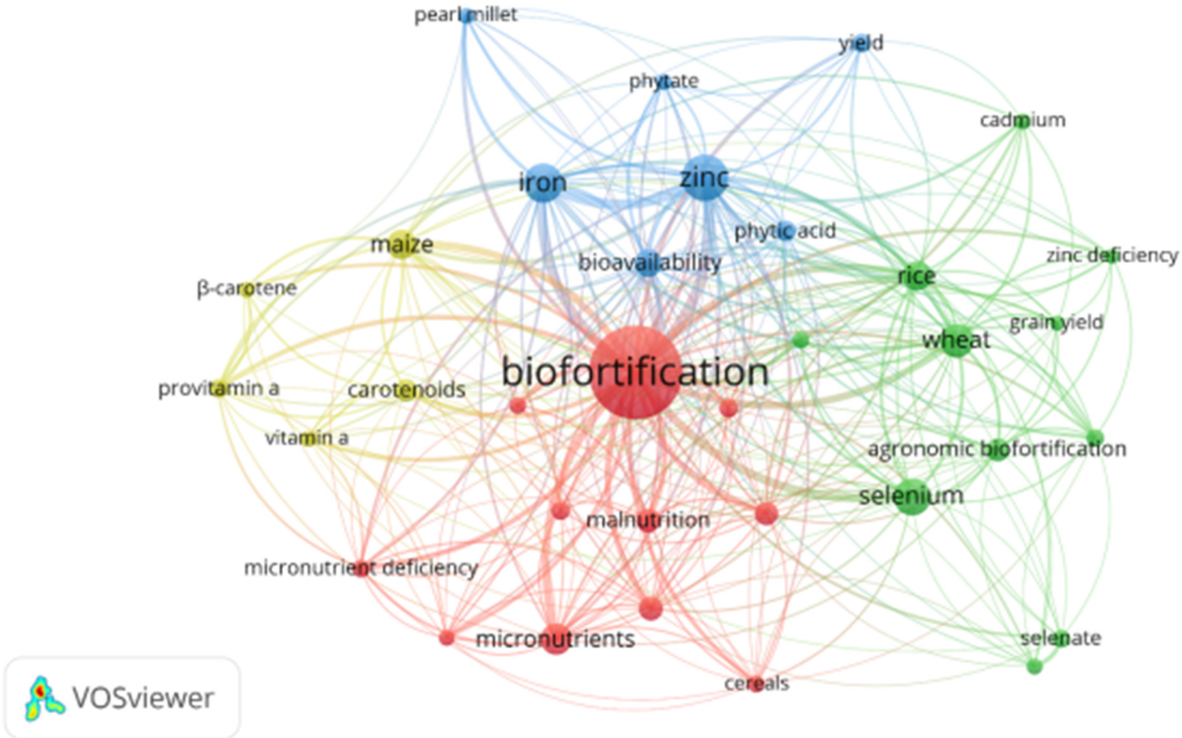

Figure 13. Author keyword co-occurrences in biofortification research.

This analysis shows that the top five keywords are biofortification, zinc, iron, wheat, and rice, with values of 868, 421, 326, 181, and 145 total link strength (TLS) of occurrences, respectively. Certain keywords (agronomic biofortification, pearl millet, and phytate) show a minimum TLS of less than 50 in this group. Four groups of closely connected terms are identified, and quantitative network indicators can be used to describe the relationships between the clusters. Cluster 1 includes the terms biofortification (the keyword with the maximum number of occurrences), breeding, cereals, fortification, hidden hunger, malnutrition, micronutrient deficiency, micronutrients, minerals, and nutrition. The other top keywords of zinc and iron are in cluster 3, whereas wheat and rice are placed in cluster 2.

3.6. Bibliographic Coupling of Sources

Journals are deemed to be bibliographically connected if they quote the same third publication, which is considered a measure of subject matter similarity among several publications. The bibliographic connection between a few chosen journals is shown in Figure 14. The circle's size and color correspond to different levels of bibliographic coupling and coupling clusters, respectively. Journals with a minimum of 20 publications and 50 citations were included. Of the 448 sources, 14 met the threshold. Quantitative network indicators can be used to describe the connections between clusters, which represent groups of journals with closely linked content. Using the VOSviewer, bibliographic couplings from biofortification articles were grouped into three groups and are shown graphically. Journals with the most active bibliographic coupling included *Frontiers in Plant Science* (98 documents, and 17,824 total link strength); *Nutrients* (68 documents, and 5137 total link strength); and *PLoS ONE* (52 documents, and 5490 total link strength value). All these three journals were placed in cluster 1.

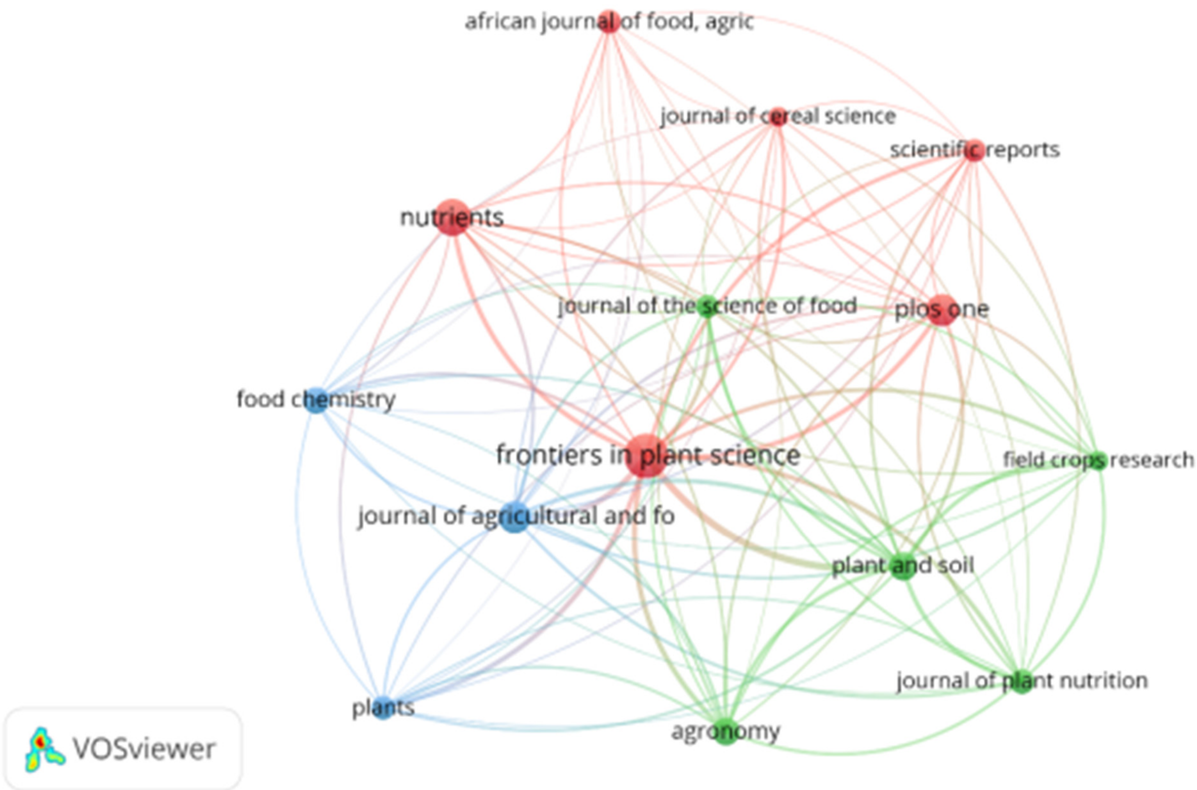

Figure 14. The bibliographic coupling of sources in biofortification.

3.7. Co-Citation Analysis of Cited References

In this section, 1799 biofortification publications from 2010 to 2021 are considered for a co-citation network of the cited references and are drawn using VOSviewer. The minimum number of citations of a cited reference is taken as 10. Of the 102,592 cited references, 110 meet the threshold. For each of the 110 cited references, the total strength of the co-citation links with other cited references is calculated. The cited references with the greatest total link strength are selected. Figure 15 shows the top 20 cited references. Co-Citation Analysis of cited references in biofortification were classified into four clusters with 6 cited references in cluster 1, followed by 5 cited references each in clusters 2 and 3. Cluster 4 has 4 cited references. It can be depicted from the figure that, most of the articles in the period of analysis, co-cited the article, "Enrichment of cereal grains with zinc: Agronomic or genetic biofortification?", authored by Ismail Cakmak in 2008 [50], published in the *Journal of Plant and Soil.* The article has 149 as the total link strength (TLS) and 134 citations among the top 20 cited references.

3.8. Co-Citation of Cited Sources

Figure 16 presents the co-citation network of sources in biofortification research. Sources with a minimum of 100 citations are included. Of the 23,198 sources, 153 meet the criterion. The top 20 sources were considered for representing a network through VOSviewer. It shows that the top five sources are *Plant Physiology* (citations: 1409, TLS: 36,187), *Plant Soil* (citations: 2506, TLS: 29,433), *Plant Cell* (citations: 900, TLS: 27,626), *Plant Physiology* (citations: 786, TLS: 20,312), and *Plant Journal* (citations: 608, TLS: 19,095) respectively. Sources are grouped into 2 clusters, with 11 sources and 9 sources, respectively, in cluster 1 and cluster 2.

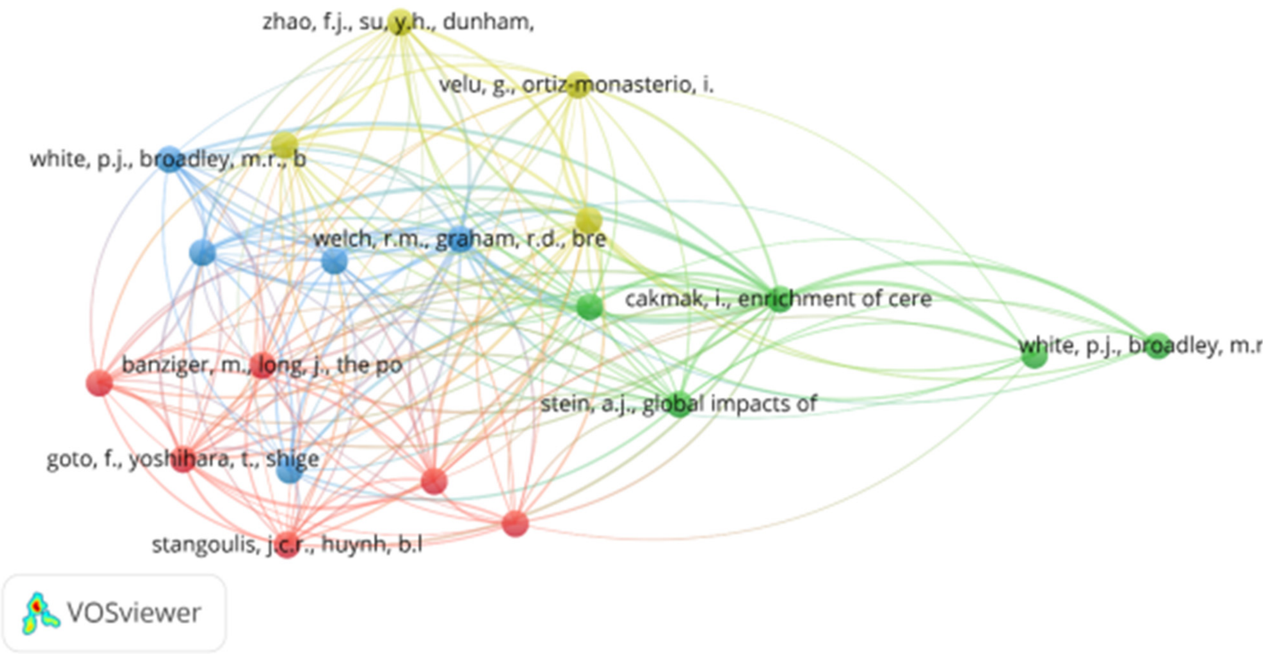

Figure 15. Co-citation analysis of cited references.

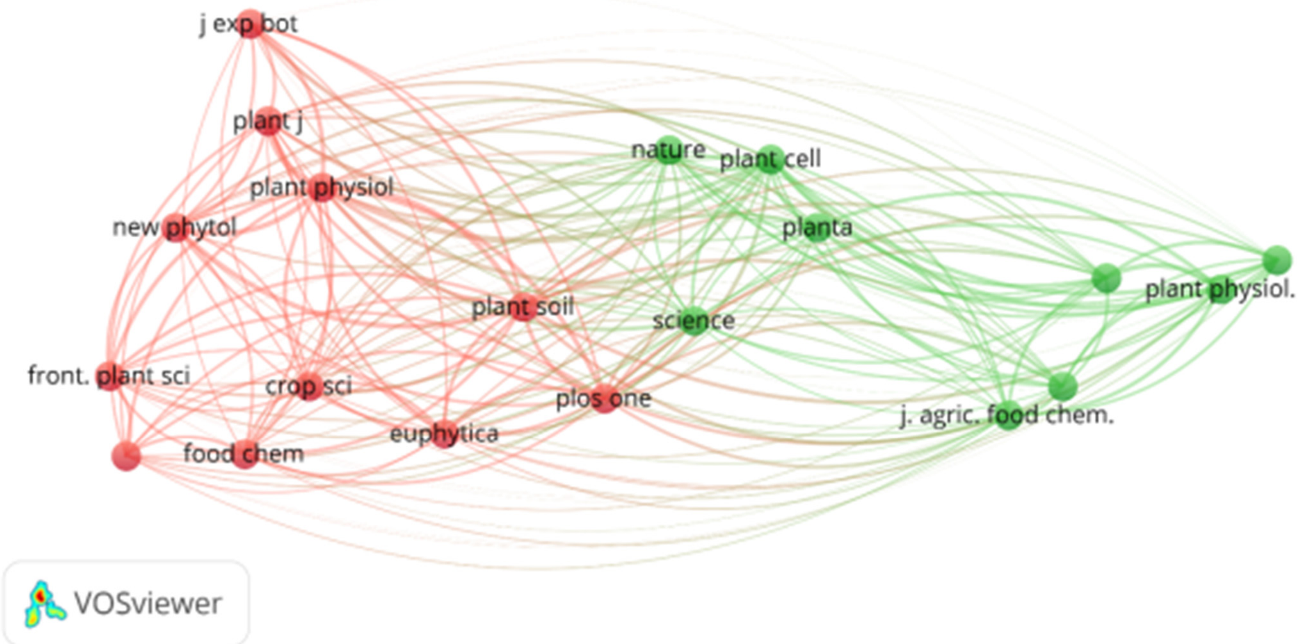

Figure 16. Co-citation network of cited sources in biofortification research.

4. Discussion

In this review, we analyzed the growing demand for biofortification in different parts of the world due to increasing micronutrient deficiencies, as the population of various countries grows and agricultural land is a limited resource that is being further degraded and becoming less fertile. Current food production is not sufficient to feed the growing population and what is provided lacks several micronutrients. Therefore, the need to address malnutrition with improved food quality has arisen. In this context, several solutions, such as supplementation, food fortification, diet diversification, and biofortification, have been put forth. Biofortification, as a ground-level task, i.e., improving the nutrient content directly in the plants, is considered the most efficient solution, as has now been recognized in this paper, based on a scientometric approach.

It is evident from our analysis, which shows an increasing trend in the number of publications and citations, that research into biofortification has gained importance in recent years. The highest number of publications is shown for those countries having larger populations, where malnutrition is a major problem, with India, the United States, and China accounting for 68.8% of the publications worldwide. India ranks highest, with the largest number of publications, and ICAR-IARI, in New Delhi, is the topmost organization in terms of increased research and articles. Many bio-fortified varieties have been released through conventional and transgenic approaches, as well as increasing the nutrient content of crops in farmers' fields, which were developed via agronomic biofortification, i.e., using organic and inorganic fertilizers. Among the various authors contributing to this research, F. Hossain, linked with IARI in Delhi, published 47 publications, followed by three authors in the range of 31 to 34 publications, indicating the potential of this topic for further investigation. *Frontiers in Plant Science* contributed 20.6% of publications in the top ten journals and emerged as the topmost scientific journal. Agricultural and biological sciences make the highest contribution of 44.4% in terms of subject area, followed by other categories of subject area. This indicates the importance of improving the nutrients in plants at the farmers' field level, rather than adding nutrients externally to the processed foods. When it comes to the CiteScore of top journals in this field, *Food Chemistry* is the journal maintaining a consistently higher CiteScore, followed by the *Journal of Agricultural and Food Chemistry*, *Agronomy*, etc. This data can be utilized by scientists to gather information, as well as when choosing journals for publication. The keywords, along with their co-occurrences as mentioned in Table 3, clearly indicate the frequency with which two words appear together; among the different keywords identified, "biofortification" is the topmost entry, followed by zinc, iron, wheat, and rice. The data regarding keyword co-occurrences will help the researcher to identify the potential areas of biofortification, nutrients to be improved, crops to be targeted, etc.

Thus, through this scientometric approach, researchers can plan their areas of work, identify the crops and nutrients to be targeted for biofortification, choose the institutions with which to collaborate, the journals and subject areas from which to access the relevant data, and any other information regarding research work. It also helps the researcher to target their publications to journals that may receive significant numbers of citations and that are viewed by many researchers related to the topic in question. They could also further investigate these areas and thereby contribute to improving the health of living beings, as well as eradicating the problem of malnutrition.

5. Conclusions

In this paper, the authors analyzed the research output of biofortification, employing scientometric analysis in which the patterns of publishing trends are mapped to measure research output. In this analysis, the scientometrics concept is used to establish research productivity and the leading countries and organizations that perform better in the field, most productive authors, most influential journals, most used keywords, citations, and sources for citations. For the full analysis, the Scopus database was used, and the data were collected in August 2022. A filtered search query was used to search the Scopus database using fixed inclusion criteria. The following results were obtained through scientometric analysis. In terms of research productivity, the number of publications before 2010 is far fewer and only one citation appeared on this topic. The publications gained momentum after 2017 and reached a maximum during 2020. The number of citations is greatest during 2021. India scored highest among the 40 nations, with the largest number of articles, followed by the United States and China, which together accounted for 68.8% of all publications worldwide. Six countries had between 100 and 200 publications, while the remaining 31 had between 50 and 100 or even fewer. The University of Agriculture, Faisalabad and Harvestplus have the fewest numbers of publications among the top 10 organizations in biofortification research, while ICAR in New Delhi has the most. The top 10 organizations were responsible for approximately 38% of all articles. F. Hossain, linked with IARI, Delhi, has produced the most publications among the top 10 writers, followed by three authors with roughly similar numbers of papers at between 31 and 34, and others with 20 and above. *Frontiers in Plant Science* supplied over 20% of articles in the top ten journals, which accounted for 26.4 percent of all publications in this discipline. *Nutrients* came in second, with a contribution of about 14 percent, and the *Journal of Plants* made the smallest contribution. Regarding the top 10 journals, the *Journal of Food Chemistry* consistently maintained the top spot with the highest CiteScore of 13.1 in 2021, followed by the *Journal of Agricultural and Food Chemistry*, while the *African Journal of Food Agriculture Nutrition and Development* contributed the least. With a total of 3906 keywords and a minimum of 20 times of author-keyword co-occurrences, the phrase "biofortification" is used the most frequently, with a TLS of 868, followed by the words "zinc" and "iron", which have TLSs of 421 and 326 respectively. The least frequent of the 20 co-occurrences is the word "phytate". Out of the 448 sources of journals with bibliographic coupling, 14 match the criteria, and Frontiers in plant science and Journal of nutrients are ranked top and second in terms of bibliographic coupling, respectively. Out of 102,592 referenced references, 110 matched the criteria for co-citation analysis; over this time period, Ismail Cakmak's (2008) [50] work obtained the most co-citations from authors. Plant physiology, plant soil, and plant cells are the top three of the top 20 sources for co-citation of referenced sources, with 153 of them meeting the requirement of at least 100 citations.

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