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Review

A Systematic Review on *Amaranthus*-Related Research

Muhali Olaide Jimoh [1,2,*], Kunle Okaiyeto [3], Oluwafemi Omoniyi Oguntibeju [3,*] and Charles Petrus Laubscher [1,*]

1 Department of Horticultural Sciences, Faculty of Applied Sciences, Cape Peninsula University of Technology, Symphony Way, Bellville, P.O. Box 1906, Cape Town 7535, South Africa
2 Department of Plant Science, Olabisi Onabanjo University, P.M.B. 2002, Ago-Iwoye 120107, Ogun State, Nigeria
3 Phytomedicine and Phytochemistry Group, Department of Biomedical Sciences, Faculty of Health and Wellness Sciences, Cape Peninsula University of Technology, P.O. Box 1906, Bellville 7535, South Africa; okaiyetok@cput.ac.za
* Correspondence: authors: moajay006@gmail.com (M.O.J.); oguntibejuo@cput.ac.za (O.O.O.); laubscherc@cput.ac.za (C.P.L.)

Abstract: Leafy vegetables promote reparation of energy loss due to oxidative stress, and they have the potential to alleviate hunger and malnutrition as well as other forms of metabolic imbalance ravaging the world. However, these vegetables are underutilized, despite the fact that they harbor essential minerals needed for critical cellular activities. As amaranth is one of the earliest vegetables reputed for its high nutraceutical and therapeutic value, in this study, we explored research on the *Amaranthus* species, and identified areas with knowledge gaps, to harness the various biological and economic potentials of the species. Relevant published documents on the plant were retrieved from the Science Citation Index Expanded accessed through the Web of Science from 2011 to 2020; while RStudio and VOSviewer were used for data analysis and visualization, respectively. Publications over the past decade (dominated by researchers from the USA, India, and China, with a collaboration index of 3.22) showed that *Amaranthus* research experienced steady growth. Findings from the study revealed the importance of the research and knowledge gaps in the underutilization of the vegetable. This could be helpful in identifying prominent researchers who can be supported by government funds, to address the malnutrition problem in developing countries throughout the world.

Keywords: amaranths; bibliometric; leafy vegetables; malnutrition; nutraceuticals

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1. Introduction

Hidden hunger (a form of undernutrition) can affect the immune system and make children and the elderly susceptible to different kinds of diseases [1–3]. In Sub-Saharan Africa, symptoms associated with macronutrient deficiencies include being underweight, overweight, child wasting, stunting, and homeostatic dysfunctions [4–6]. To combat these deficiencies, most developing countries and advanced nations have adopted various measures, such as sustained food supplementations for less privileged communities, expanding access to maternal and child healthcare, and extending social and agricultural incentives to enhance food production [6]. Despite these multimodal strategies, the number of households and communities faced with dietary challenges continues to rise.

Unfortunately, the most affected populations reside in local areas enriched with diverse vegetables [1]. Wild vegetables are the mainstay of dietary nutrients, and they are capable of addressing nutrient deficiencies ravaging the world [2,7–9]. Essential minerals (macronutrients and micronutrients) required for critical cellular activities and periodic reparations of damaged tissues are locked in plant tissues. Leafy vegetables facilitate the reparation of energy loss due to oxidative stress by trapping free radicals and their analogous biomolecules [10,11]. However, underutilization of leafy vegetables has resulted in proven evidence of metabolic imbalances, categorized as malnutrition, undernutrition, and stunting [6].

Amaranths are some of the earliest vegetables that have existed, globally, as grains, leafy vegetables, dye plants, ornamentals, and weeds, in tropical, subtropical, and temperate climates [2]. *Amaranthus* is a plant genus comprised of about 74 annual species, with a wide morphological diversity, distinctly characterized by monoecy and dioecy [12]. They are a promising group of plants that could deliver plant-based proteins, high-quality nutrients, unsaturated fatty acids, and other essential organic minerals derived from their leaves, seeds, and roots [13,14]. Amaranths adapt easily to adverse environmental conditions because they manufacture food through the C4 photosynthetic pathway [15]. They have evolved certain physiological characteristics that make them easily cultivated, allow them to survive attacks from pathogenic organisms, and enhance their phenotypic plasticity and genetic diversity [9,15,16]. Several bioactive compounds derived from the *Amaranthus* species have been reported on extensively in the literature. These include phenolic phytochemicals, lectins, anthocyanins, flavonoids, and antioxidant nutrients capable of entrapping free radicals that may impair the proper functioning of biological systems [17–22].

Commonly cultivated species of *Amaranthus* in Sub-Saharan Africa—for grain, leafy vegetables for human consumption and animal feed, treatment of chronic diseases, e.g., diabetes, hypertension, cardiac disorders, and other nutraceutical purposes—include *Amaranthus cruentus* L. [23–25], *Amaranthus caudatus* L. [14,21,23,26,27], *Amaranthus hypochondriacus* L. [28–30], *Amaranthus viridis* L. [26,31,32], *Amaranthus spinosus* L. [23,33–35], *Amaranthus muricatus* (Gillies ex Moq.) Hieron. [36,37], *Amaranthus dubius* Mart. ex Thell. [23,38,39], *Amaranthus tricolor* L. [23,39,40], *Amaranthus crispus* (Lesp. and Thévenau) A. Braun ex J.M. Coult. and S. Watson [41], and *Amaranthus tunetanus* Iamonico and El Mokni, a newly discovered amaranth species from Tunisia [42], among others.

The nutraceutical values of amaranths have been reported widely in scientific publications [13,15,21,43–45]. Findings from different experiments have indicated that *Amaranthus* has a higher proximate composition than commonly consumed food crops, such as corn (*Zea mays*), buckwheat, rye, and rice [15]; comparable nutritive characteristics to commonly patronized vegetables, e.g., spinach (*Spinacia oleracea* L.) [31]; equivalent nutrient content to some fodder crops, such as barley, maize, and wheat [46]; and is rich in extremely rare amino acids (e.g., lysine and tryptophan) that could replace animal protein and supplement human diets with moderate-quality amino acids [47,48]. Metabolic diseases, such as diabetes, ulcers, congestive cardiac, liver, and renal failure, cancer, helminthic infections, and most degenerative diseases, such as ageing hypertension, atherosclerosis, obesity, and being chronically underweight are induced by damages done to cells and tissues by free radicals [17,49–52]. Several species of *Amaranthus* are reported to play important roles in the regression of oxidative stress-induced disorders due to their ability to scavenge free radicals, thereby neutralizing their degenerating consequences [13,22,53–57].

New advances in bioremediation research suggest that the use of plant-based materials is efficient, with little or no adverse effects [58–61]. The use of plants to stabilize, degrade, and extract pollutants has become a safer, cost-effective, and complementary green technique compared to engineering-based approaches, as plant tissues serve as channels for uptake, chelation, and volatilization of pollutants [62–64]. It is also common knowledge that green plants sequester carbon dioxide and other gaseous biomolecules, bringing about non-invasive environmental clean-up [54,59,61,65]. Thus, several species of Amaranthaceae have been implicated in-efficient CO_2 sequestration and phytomining of heavy metals introduced into the environment due to natural processes or anthropogenic activities [34,60,66,67]. In some cases, tissues of some amaranth species have been regarded as phytorefineries of heavy metals capable of polluting the environment [34,38,60,68].

Based on the nutraceutical applications of *Amaranthus* spp., it is imperative to carry out a bibliometric analysis of this important group of plants, to harness the biological and economic potentials of the species documented in the literature throughout the past 10 years. The focus of this bibliometric study was to review the trends of research outputs on the *Amaranthus* species, as it is one of the world's earliest domesticated species [2,69].

The method of bibliometrics provides information on authors' citations and affiliations, and measures the relevance of scientific contributions to society in general and the academic community in particular [70,71]. This will help in the exploration of key research outputs on the *Amaranthus* species and identify areas with knowledge gaps on ethnobotany, cultivation, ethnopharmacology, biological activities, and medicinal applications of amaranths for human consumption and industrial use.

2. Materials and Methods

2.1. Data Collection

The Web of Science Core Collection (WoSCC) on the Web of Science (WoS) database was explored, as described by [72,73], to retrieve data on *Amaranthus* research from 2011 to 2020. The title search was selected and the keyword "(*Amaranthus** OR amaranth*)" was used to retrieve publications on the subject within the specified period. A total of 2017 documents were obtained (Figure 1). As the focus of the research was on research and review articles on *Amaranthus*, other document types (correction (13), letter (5), poetry (1), meeting abstract (87), proceedings paper (11), art exhibit review (4), retracted publication (1), early access (10), data paper (1), retraction (1), editorial material (29), news item (9)) were excluded, to arrive to 1845 documents. The target was on those documents written in English; non-English written documents were excluded from the results (1787 documents). Thereafter, the target of the search was on those documents in Science Citation Index Expanded (1656 documents); other documents were also excluded. Finally, the validation of documents was independently carried out by two of the authors (Kunle Okaiyeto and Muhali Jimoh); 7 documents that did not meet the selection criteria were further excluded. A total of 1649 documents were saved in BibTeX and tab-delimited formats for data analysis and data visualization, respectively.

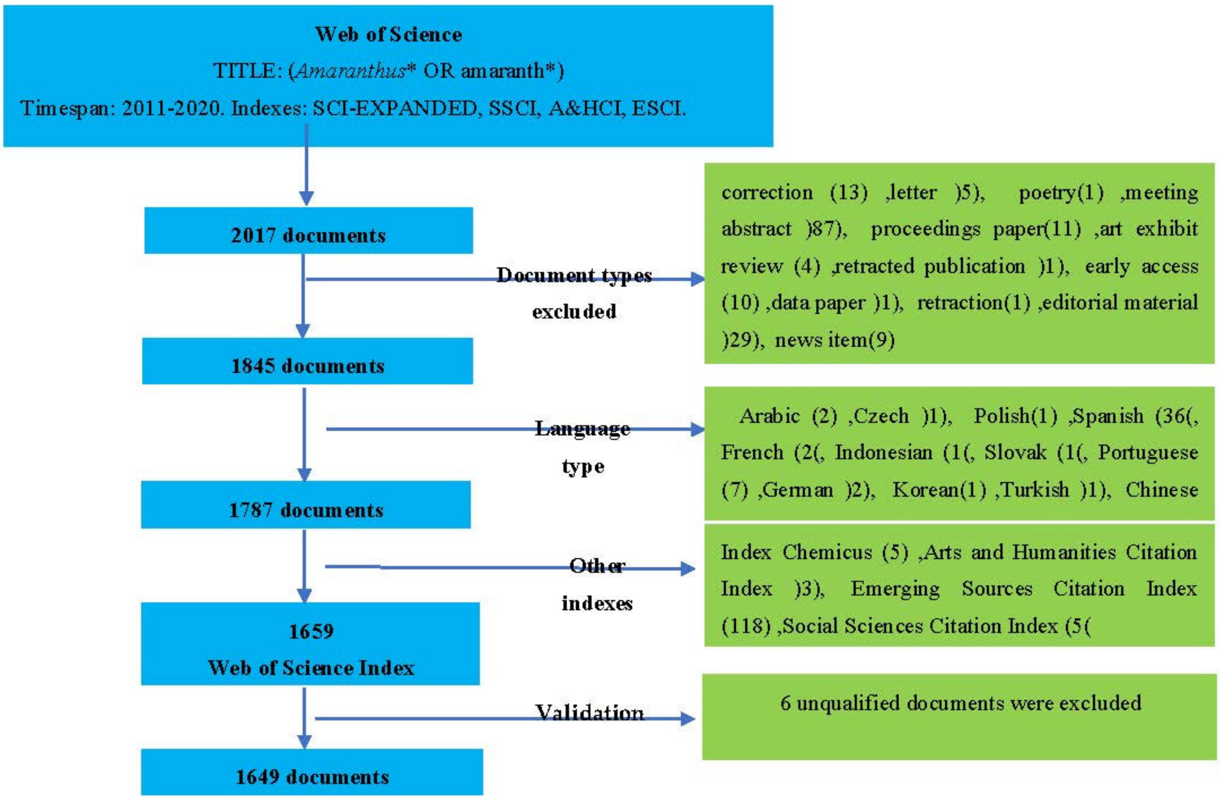

Figure 1. PRISMA flowchart of data collection from Web of Science Core Collection (WoSCC) on Amaranthus research from 2011 to 2020.

2.2. Data Analysis

As highlighted by the report of [74], "bibliometric analysis of literature may help to suggest new research directions or alternative research priorities". In the study, the retrieved data from WoS was imported to the biblioshiny package in the R-statistical tool [53]. Thereafter, analyses of the most relevant authors, documents, institutions, countries, citation analysis of the most cited authors, institutions, and countries were also carried out.

2.3. Data Visualization

Social mapping and data visualization are vital tools used to analyze the existing research collaborators in a particular field [75]. The data saved in tab-delimited format from WoS was imported to VOSviewer software (version 1.6.14) [76]. Thereafter, analyses on co-authorship authors, co-authorship institutions, co-authorship countries, co-occurrence author keywords, and author co-citation analyses were conducted.

2.4. Main Information

A total of 1649 published documents focusing on *Amaranthus* research was retrieved from the Web of Science repository between the years 2011 and 2020. These documents, authored by 5180 researchers, originated from 565 sources, comprising of 1612 research and 37 review articles. The average years from publication was 4.82 and average citations per documents was 12.4. These documents comprised 4096 keywords; the author keywords—4864. There were 34 authors of single-authored documents and 5146 authors of multi-authored documents. A collaboration index of 3.22 was observed among the authors; the authors per document—3.14, and the co-authors per documents—4.48.

2.5. Annual Scientific Production

In this section, the annual scientific production of *Amaranthus* research was evaluated over a ten-year period, from 2011 to 2020 (Figure 2). *Amaranthus* research experienced a steady growth in the number of publications over the years. The most productive year was 2019, with the highest number of articles (222) representing 13.5% of the total articles produced in a decade (2011–2020), while the least number of publications (106 articles) were recorded in 2011. From the year 2017, there has been a surge in amaranth-related research, with no less than 200 articles published annually. This affirms the general perception that attention has shifted to the use of plant-based natural products in the past decade with an emphasis on the amaranth species [56,77–81].

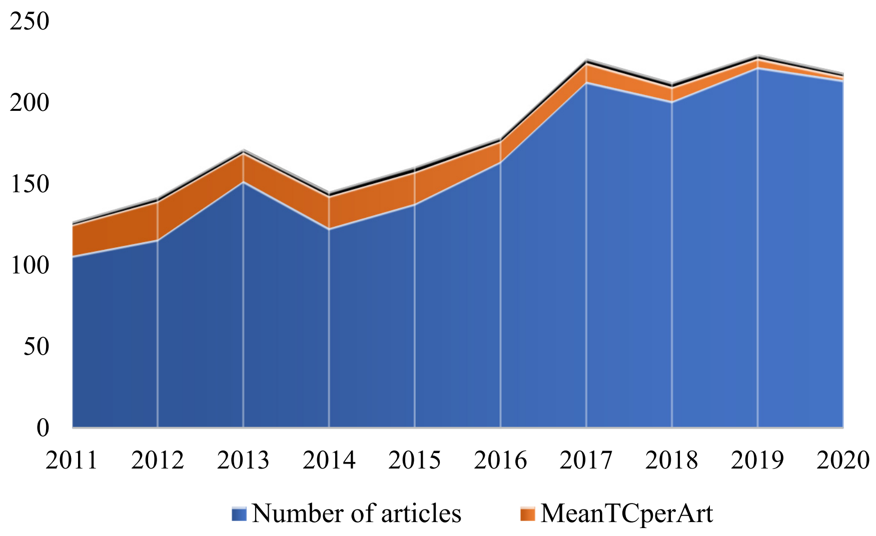

Figure 2. Annual scientific production on amaranths from 2011 to 2020.

2.6. Most Relevant Authors

Data retrieved from WoS showed that 5180 authors contributed to the production of 1649 scientific publications on the *Amaranthus* between 2011 and 2020. About 5146 articles, amounting to 99.3% of total publications extracted, were multi-authored, while 34 articles (0.7%) were published by single authors (Table 1). This may imply high collaboration networks among the authors with an analogous interest in amaranth-related research. The most prolific author was Norsworthy JK, with 34 articles, followed by Tranel PJ (29 articles), Oba S and Sarkar U (28 articles). The h-index is an important bibliometric indicator used to characterize the broad impact of an author's output and his/her relevance in the academic society [82,83]. According to [82], the inventor, h-index (Table 2) measures author productivity, using criteria such as "total number of papers", "total citations", "number of citations per paper", "number of significant papers", and "number of citations to each of the most-cited papers".

Table 1. Main information of global amaranth-related research from 2011 to 2020.

Description	Results
Timespan	2011:2020
Sources (journals, books, etc.)	565
Documents	1649
Average years from publication	4.82
Average citations per documents	12.4
Average citations per year per doc	2.029
References	47,877
Document types	
Article	1612
Review	37
Document contents	
Keywords plus (ID)	4096
Author's keywords (DE)	4864
Authors	
Authors	5180
Author appearances	7393
Authors of single-authored documents	34
Authors of multi-authored documents	5146
Author collaborations	
Single-authored documents	53
Documents per author	0.318
Authors per document	3.14
Co-authors per documents	4.48
Collaboration index	3.22

Keywords plus (ID), author's keywords (DE).

Table 2. A total of 20 leading authors on amaranth-related research from 2011 to 2020.

Author	Articles	h-Index	g-Index	m-Index	TC	PY-Start
Norsworthy, J.K.	34	13	23	1.18	601	2011
Tranel, P.J.	29	15	25	1.36	647	2011
Oba, S.	28	21	28	2.33	810	2013
Sarker, U.	28	20	28	2.86	795	2015
Iamonico, D.	25	10	14	0.91	226	2011
Jhala, A.J.	18	9	16	1.13	272	2014
Anon, M.C.	13	9	13	0.90	191	2012
Cristina Anon, M.	13	10	13	0.91	378	2011
Kruger, G.R.	13	8	13	1.00	216	2014
Park, Y.J.	13	5	7	0.46	64	2011
Singh, S.	13	7	12	0.64	225	2011
Steckel, L.E.	13	8	13	0.89	318	2013
Young, B.G.	13	7	13	0.78	179	2013

Table 2. *Cont.*

Author	Articles	h-Index	g-Index	m-Index	TC	PY-Start
Culpepper, A.S.	12	9	12	0.90	258	2012
De	12	5	8	0.46	69	2011
Gaines, T.A.	12	9	12	0.82	366	2011
Jennings, K.M.	12	4	7	0.44	54	2013
Wang, C.	12	7	10	1.17	107	2016
Bradley, K.W.	11	8	11	0.73	216	2011
Jugulam, M.	11	6	11	1.20	183	2017

Note: TC = total citations; NP = number of publications; PY = publication year; h-index = Hirsch index.

2.7. Most Relevant Institutions

Table 3 depicts the most relevant institutions on Amaranth research from 2011 to 2020. Out of the top 20, the University of Arkansas had the highest publications (94 articles) followed by the University of Illinois, with 93 published articles, both from the USA. Eleven (11) American Universities made the top 20 list. Some institutions from South Asia had high publication records (among the most relevant institutions) on amaranth-related research, whereas no African university made the top 20 list in the period under review. Findings from this analysis suggest that places of origin of most *Amaranthus* spp. (grain amaranth—native to Central and South America; *A. lividus*—central or south Europe; *A. tricolor*—southern China or India) do influence academic research and institutional publication records [2,84–86]. It may also indicate the dearth of research in African institutions or the lack of indexing of publications in renowned repositories, such as the Web of Science. This is a gap that needs to be filled by authorities of institutions in the African continent, so that the pharmacological potentials of these rich vegetables can be utilized maximally.

Table 3. Top 20 most relevant institutions on amaranth research from 2011 to 2020.

Affiliations	Country	Articles
University of Arkansas	USA	94
University of Illinois	USA	93
University of Nebraska	USA	67
Bangabandhu Sheikh Mujibur Rahman Agric University	Bangladesh	64
Universidad Nacional de La Plata	Argentina	59
Kansas State University	USA	55
North Carolina State University	USA	49
Instituto Politecnico Nacional	Mexico	35
University of Sao Paulo	Mexico	34
Mississippi State University	USA	32
Purdue University	USA	32
Islamic Azad University	United Arab Emirates	30
University of Georgia	USA	29
Institute of Botany	China	27
University of Western Australia	Australia	26
Colorado State University	USA	25
Jiangsu University	China	25

2.8. Twenty Topmost Journals

Of the most relevant journals that published amaranth-related research in the past ten years, *Weed Technology* and *Weed Science* recorded the highest publications with 97 and 83 articles, respectively, although the total citation was higher in the latter (1441 citations) than the former (1196 citations). Although total citations were comparatively high for *LWT-Food Science and Technology* (947 citations) and *Food Chemistry* (935 citations), the number of *Amaranthus*-related research articles published in the two journals (35 and 23 articles, respectively) from the years 2011 and 2020 were distantly low compared to that of *Weed Technology* and *Weed Science* (Table 4). It could also be inferred from this research that most amaranths are still regarded as weeds, given that at least two journals with a specific interest in weeds were most relevant in amaranth-related articles in the period under review. Nevertheless, no less than 11 food- and nutrition-based journals namely, *LWT-Food Science and Technology*, *Food Chemistry*, *Journal of Agricultural and Food Chemistry*, *Journal of Cereal Science*, *Journal of Food Science and Technology-Mysore*, *Plant Foods for Human Nutrition*, *International Journal of Food Science and Technology*, *Food Research International*, *Journal of Functional Foods*, and *Journal of the Science of Food and Agriculture* (Table 4) were captured in most relevant sources. The growing trend of research on the *Amaranthus* spp. In food- and nutrition-based journals suggests that more scientific investigations concerning the nutritional and medicinal use of amaranths are "coming through", and attention is shifting toward their applications as food supplements and pharmaceutical precursors [9,13,21,56]. This trend must be sustained in order to bring more of the amaranth species in the wild closer to people, and more research objectives should be redirected to dietary and pharmacological uses, as recommended by [9,15,87–90].

Table 4. Twenty of the top-most journals in amaranth-related research from 2011 to 2020.

Source	NP	TC	h-Index	g-Index	m-Index	PY-Start
Weed Technology	97	1196	19	29	1.73	2011
Weed Science	83	1441	24	34	2.18	2011
LWT-Food Science and Technology	35	947	18	30	1.64	2011
PLOS One	26	445	13	20	1.30	2012
Scientific Reports	25	405	12	19	2.00	2016
Food Chemistry	23	935	17	23	1.55	2011
Phytotaxa	22	123	6	10	0.60	2012
Frontiers In Plant Science	19	205	10	13	1.43	2015
Journal of Agricultural and Food Chemistry	19	498	13	19	1.18	2011
Pest Management Science	19	433	11	19	1.00	2011
Journal of Cereal Science	17	170	8	12	0.73	2011
Journal of Food Science and Technology-Mysore	17	145	8	11	0.80	2012
Plant Foods for Human Nutrition	17	263	9	16	0.82	2011
Mitochondrial DNA Part B-Resources	14	36	4	5	1.00	2018
Environmental Science and Pollution Research	13	102	7	9	0.78	2013
International Journal of Food Science and Technology	12	246	7	12	0.70	2012
Taxon	12	145	7	12	0.70	2012
Food Research International	11	189	8	11	0.89	2013
Journal of Functional Foods	11	142	6	11	0.67	2013
Journal of the Science of Food and Agriculture	11	142	8	11	0.80	2012

Note: NP = number of publications; TC = total citations; PY = publication year; h-index = Hirsch index.

2.9. Most Productive Countries

The highest citation metrics were recorded in publications from the USA, followed by India, China, and other countries that made the top 20 in citation metrics (Figure 3). The countries of origin of these amaranths led in the citation metrics, as obtained for the most relevant institutions, indicating that species biogeographic origin influences publication and citation records [86]. Furthermore, it has been reported that the personalities of the investigators or authors in the academic family, multiple data collections, external funding, and collaborative research across disciplinary, institutional, continental, or intercontinental boundaries, play key roles in publications [91–93]. The interactions of these factors, combined with the species' biogeographic origin, may have resulted in a high number of publications in countries such as USA, India, and China [86,91].

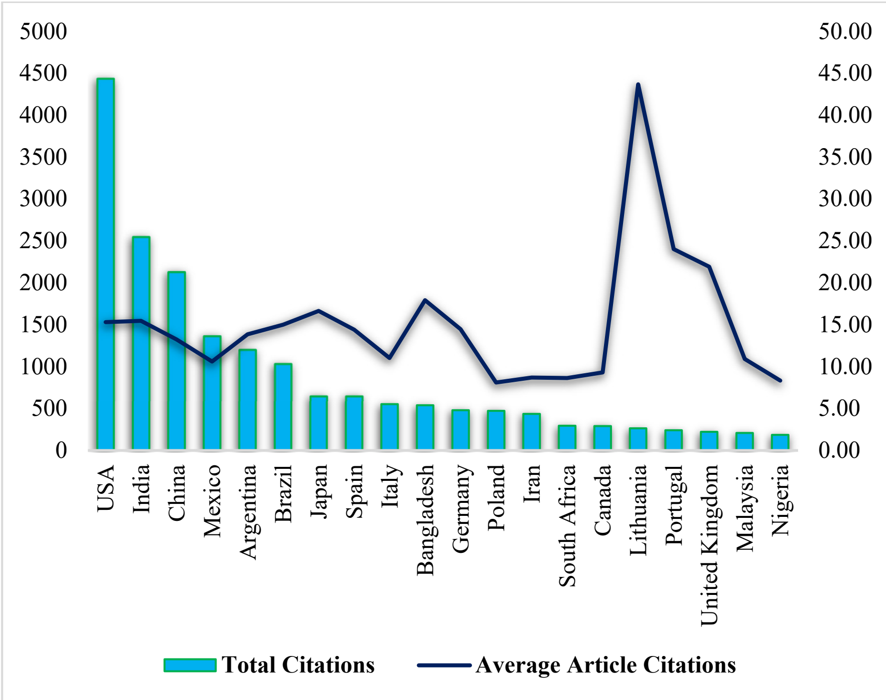

Figure 3. Countries' citation metrics on amaranth-related publications between 2011 and 2020.

2.10. Data Visualization

Co-Authorship Authors

Co-authorship authors were analyzed using VOSviewer to investigate the social network that existed among the authors on the subject. In this section, the fraction counting method was chosen, 25 was designated as the maximum number of authors per document, and their initials replaced the first names of the authors. Thereafter, 5 was chosen as the minimum number of documents per author, to find the prominent authors; only 179 out of 5232 authors met the threshold. Out of 179 authors, the total strengths of the co-authorship links with other authors were calculated and the authors with the greatest total link strengths were selected. The top five authors were Tranel PJ (36 documents, 860 citations, 29 links, and 33.00 total link strength), Sarker U (28 documents, 795 citations, 27.00 total link strength), Norsworthy JK (36 documents, 615 citations, 17 links, 26.00 total link strength), Oba S (28 documents, 810 citations, 26.00), Jhala AJ (21 documents, 320 citations, 21.00). From these results, it is interesting to note that the Tranel PJ and Norsworthy JK had the highest number of documents (36) with different citations, whereas Sarker U and Oba S had the same number of documents (28) but with different citations. The variations in the documents and citations attributed to each author depended on several factors that influenced research outputs [70]. Subsequently, out of 179 items, only 103 items comprised the largest network (Figure 4a); similarly, the density visualization was displayed (Figure 4b). The dimensions of the circles are an indication of the number of documents associated with each author [94]. The shorter the line between two items, the closer the relationships between the authors in terms of collaboration. In addition, the thickness of a line represents the scale of collaboration between the authors [95]. In this study, 103 items displayed were grouped into 10 clusters of different colors with an overall connection of 369 links and a total link strength of 384.00. This analysis shows that the most productive author, Tranel PJ, had the strongest link, indicating that this researcher might be the pioneer on the subject. In regard to the clusters—cluster 1 had the highest with 19 authors followed by clusters 2 and 3 (12 authors) and clusters 4 and 5 (11 authors), cluster 6 (10 authors), cluster 7 (9 authors), cluster 8 (8 authors), cluster 9 (7 authors), and cluster 10 (4 authors). The bar indicator in Figure 5a represents the year of active research with different colors. Research collaborations bring about an increase in outputs, an exchange of ideas and skills, division of labor, and funding [96]. Authors with more collaborations tend to have higher research outputs than those with low collaborations. Interdisciplinary collaborative research potentially leads to high-quality scholarly productivity [97,98] as it usually brings highly skilled scholars with vast experience together to undergo quality research and co-author publications [99].

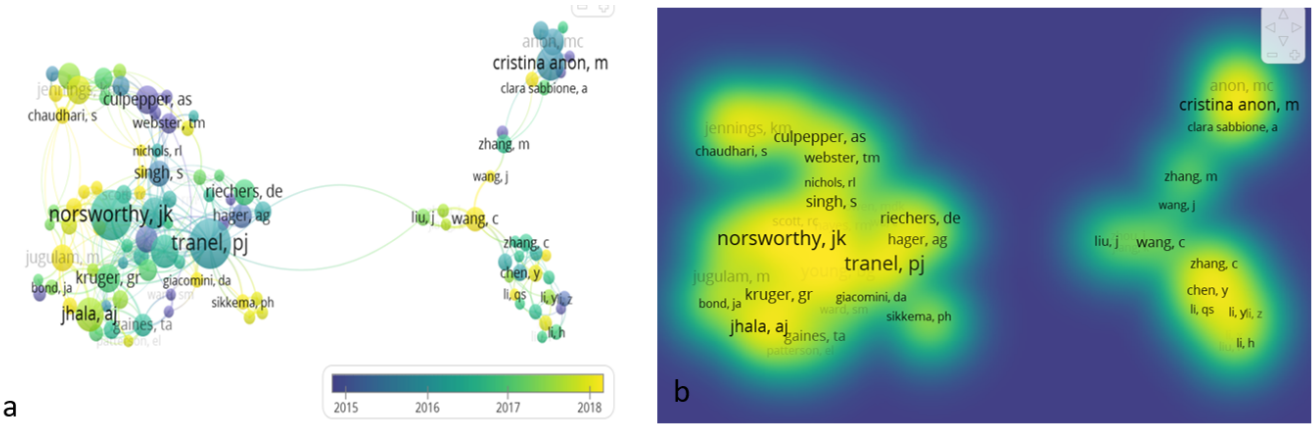

Figure 4. "Co-authorship" authors on *Amaranthus* research. Overlay visualization (**a**), density visualization (**b**). Co-authorship institutions.

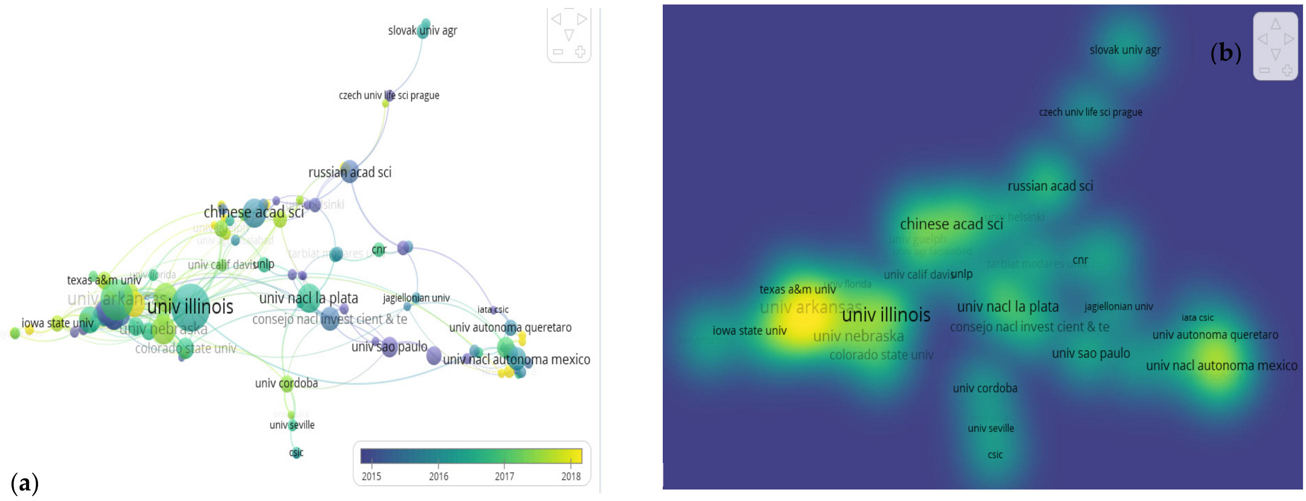

Figure 5. Co-authorship institutions on *Amaranthus* research overlay visualization (**a**), density visualization (**b**). Co-authorship countries.

In this section, we investigated the collaboration that existed among the institutions of the corresponding authors using VOSviewer. Fractional counting was selected and 25 was set as the maximum number of institutions per document. Five was set as the minimum number of institutions per document and 135 met the thresholds out of 1633 institutions. The total strength of the co-authorship links with other institutions was calculated and the institution with the greatest total link strength was selected and displaced. The top five institutions were the University of Illinois (with 55 documents, 1221 citations, 32.00 total link strength), Bangabandhu Sheikh Mujibur Rah (28 documents, 795 citations, 26.00 total link strength), Gifu University (29 documents, 812 citations, 26.00 total link strength), University of Arkansas (45 documents, 780 citations, 25.00 total link strength), and the U.S. Department of Agriculture—Agricultural Research Service (USDA-ARS) (28 documents, 725 citations, 23.00 total link strength). It was observed that some institutions were not connected, and the largest set of connected institutions were 103 out of 135, as depicted in Figure 5. We categorized the 103 institutions into 14 clusters, which are represented in different colors. Cluster 1 comprises 13 institutions, clusters 2, 3, and 4 (11 institutions), cluster 5 (9 institutions), clusters 6, 7, and 8 (8 institutions), cluster 9 (7 institutions), clusters 10 and 11 (5 institutions), cluster 12 (4 institutions), and clusters 13 and 14 (2 institutions). Overall, the 103 institutions had 296 links with a total link strength of 351.00. The University of Illinois belonged to cluster 3 and had the highest number of documents (55) with 25 links and a total link strength of 35.00, followed by the University of Arkansas in the cluster group with 45 documents, 20 links, and a total link strength of 25.00 (Figure 5). The size of the circle reflects the average number of documents associated with the institution and the length and thickness of the lines between the two institutions show their collaboration [72]. Institutions with more collaborations had higher research outputs than those with low collaborations.

We analyzed the collaboration network that existed among the countries involved in *Amaranthus* research in this section using a fractional method from VOSviewer. Five were set for the minimum number of documents of a country and 59 met the thresholds out of 93 countries (Figure 6). The top five countries in term of total link strength were the USA (350 documents, 5347 citations, 91.00 total link strength), Spain (70 documents, 926 citations, 52.00 total link strength), Mexico (145 documents, 1788 citations, and 50.00 total link strength), China (178 documents, 2310 citations, 47.00 total link strength), and Japan (69 documents, 1196 citations, 41.00 total link strength). In terms of citations, the top five countries with the highest citations were the USA (it had the highest), followed by India, China, Mexico, and Argentina. The largest set of connections that existed among 58 out of 59 countries are represented in Figure 6. Overall, these countries are grouped in eight different clusters with 274 links and 440 total link strengths. Cluster 1 comprised 11 countries, cluster 2 (10 countries), cluster 3 (9 countries), cluster 4 (8 countries), clusters 5 and 6 (6 countries), cluster 7 (4 countries), and cluster 8 (4 countries). The USA dominated the research, with the highest number of links, as well as several powerful countries across the globe (Figure 6). For example, the USA belonged to cluster 5 with 34 links and a 91.00 total link strength, while Spain had a total link strength of 52.00. Overall, the research tends to be dominated by authors within the country; that is, the collaborations of authors are among authors from the same country as compared to multiple-country collaborations. Researchers from the USA, India, and China dominated the field because they are the world research scholars, and the governments of these countries support research immensely with funding [70].

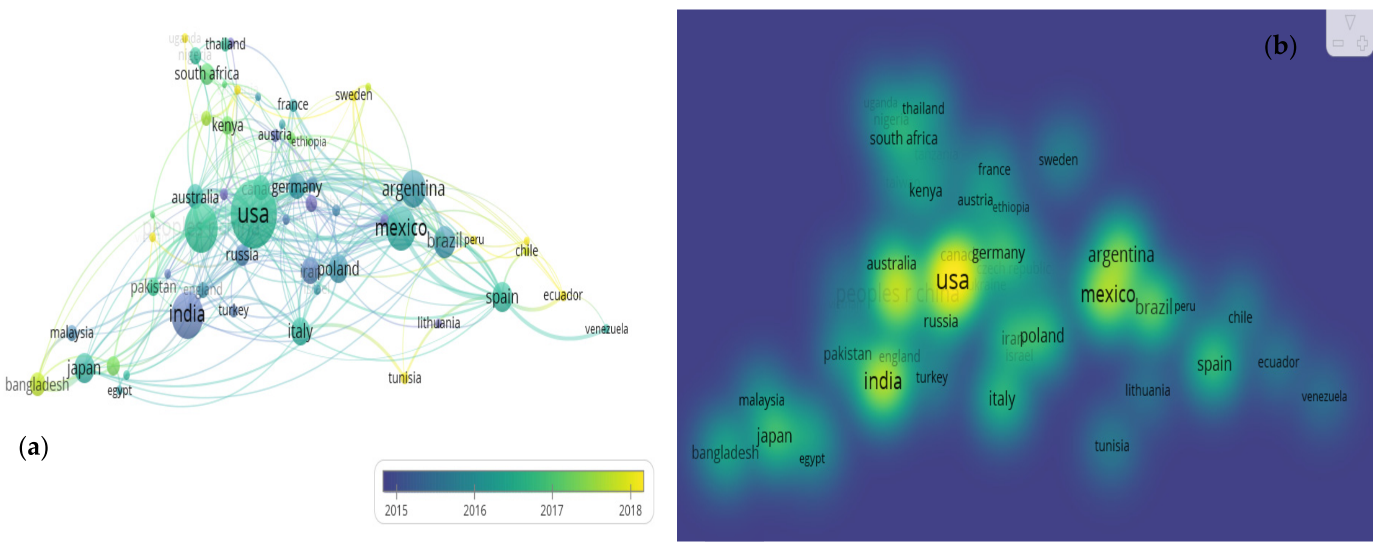

Figure 6. Co-authorship countries on *Amaranthus* research. Overlay visualization (**a**), density visualization (**b**).

2.11. Co-Occurrence of Author Keywords

Keywords are phrases that mirror the underlying subject matter of a publication [95,100]. To identify the research hotspots in *Amaranthus* research, co-occurrence keyword analysis was relatively imperative, because, through this analysis, "trend" topics and research hotspots can easily be identified; this perhaps can guide future research directions, to address research gaps in particular fields [94,101,102]. Bibliometric analysis plays an important role in the decision-making process in science, especially in research funding [103]. Therefore, in the present study, the author's keywords were analyzed with VOSviewer. According to the data retrieved from WoS, 4864 author keywords were used in the 1649 documents in this research (Figure 7). The frequency of these keywords was evaluated. The size of the circle in Figure 7 is proportional to the number of publications in which the keyword occurs, and the distance between two keywords reflects their relatedness [104,105]. The word "amaranth" appeared 257 times, "*Amaranthus*" appeared 93 times, "Amaranthaceae" appeared 68 times, "herbicide resistance" appeared 67 times, "antioxidant activity" appeared 36 times, "antioxidant" appeared 31 times, "palmer amaranth" appeared 29 times, "*Amaranthus hypochondriacus*" appeared 24 times, "germination" appeared 24 times, "glyphosate" appeared 24 times, "resistance" appeared 24 times, "weed control" appeared 24 times.

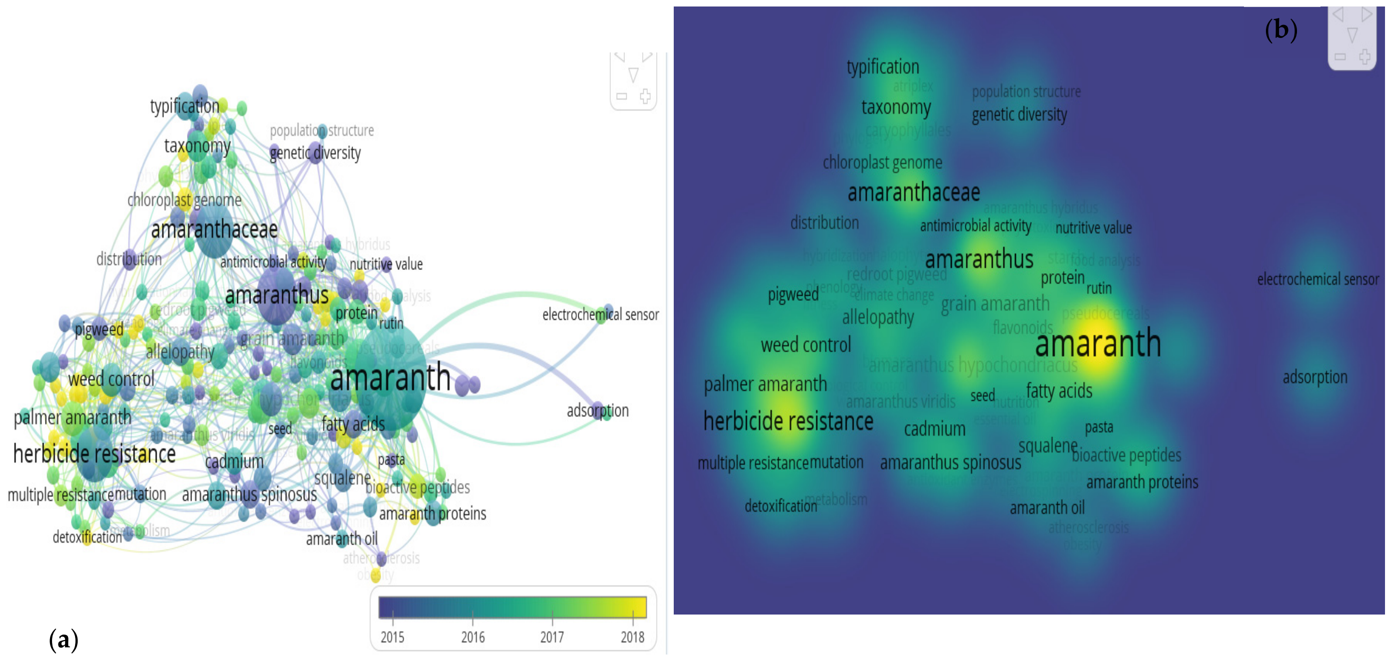

Figure 7. Keywords analysis on research publications on *Amaranthus* from 2011 to 2020. Overlay visualization (**a**), density visualization (**b**).

The identified keywords reflect the global research conducted on *Amaranthus*. For example, *Amaranthus* as a source of an antioxidant [11,26,106]. Studies on phytochemical screening of *Amaranthus* revealed some important bioactive compounds that could be responsible for the various biological activities [22,107]. Other biological activities, such as antimicrobial [108–110], anti-inflammatory [32,111–113], anti-malarial [114], anti-diabetes [35,115], anti-carcinogenic [39,116], and hepatoprotective [117] were reported in the literature. Detoxification is another keyword in *Amaranthus* research and a study on the detoxification effect of *Amaranthus* was reported by [26]. Reports on herbicide resistance of *Amaranthus* were documented by some researchers in the literature [118–120]. Studies on electrochemical sensor determination of *Amaranthus* in foods were documented in the literature [121–123]. Other reported studies on *Amaranthus* include bioactive peptides [21,113,124], amaranth oil [28,60,125,126], and *Amaranthus* taxonomy [87,127].

2.12. Author's Co-Citation Analysis

The number of times an article is cited as a reference in another article reflects its scientific impact [94]. Citation analysis is used to evaluate the quality of publications or impact of the author in a particular field of interest [127]. On the other hand, author co-citation analysis is used to determine the connection of authors based on the number of times in which they are cited together in a particular publication [102]. As highlighted in the report of [102], "through co-citation analysis, the important knowledge bases of the research field can be found efficiently and conveniently from the mass of cited references". In the present study, the author's co-citation analysis was carried out using the fractional counting method in VOSviewer. Twenty (20) was set as a threshold for the minimum number of citations of an author, 315 met the criterium out of 34190 authors (Figure 8). Thereafter, the total strength of the co-citation links with other authors was calculated. The authors with the greatest total link strengths were selected. The top five authors were Norsworthy JK (267 citations, 246.91 total link strength), Steckel LE (224 citations, 214.60 total link strength), Culpepper AS (201 citations, 186.64 total link strength), Sarker U (438 citations, 172.02 total link strength), Heap I (166 citations, 164.73 total link strength). Out of the 315 authors, only 314 authors had connections with each other; this set is displayed and depicted in Figure 8. The 314 authors are grouped into four clusters represented in different colors. Cluster 1 (red) comprises 26 authors, cluster 2 (green) comprises 112 authors, cluster 3 (blue) comprises 64 authors, and cluster 4 (yellow) comprises 12 authors. These four clusters are represented in different colors. The 314 authors in the four clusters have 18547 links and a 6330.68 total link strength.

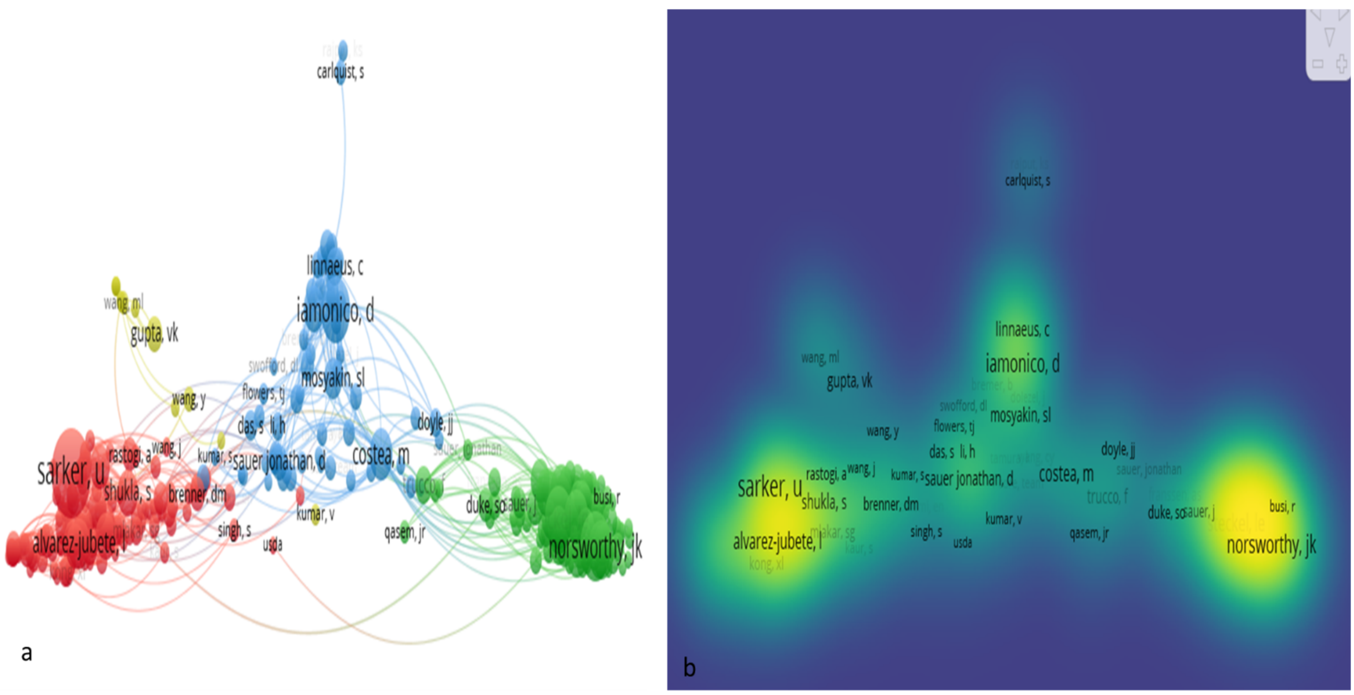

Figure 8. Author co-citation analysis on *Amaranthus* research from 2011 to 2020. (**a**) Overlay visualization, (**b**) Density visualization.

3. Conclusions and Study Limitations

Nutrition-related research is crucial for human growth and general well-being, which is highly significant in fighting against malnutrition in developing countries throughout the world. In this study, we emphasize the significance of biogeographic origins in relation to publication metrics. We further recommend the redirection of more research objectives to the dietary and pharmacological uses of amaranth, to bring these "wild relatives" closer to people. Findings from the study further reveal the importance of *Amaranthus* research in nutrition, and the results of the analyses could be used as baseline data to implement nutritional programs directed toward solving nutrition-related issues. Despite the numerous advantages associated with the analysis, it is also important to highlight some of its limitations. Firstly, the analysis was only based on documents retrieved from WoS without considering other databases, such as Scopus, PubMed, Dimension, or Google Scholar; hence, this study might not represent all publications on the subject. Again, the content or quality of the publication was not considered in the analysis. Non-English publications were excluded, resulting in a language bias. The citation analysis might include self-citations of the authors, and this might create some biases in the analysis, as it introduces flaws in the h-index of the authors.

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