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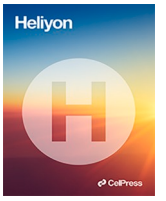

Review article

Is the use of biosensor in monitoring food quality experiencing an uplift trend over the last 30 years?: A bibliometric analysis

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ABSTRACT

Recently, there has been intense competition among food industries worldwide as they strive to fulfill the ever-growing consumer expectations regarding both the quantity and quality of food. The increasing demand for high-quality food has motivated researchers and academics to constantly innovate and develop real-time and precise tools for monitoring food quality. One such tool that has emerged is biosensors, which have already been widely investigated; however, no bibliometric reviews have discussed biosensor use holistically, comprehensively, and objectively. Therefore, this review aimed to analyze the trend of biosensor publications for monitoring food quality based on the number of documents published from 1991 to 2021, analyze the contribution of various journals, institutions, and cooperation between countries, highlight the most influential authors and articles, and predict the development of this topic. The Method used in this study is bibliometric analysis which consists of four stages, namely data mining from the Scopus database which are limited to data for the last 30 years (1991–2021), refining data, data visualization and interpretation data. There are 604 articles obtained from Scopus and visualization shows that biosensor use for monitoring food quality has significantly increased in the past three decades. Biosensors and Bioelectronics is the leading journal in publishing manuscripts on the topic of biosensors. In terms of the largest contribution, China produced the highest number of publications on related topics, while the United States has the highest collaborations between countries. Moreover, Whitcombe MJ has the most influential articles, while Wang S had the largest number of outputs. The frequently used keywords are "biosensors," "food safety," and "food analysis." These results are important references to determine the state of the art and directions for further investigations.

1. Introduction

Currently, food consumption has significantly increased, owing to population and income growth, which has caused lifestyle changes in many people [1–4]. Consequently, food industries worldwide are in constant competition to create innovations and meet consumer demands. However, excess supply, unequal distribution systems, bacterial and parasitic contamination, poor transportation and storage systems, and unattractive marketing techniques cause considerable wastage [5–10]. According to a Food and Agriculture Organization report [5,11], 1.3 billion tons of food products are wasted yearly. Meanwhile, approximately 800 million people still lack

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food, and 690 million individuals are malnourished (stunting) [3,12].

Related to the high production of food waste due to several factors, as well as the high incidence of malnutrition. These problems have become urgent issues and have received intensive attention from all countries. Therefore, support is urgently needed for the Sustainable Development Goals program objectives related to the food system, such as zero hunger, good health and welfare, and sustainable consumption and production, in line with pillars 2, 3, and 12, respectively [3,13,14].

Researchers and academics have been dedicated to the development of advanced tools for monitoring food quality such as thermometers, pH meters, microscopes, spectrophotometers, and biosensors. Recently, biosensor gain significant attention from the scientific community. Biosensors represent a fusion of biological components, such as enzymes or antibodies, with electronic sensory elements [15,16]. These devices possess a remarkable ability to specifically detect and identify certain components or substances in food, including pathogens, pesticide residues, allergens, and nutritional content. The integration of biological and electronic elements within biosensors enables them to provide rapid and precise results. Biosensors offer real-time monitoring capabilities, high sensitivity, and the potential for swift and accurate assessment of food quality [17–24].

However, these tools involve multiple disciplines, making it difficult to identify trends in a single review article; thus, a great degree of subjectivity is likely in the literature selection. Nonetheless, this gap can be overcome through bibliometric analysis, which can provides a more accurate analysis.

Presently, a review that comprehensively examines the trends and development patterns of biosensors for food quality monitoring remain unavailable. Therefore, this review conducted a bibliometric analysis using statistical and quantitative methods for collecting published articles. The collected information was used to determine the development of biosensor use and the influence of the states, institutions, journals, articles, and certain authors. Through this analysis, state of the art and direction of further investigation can be identified, and collaboration from various aspects can be made possible as has been performed in several studies [25–27]. Some important software tools that were used were Openrefine (version 3.6.1), Excel (version 2007), VOSviewer© (version 1.6.18), Tableau (version 2022.2), and RStudio® (version 4.2.1).

The significance of this study stems from its potential to provide valuable insights and contribute to the comprehension of biosensors in food quality monitoring. This study can assist guide future research efforts and improve collaboration among stakeholders by analyzing the state of the art and identifying directions towards further research. By integrating and analyzing a wide range of published studies on biosensors for food quality monitoring, this work contributes to the current body of knowledge. In this field, this research can indicate major advances, emerging trends, and prospective areas for development. Researchers and practitioners can obtain a greater understanding of the present state of research by offering a thorough overview, allowing them to expand on existing knowledge and prevent redundant efforts.

Furthermore, the study's emphasis on collaboration can promote multidisciplinary cooperation and knowledge exchange among researchers, institutions, and authors. The study can facilitate networking and collaboration opportunities by identifying significant institutions, journals, and authors in the field of biosensors for food quality monitoring. This can lead to collaborations which accelerate research progress, foster creativity, and eventually drive improvements in biosensor technology for future food quality monitoring. This study has the potential to benefit the scientific community, industry practitioners, and ultimately consumers by shining a light on current trends and advancements.

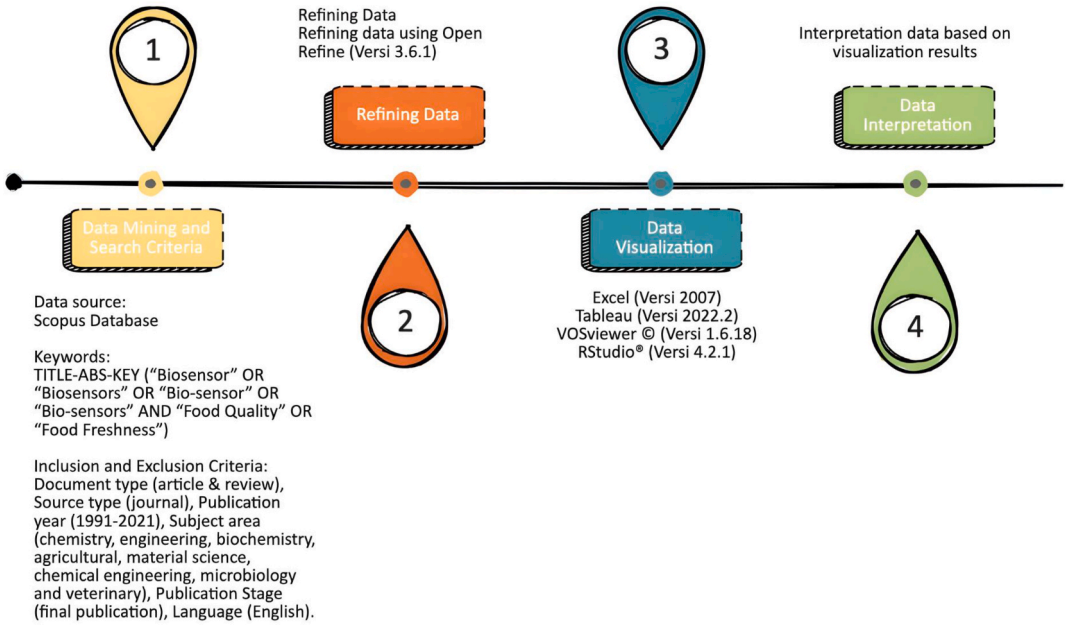


Fig. 1. Flowchart of the bibliometric review.

The specific objectives of this review were as follows: (1) to analyze the trend of biosensor publications for monitoring food quality based on the number of documents published from 1991 to 2021, (2) to analyze the contribution of various journals, institutions, and cooperation between countries, (3) to highlight the most influential authors and articles, and (4) to predict the development of the topic of biosensors for food quality monitoring according to bibliometric analysis.

2. Methodology and data statistics

This bibliometric review followed a series of stages, as shown in Fig. 1. In the first stage, relevant keywords were needed to search for a particular topic on the Scopus database. The search string used for data extraction included TITLE-ABS-KEY "Biosensor" OR "Biosensors" OR "Bio-sensor" OR "Bio-sensors" AND "Food Quality" OR "Food Freshness". Before 1991, studies on biosensors for monitoring food quality were limited. Therefore, this review only accepted publications for the last 30 years, from 1991 to 2021. Considering the large number of disciplines, data screening involved only eight fields: chemistry, engineering, biochemistry, agriculture, material science, chemical engineering, microbiology, and veterinary. The types of publication sources used were limited to journals, including 38% articles and 22% reviews published in the English language. The final database consisted of 604 publications. The data mining was conducted on October 31, 2022 and therefore, any subsequent publications after were not included in this study.

In the second stage, 604 publications obtained from the Scopus database were downloaded and further selected using Open Refine to minimize data bias caused by inconsistency and repetition of words [28,29]. In the third stage, the results of data refining were exported to the programs Tableau, VOSviewer, and RStudio for data analysis through visualization [30–32], followed by data interpretation as the final stage.

3. Bibliometric study of biosensors for monitoring food quality over the last 30 years

3.1. Trend of biosensor publications for monitoring food quality based on the number of document published from 1991 to 2021

Based on bibliometric analysis visualization in Fig. 2, studies on food quality monitoring biosensor show a trend that tends to rise annually. The development of this study reflected from two selected publication types of documents, namely, articles and reviews, based on the number of documents published. From 1991 to 2021, the number of documents published in this study was 604 with a growth rate of 9.82% annually, providing details of 378 articles and 226 reviews. For the first 10 years (1991–2000), both types witnessed highly erratic patterns. In 2001, 5 articles were published, and until the rest of the first decade, the number continuously fluctuated between 2 and 9. Only 3 reviews were published in 1996; this figure continued to decline to only 2 documents in 2000. From 2010 onwards, the reviews significantly recovered, with 19 reviews in 2011, and rapidly increased with a minor fluctuation, reaching

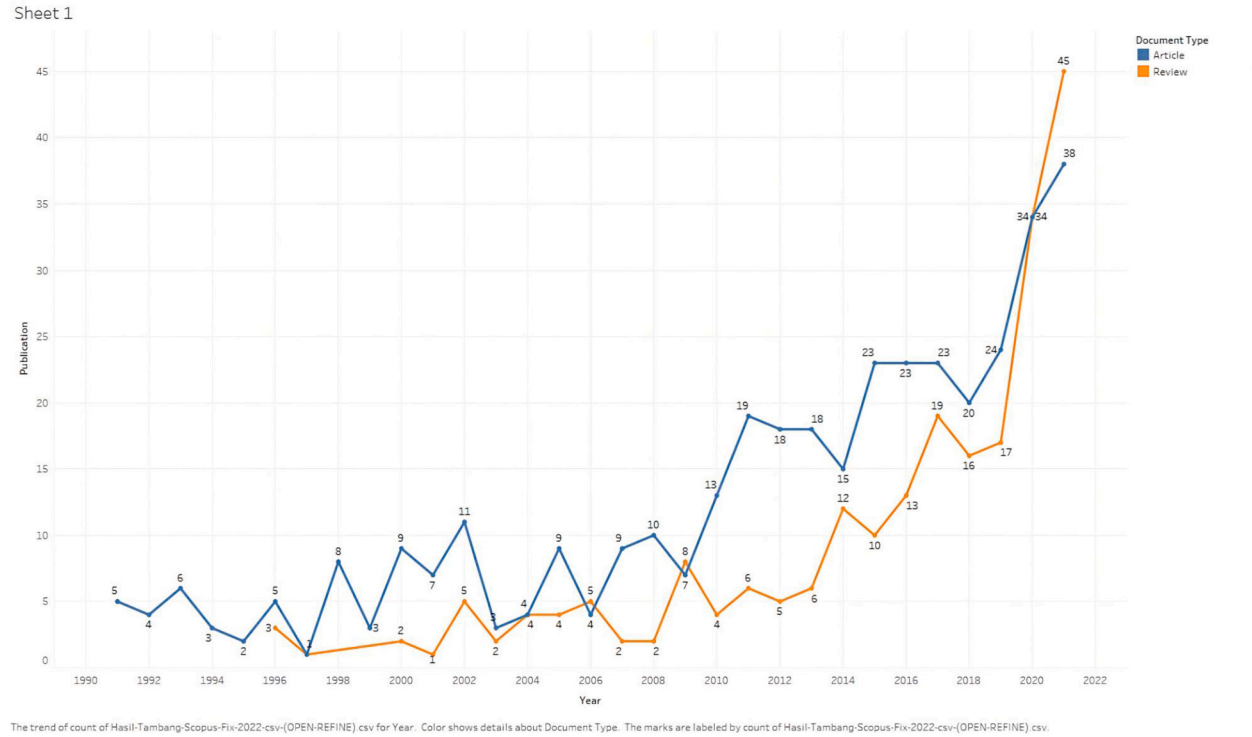


Fig. 2. Trend of the publications of biosensor use for monitoring food quality from 1991 to 2021.

38 reviews in 2021. In 2019, more reviews were published than the articles, but they became equally popular with the articles, reaching 34 reviews before rising considerably to 45 reviews in the final stage compared with the initial number of 3 in 1996. The high number of publications on this topic is due to the increasing consumer awareness and concern for food safety and quality [33,34], which has resulted in a growing demand for easy, real-time food quality monitoring without the need for expensive and time-consuming laboratory testing. Studies on this topic are attracting more and more attention nowadays and are projected to continue increasing in the future. This is in line with the findings of Griesche and Baeumner [35] who revealed that the high demand for biosensors in ensuring food safety is indicated by the projected market growth from 17 billion dollars in 2018 to 24.6 billion dollars in 2023 [36]. As a result, the advantages of biosensors in their application to food safety are an area of research that is gaining increasing interest.

3.2. Country contribution analysis

Out of 72 contributing countries, only 41 had at least 3 documents. Table 1 and Fig. 3a show the 10 countries with the highest number of publications. China had the highest number of publications, producing 91 publications with more than 3000 citations. The high number of publications and citations from this nation is suspected due to the country's past history of several food safety incidents (melamine-contaminated milk, tainted infant formula, and illegal food additives) that have raised public concern and required government action. These issues prompted the Chinese government to place a strong emphasis on improving food safety measures [37]. Biosensors offer a fast and sensitive method for detecting contaminants and ensuring food safety [18,38]. Therefore, Chinese researchers are actively pursuing the development and application of biosensor technologies to monitor food quality. Chinese researchers have made significant contributions to scientific publications on food safety and biosensors. The high publication rate demonstrates the country's commitment to addressing food safety issues through scientific research. This is supported by Yan C [39] who stated that biosensors are in high demand in China, with a large market share. With the introduction of novel biosensors, biosensors are characterized as a fast-growing market. This is what drives researchers in China to innovate and publish in the field of biosensors on a regular basis.

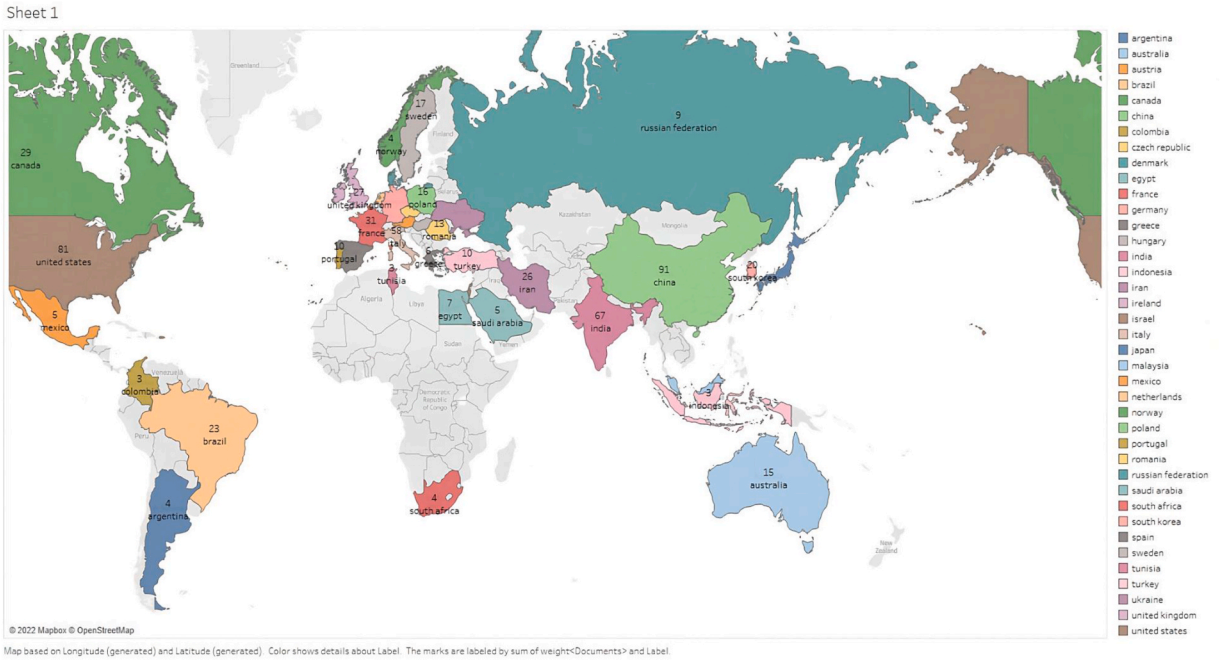
The United States ranked second, with 81 publications. The US also had an outstanding performance both in quantity and quality, as evidenced by the highest number of citations (>4000), different from other countries. This result is certainly supported by the policy of the US government, which allocates a large investment of 3.5% in research and development [40]. The United States has consistently been a leader in scientific research output across various disciplines, including biosensor studies. According to the National Science Foundation (NSF) in 2019 [41], the United States accounted for approximately 25% of the world's total scientific publications. Ranked third in terms of the number of publications, India demonstrated an impressive research output, publishing 67 publications with a significant total of 3352 citations. However, according to data from the World Bank [40], India received the smallest share (0.8%) of research and development funding among all the countries included in the study. On the other hand, Germany's contribution to the topic was comparatively lower, with only 27 publications, and despite having the second largest percentage of research and development expenditure (RDE) allocations after the United States (3.1%), it received the lowest total citations (<1000). These observations highlight a substantial disparity in terms of optimizing research and development expenditure (RDE) between the two countries. Regarding collaboration, according to the visualization in Fig. 3b, the color difference in the network between countries indicates the difference in clusters, the size of the nodes represents the number of publications, and the thickness of the line depicts the link strength between countries. This figure shows that the US leads other countries in publications related to biosensor studies for monitoring food quality. A total of 24 countries cooperated with the US, with 38 total link strengths. The collaboration network was mainly served by China, India, and Italy. The US researchers frequently collaborate with scientists from other countries, these collaborations lead to increased citations. This is in line with a couple of studies which investigated whether higher citation rates could be found for internationally co-authored papers, Hsu and Huang et al. [42] and Chinchilla-Rodríguez et al. [43] reported that internationally co-authored papers on average tend to have higher citation rates. China gets the second place in the most collaborations category, thus country had a total link strength of 23 and had cooperated with more than 10 countries.

Table 1
Top 10 influential countries investigating biosensor use for food quality monitoring (1991–2021).

Ranking	Country	TP	TC	RDE
1st	China	91	3342	2.4
2nd	United States (US)	81	4247	3.5
3rd	India	67	3352	0.8
4th	Italy	58	2895	1.5
5th	Spain	37	1747	1.4
6th	France	31	1920	2.3
7th	Canada	29	2459	1.6
8th	Germany	27	998	3.1
9th	United Kingdom (UK)	27	2181	1.7
10th	Iran	26	1551	0.9

TP: total publications, TC: total citations, RDE: research and development expenditures (% of GDP).

a



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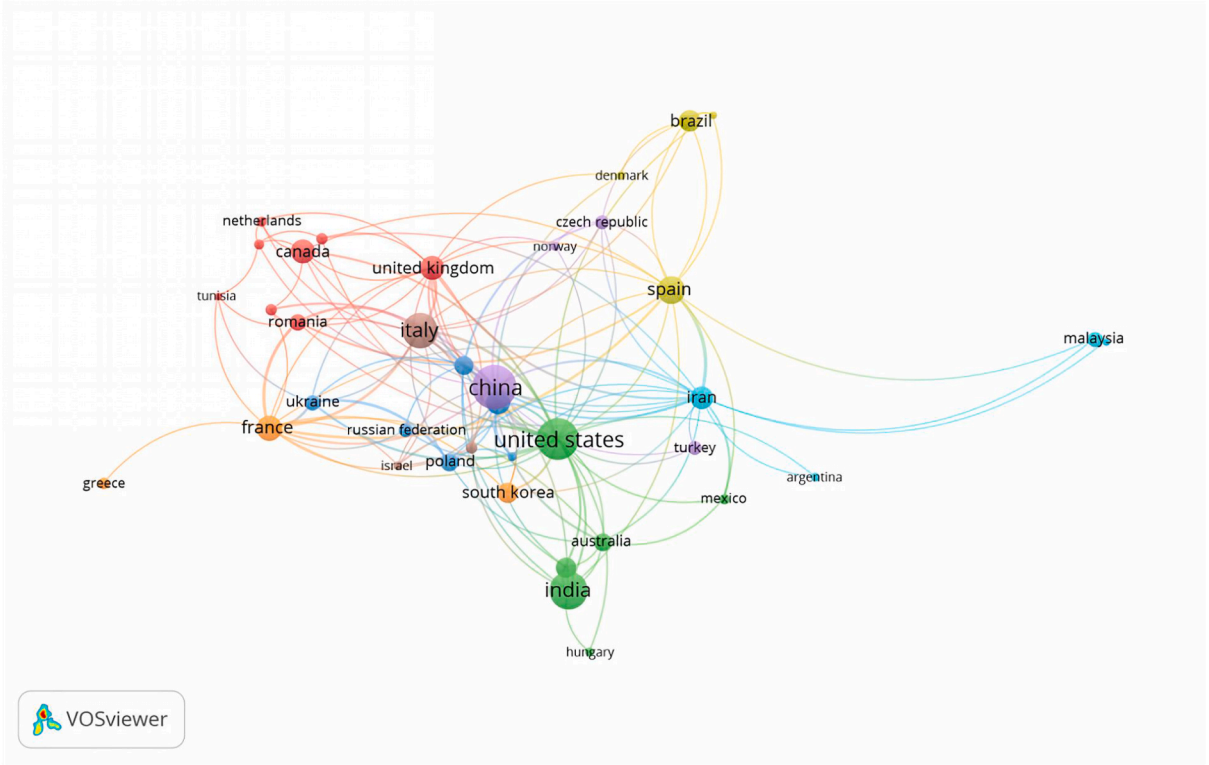

Fig. 3. a) Top 10 countries with the highest number of biosensor studies for food quality monitoring, and b) network of collaborations by countries.

3.3. Institutions contribution analysis

Fig. 4 displays the 10 institutions with the highest number of publications considering the author's affiliation; 5 of them originated from China. The diagram shows that the Consiglio Nazionale delle Ricerche in Italy had the highest contribution regarding publications in biosensors on food (19 documents), the second influential academic institution was Ministry of Education of the People's Republic of China with 12 publications. This was followed by Zhejiang University with 11 publications. In contrast, the lowest publications were the University of Guelph in Canada and Jiangsu University in China, with 7 publications each. These 5 institutions (Ministry of China Education (12); Zhejiang University (11); Jiangnan University (10); Chinese Academy of Science (8) and Jiangsu University (7)) in Fig. 4 contributing to 48 publications out of 91 total publications from China.

3.4. Most prolific authors

Out of 2330 authors, only 92 had at least 3 documents. Fig. 5a shows the top 10 authors with the highest publications. Authors with the highest number of publications related to the field of biosensors for monitoring food quality (Wang S, Watanabe E and Zhang Y) have 7 documents for each. Followed by Luong JHT with 6 documents and the lowest number of publication (5 documents) produced by 6 out of 10 Authors. However, only Watanabe E and Zhang Y had publication in 1991, In contrast to Zhang Y, who began publishing in 2016. An analysis is needed to identify whether publications related to this topic experienced a boom in the last decade; this analysis indicates an increase in biosensor studies on food quality.

As shown in Fig. 5b, Luong JHT had 625 citations, thereby more than twice that of 9 other authors. This result is supported by Fig. 5a, which shows that the number of citations for Luong JHT's publications increased in 2011, as marked with bright blue nodes. From the H-index aspect, Zhang Y had the highest rank, with a total of 7. This H-index is a benchmark for authors and their impact on other publications. However, this measurement did not determine the quality of the work. Given the differences in publication culture between disciplines, comparing the H-index of authors from various disciplines is not permissible [44].

3.5. Top 10 influential journal

The 604 selected publications were published in 251 different journals, however it is important to notice that more than 50 journals published only one paper. Table 2 presents the top ten journals on biosensor study for monitoring food quality. Five journals have more than 20 publications. Similarly, nine journals fall into the quartile 1 category, and 4 were from the Netherlands. The journal of Biosensors and Bioelectronics (Elsevier) ranked first, with 68 publications and total citations of 3947 since 1991; the citation score was 20.2. The top two and three journals were Sensors and Biosensors, with 25 and 23 publications, respectively; both were from the same country (Switzerland) but had different quartiles (Q1 and Q2, respectively). Meanwhile, the Journal Agricultural and Food Chemistry from the United States ranked last due to having the lowest number of publications (nine documents) and only had 541 citations.

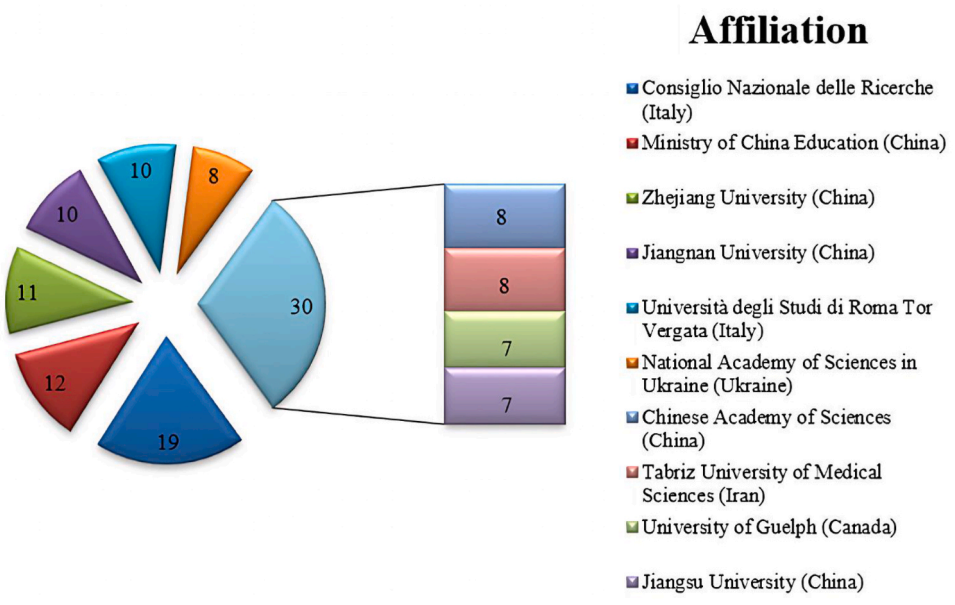

Fig. 4. Top 10 most highly productive institutions.

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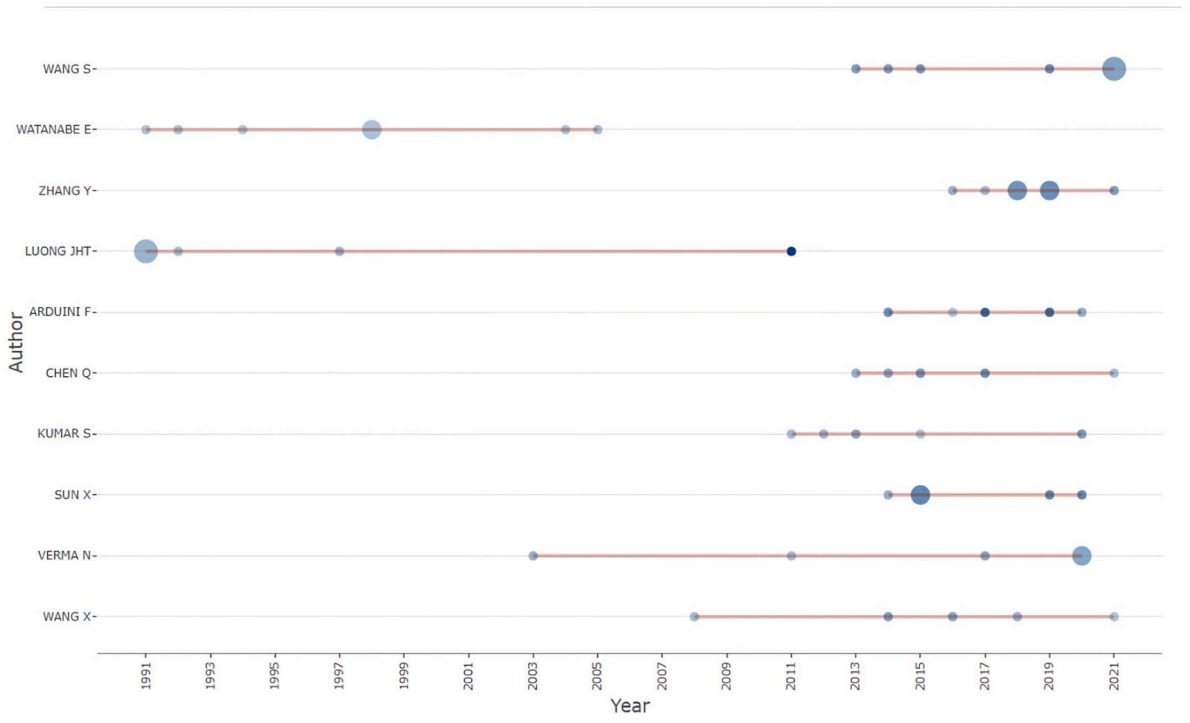

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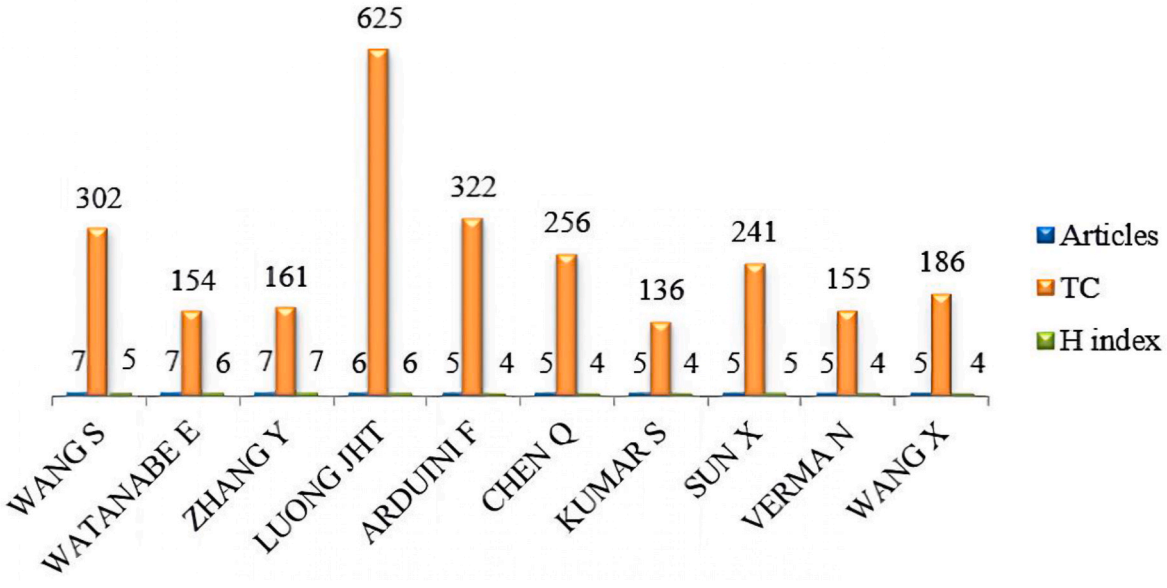

Fig. 5. a) Author's production over time and b) author impact.

3.6. Highly cited articles

Table 3 highlights the top ten most cited articles investigating biosensors for food quality monitoring, with more than 200 citations and publications from 2002 to 2017. Whitcombe MJ et al.'s "Rational development of molecularly imprinted polymer-based sensors for protein detection" published in the Chemical Society in 2011 was the best-performing publication, with 571 citations. The review

Table 2
Source impact.

Sources	Articles	TC	CS	Q	Publisher	Country	PY Start
Biosensors and Bioelectronics	68	3947	20.2	Q1	Elsevier	United Kingdom	1991
Sensors (*available only for open access*)	25	923	6.4	Q1	MDPI	Switzerland	2015
Biosensors (*available only for open access*)	23	729	5.6	Q2	MDPI	Switzerland	2017
Trac - Trends in Analytical Chemistry	23	1473	21.4	Q1	Elsevier	Netherlands	2007
Sensors and Actuators, B: Chemical	21	1224	15.0	Q1	Elsevier	Netherlands	1996
Analytica Chimica Acta	20	1250	10.5	Q1	Elsevier	Netherlands	1992
Food Chemistry	20	1307	13.1	Q1	Elsevier	United Kingdom	2000
Trends in Food Science and Technology	14	875	18.1	Q1	Elsevier	United Kingdom	2002
Talanta	11	306	10.6	Q1	Elsevier	Netherlands	2001
Journal of Agricultural and Food Chemistry	9	541	8.6	Q1	American Chemical Society	United States	2001

TC: total citation, CS: cite score (2021), Q: quartile, PY: publication year.
Rank: Ranking according to the number of articles in the current database

Table 3
Top 10 most cited articles investigating biosensors for food quality monitoring.

First Author	Article Title	DOI
Whitcombe MJ	The rational development of molecularly imprinted polymer-based sensors for protein detection	10.1039/c0cs00049c [45]
Prasad R	Nanotechnology in Sustainable Agriculture: Recent Developments, Challenges, and Perspectives	10.3389/fmicb.2017.01014 [46]
Yam KL	Intelligent Packaging: Concepts and Applications	10.1111/j.1365–2621.2005.tb09052.x [47]
Mello LD	Review of the use of biosensors as analytical tools in the food and drink industries	10.1016/S0308-8146 (02)00104–8 [48]
Minussi RC	Potential applications of laccase in the food industry	10.1016/S0924-2244 (02)00155–3 [49]
Neethirajan S	Nanotechnology for the Food and Bioprocessing Industries	10.1007/s11947-010-0328-2 [50]
Jane A	Porous silicon biosensors on the advance	10.1016/j.tibtech.2008.12.004 [51]
Vashist SK	Advances in carbon nanotube-based electrochemical sensors for bioanalytical applications	10.1016/j.biotechadv.2010.10.002 [52]
Restuccia D	New EU regulation aspects and global market of active and intelligent packaging for food industry applications	10.1016/j.foodcont.2010.04.028 [53]
Andreescu S	Twenty years study in cholinesterase biosensors: From basic study to practical applications	10.1016/j.bioeng.2006.01.001 [54]

Table 4
Clusters of the main keywords obtained on the VOSviewer software.

Cluster	Number of Items	Keywords on VOSviewer Network
1	15	aptamer, aptasensor, bacteria, biogenic amines, detection, dna biosensor, electrochemical, electrochemical biosensor, electrochemical sensor, food, gold nanoparticles, histamine, immunosensor, pesticides, screen-printed electrode.
2	8	biosensors, carbon nanotubes, enzymes, nanomaterials, nanoparticles, polyphenols, sensors, and wine.
3	7	amperometric biosensor, fish freshness, hypoxanthine, immobilization, meat freshness, xanthine, and xanthine oxidase.
4	6	food analysis, food safety, foodborne pathogens, microfluidics, nanotechnology, and point-of-care.
5	6	food quality, immunoassay, meat, milk, optical biosensor, and quality control.
6	5	amperometry, electronic nose, electronic tongue, mycotoxins, and sensor arrays.
7	4	active packaging, food packaging, intelligent packaging, and smart packaging.

sought to identify the best strategy for sensor fabrication; therefore, an assessment of protein-imprinting methods and the development of MIP-based biosensors were used for monitoring food quality, health, environment, and more. This study was based on the need for a long-term detection tool that can be used repeatedly for faster analysis, such as real-time monitoring with direct readings without laboratory requirements. This protein-targeted biosensor can be applied in several fields, including organism and toxin detection. The most successful strategy for scoring protein targets involved the use of small-to medium-sized peptides as templates, which represent the epitope of the target protein. Nanostructured materials and thin films are important formats for sensing applications. In fact, MIP nanoparticles can be considered as antibody substitutes, which shows a growing trend as they have been shown to act in vivo by neutralizing the toxic effects of bee venom components in mice [45]. The next best-performing publications were written by Prasad R et al. and Yam KL et al. [46,47], with 556 and 484 citations, respectively.

Furthermore, two articles had the oldest publication year. The first was "Review of the Use of Biosensors as Analytical Tools in the Food and Drink Industries," which was written by Mello and Kubota [48]. It aimed to review the development and application of several biosensors in the food technology industry. Similarly, Minussi RC in collaboration with Pastore GM and Duran N reviewed the potential application of laccase enzymes in the food industry. According to this study, the function of the biosensor depends on the biochemical specificity of the biologically active ingredients [49]. In this case, several biosensors containing laccase as a biologically active ingredient were developed for immunoassays [55,56], phenolic compound [57,58] and aromatic amine [59] recognition, and glucose identification [60].

3.7. Keyword analysis

Keywords are important elements that can be used to represent the contents of the entire article [61]. The analysis of the most frequently used keywords reflects the hotspots in the field of biosensors for food quality monitoring directly. Therefore, keyword analysis is necessary for addition to identifying trends in the study area and exploring topic gaps in various fields [62]. Fig. 6a shows that the three most frequent keywords in the selected documents were "biosensor," "food safety," and "food analysis," which were used 219, 44, and 28 times, respectively. Fig. 6b presents the most frequently used keyword groupings, which were divided into several groups separated by different colors. Each circle represents a keyword, the size represents the frequency, and the lines between the circles indicate that the keywords appear together in a publication [25,62]. Out of 1676 keywords, 51 were obtained with at least 7 occurrences separated into 7 cluster groups, as shown in Table 4. These clusters are proof that several investigations have been accomplished on this topic. In addition, the analysis of the significance of keywords over a period (1991–2021), can see the development of research trends related to each of the main issues which presented in Fig. 6c. The progression of keywords is shown in diagram, which provides valuable information about current trends. The size of the blue circle represents the frequency of keywords discussed, with larger circles indicating more extensive discussions. From 1998 to 2018, discussions on meat freshness initiated, but it was in 2001 that there was a noticeable increase, represented by a small blue circle. Starting from that year, the focus shifted to electropolymerization, sensor arrays, and nose electronics, with a significant rise in 2007. Optical sensors gained widespread attention in 2012. Biosensor-related topics were introduced in 2009, but it was three years later that they experienced a significant and remarkable surge, evident by a blue circle three times larger than others. Additionally, ongoing research focuses on nanosensors, antibiotics, electrochemical sensors, nanoparticles, and pesticides. Fig. 7 shows a thematic map of the 50 most frequently used keywords in the field of biosensors for food quality monitoring. This map is divided into quadrants 1, 2, 3, and 4, which were the niche, emerging or declining, basic, and motor themes, respectively. Meanwhile, the 15 main keywords were grouped and arranged according to density and centralization parameters (Table 5). The keywords "electronic nose," "electronic tongue," and "sensor arrays" are in the highly developed and isolated themes quadrant. Their placement indicates that these subtopics were widely investigated but are still isolated into a certain area, thereby limiting the impact of another related study. In the same quadrant, "food packaging," "intelligent packaging," and "active packaging" are still highly used. Furthermore, "fish freshness," "amperometric biosensor," and "xanthine" are between quadrants 2 and 3, indicating that this subtheme needs to be examined whether the topic follows an upward or downward trend. An upward trend implies that the keywords can be developed. Based on the analysis results in Fig. 6c, the three keywords were popular in 2010–2012 but are no longer nowadays. The lower right quadrant contains "biosensor," "food safety," and "food analysis," which are included in the basic themes and can be investigated for further studies. In addition, "aptamer," "electrochemical biosensor," and "electrochemical sensor" are located in the middle of quadrants 3 and 4, indicating that the subtopic has a considerable influence that can be determined [25].

3.8. Three-factor analysis

Fig. 8 shows the correlation analysis on a three-field plot. This graph presents the correlation between the parameter's authors, keywords, and journals that are ranked in the top 10 according to the highest number of articles. In terms of the proportion of publications, the keyword "biosensor" is the most targeted, except for Wang S, Chen Q, and Sun X. Watanabe E dominated in the number of publications related to the field of biosensors, followed by Verma N. Moreover, the journals Biosensors and Bioelectronics, and Sensors were the first and second largest publication target; thus, both journals included most of the analyzed publications with the keyword "biosensors." In terms of popularity, 8 out of 10 authors used "food safety" with almost the same proportion and made Trac-Trends in Analytical Chemistry the main publication target.

3.9. Limitations and future study directions

This review article has some limitations, including the use of data recorded from the last 30 years in the Scopus database. This limitation resulted from the limited access to data mining through the WOS database; therefore, the results and conclusions may differ when different sources and times are used. Considering the considerably numerous data mining results, literature sources were further selected by analyzing data according to document types, namely, articles and reviews.

Table 5
Clusters of the main keywords obtained on bibliometric software.

Cluster	Main Keywords	Keywords on Bibliometrix Software
1	5	Fish freshness, amperometric biosensor, xanthine, hypoxanthine, meat freshness.
2	12	Aptamer, electrochemical biosensor, electrochemical sensor, detection, immunosensor, biogenic amines, gold nanoparticles, electrochemical, screen-printed electrode, histamine, aptasensor, dna biosensor.
3	26	biosensor, food safety, food analysis, food, sensors, food quality, nanotechnology, pesticides, nanomaterials, nanoparticles, milk, carbon nanotubes, mycoToxins, bacteria, quality control, amperometry, foodborne pathogens, immobilization, immunoassay, meat, optical biosensor, point-of-care, polyphenols, enzyme, microfluidics, wine.
4	4	Food packaging, intelligent packaging, active packaging, smart packaging.
5	3	Electronic nose, electronic tongue, sensor arrays.

a

b

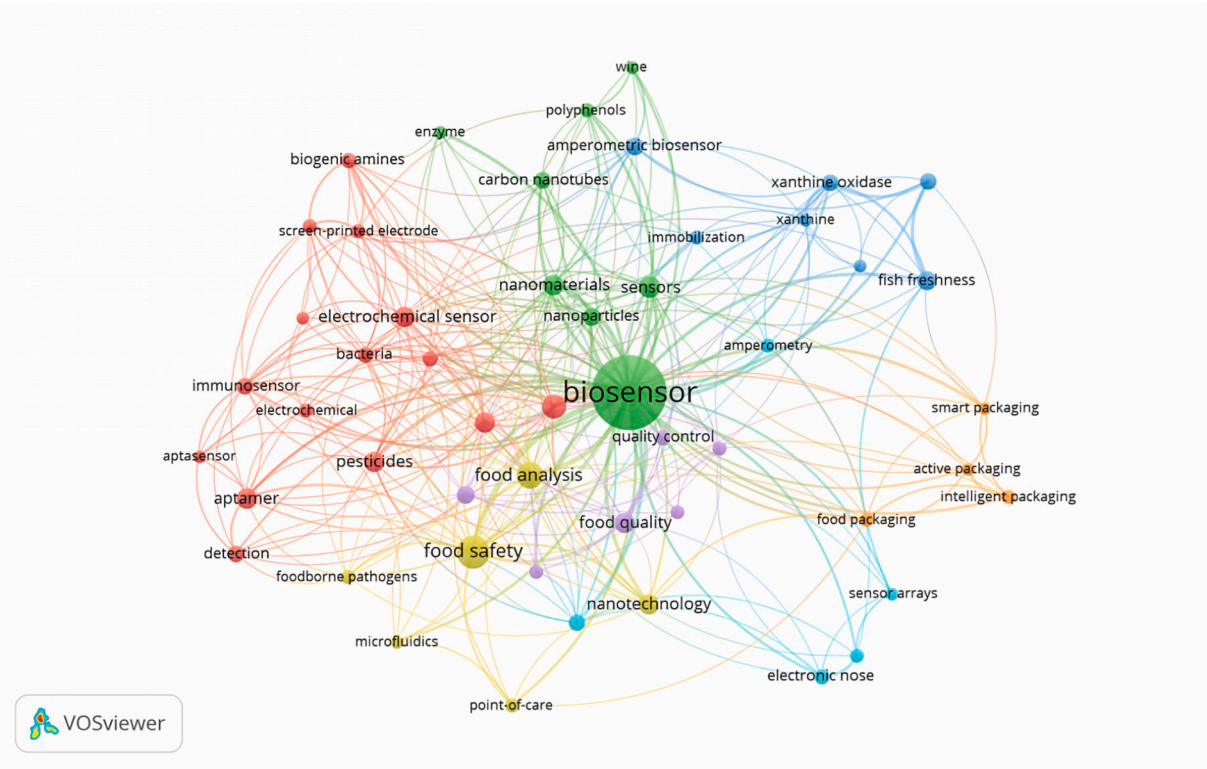

Fig. 6. a) Word tree map of most frequently used keywords in the field of biosensors for food quality monitoring, b) co-occurrence network of the most frequent authors' keywords based on a different cluster, and c) co-occurrence network of the most frequently used keywords based on time evolution.

c

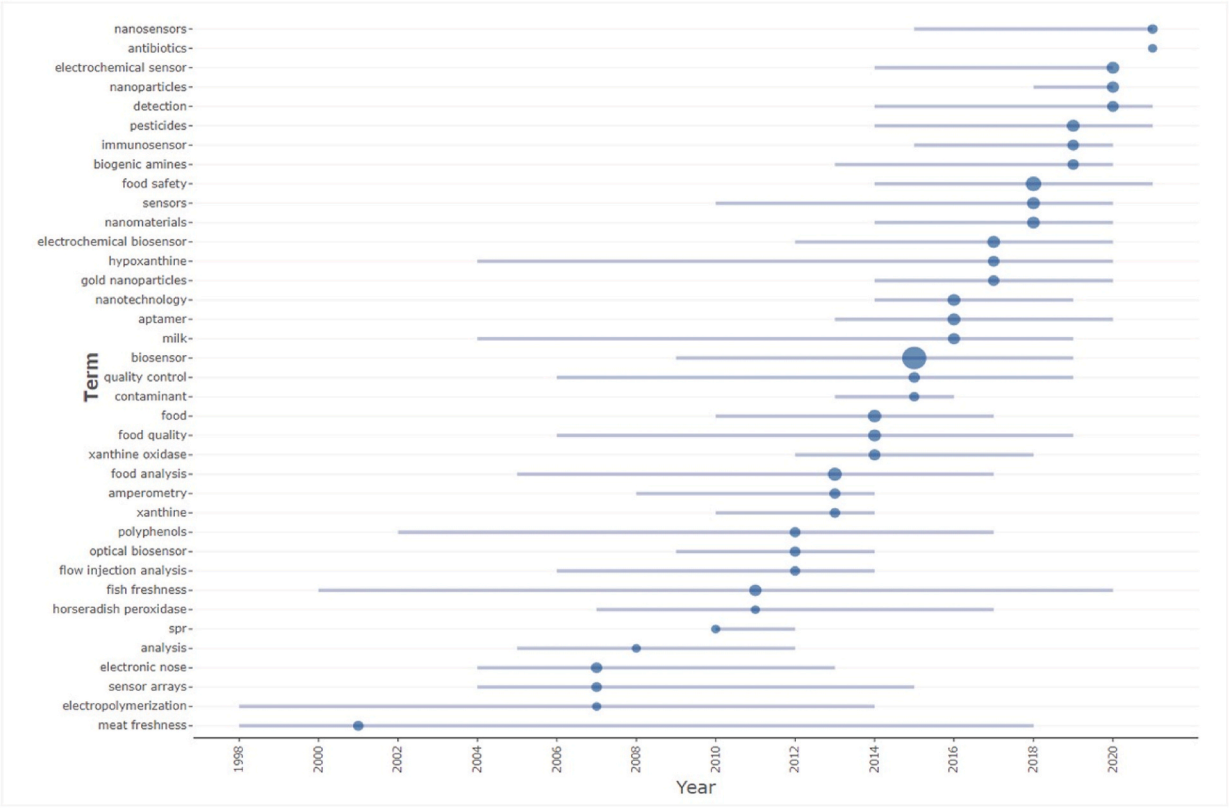

Fig. 6. (*continued*).

Bibliometric data analysis by visualization revealed that this field is projected to experience continuous development, as evidenced by an annual increase in publications related to biosensors for food quality monitoring, implying opportunities for sustainable development. This finding will help identify gaps and further review subtopics that have been developed but given less attention in the previous investigation through data visualization. Furthermore, this review can be used as a reference for finding various sources of reference for the most influential papers, journals, and authors. The results also offer several prospective opportunities for future study, as indicated by the visualization of the co-occurrence of keywords according to time evolution in Fig. 6c, which shows that ongoing research focuses on nanosensors, antibiotics, electrochemical sensors, nanoparticles, and pesticides.

4. Conclusions

The results of this review provide an important reference for increasing the knowledge of biosensor studies for food quality monitoring. By analyzing 604 documents, including articles and reviews published by Scopus, this review aids in optimizing the development of all potential scientific topics according to characterization parameters such as keywords, journals, documents, and authors. Visualization revealed that China, with five institutions, had the highest number of publications. Among the authors, Wang S, Watanabe E, and Zhang Y have the greatest contribution, and Luong JHT produced the most number of citations. Biosensors and Bioelectronics, and Sensors are the most well-known journals on the topic, thereby recommended as a forum for the future development of publications and references. Articles are written by Whitecombe MJ received the most citations, followed by Prasad R, and Yam KL. In addition, “biosensors,” “food safety,” and “food analysis” are the most frequently used keywords.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

Data included in article/supplementary material/referenced in article.

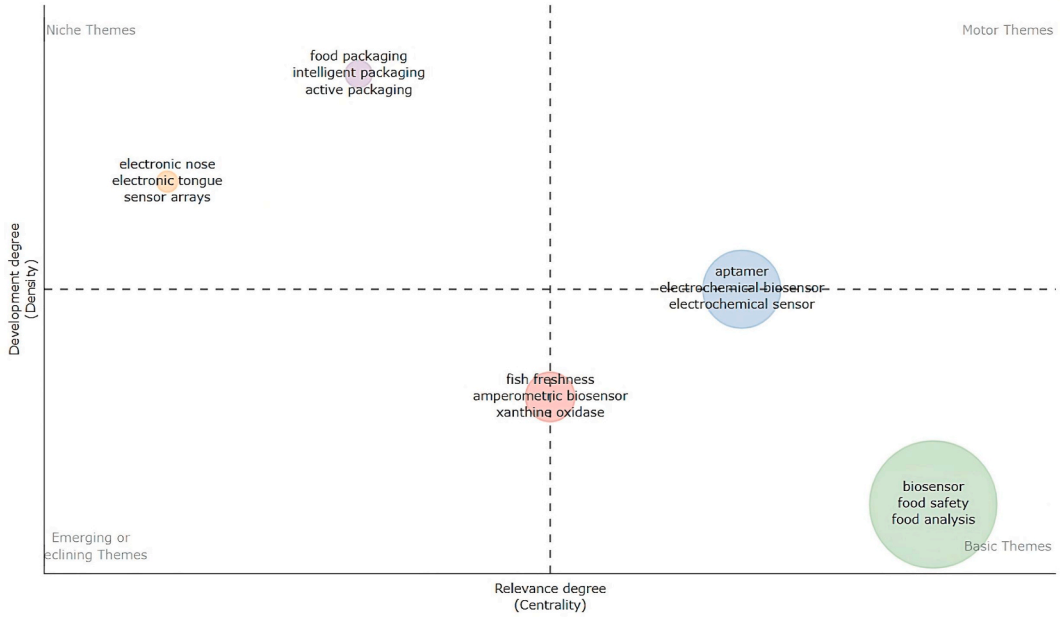

Fig. 7. Thematic map of the clusters from the 50 most frequently used keywords in the field of biosensors for food quality monitoring.

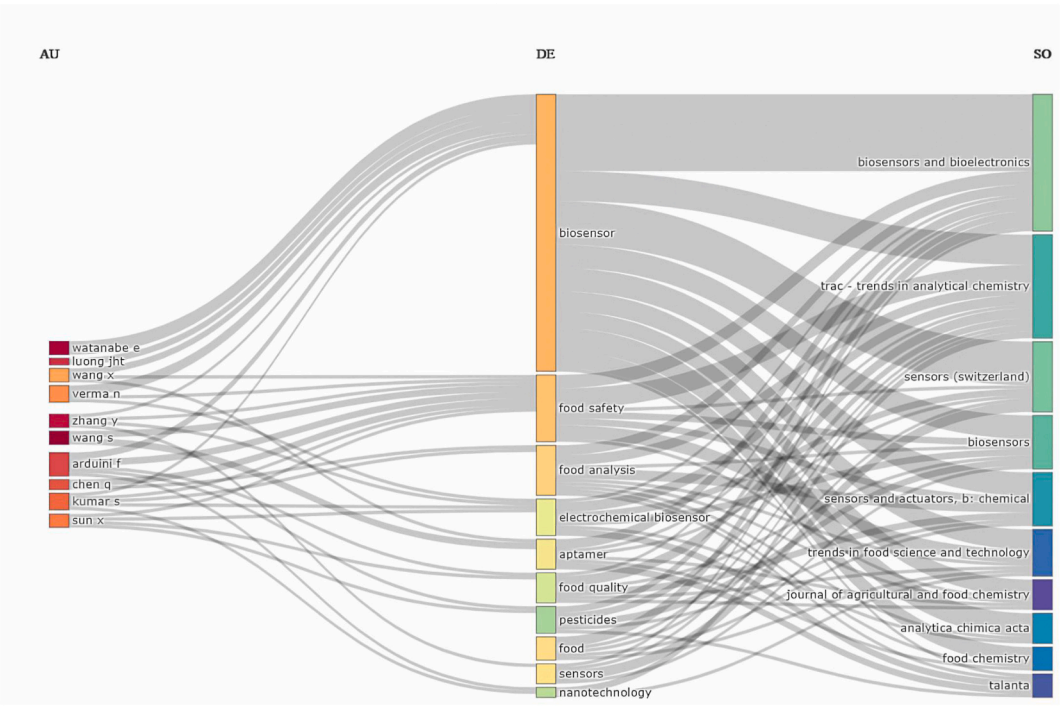

Fig. 8. Three-factor analysis of the relationship among authors (left), keywords (center), and sources (right).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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