A review of the top 100 most cited papers on food safety

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REVIEW ARTICLE

Abstract

With the ever-increasing changes and growing scientific output in the field of food safety, it has become imperative to measure, analyze, characterize and compare existing publications quantitatively. The present study aimed to identify and analyze the characteristics of the 100 top-cited studies on food safety. Food safety articles published in the Web of Science Core Collection database between 1950 and 2020 were collected, and bibliometric parameters were assessed. Data analysis was performed using VOSviewer software to visualize linkages and establish relationships between articles, keywords, research areas, authors, countries and institutions, among others, providing insight into the most impactful studies related to food safety. This study highlights that research focused on food safety is growing rapidly globally and cuts across several fields, including biotechnology, microbiology, food processing and preservation, consumer studies, and policy development. There is a dearth of research articles in the areas of chemical contamination of foods by pesticides and other chemical residues and in food fraud detection and prevention studies.

Keywords: foodborne illness; contamination; bibliometric analysis; food safety; VOS viewer

Introduction

Food safety is a basic human right and refers to stringent approaches undertaken during food production, preparation, transportation, handling and storage to ensure wholesomeness of foods and prevent the outbreak of foodborne illnesses and other associated conditions because of the sale and consumption of unsafe food. However, food safety remains a significant global public health issue, as there continue to be cases of transmissible diseases contacted through the consumption of unsafe or inadequately prepared or stored foods. The consumption of food contaminated with pathogenic bacteria, viruses, parasites, or chemicals can lead to severe clinical manifestations and contributes to over 200 diseases (World Health Organization [WHO], 2020). It is estimated that globally, 1 in 10 persons fall ill, and more than 120,000 children under the age of 5 years die every year because of unsafe food (WHO, 2015).

In recent decades, there has been an increasing number of research publications and the use of bibliometric indexes for evaluating the impact of scientific articles, careers and institutions of researchers within a research field, including food safety (Hicks, 2012; Pagell, 2014; Waltman, 2016). It has been estimated that about 2.5 million new scientific articles are published annually (Ware and Mabe, 2015). This high number of articles makes it difficult to comprehensively keep track of research progress. However, with the introduction of bibliometric databases, the collation and analysis of research publications have become easier and streamlined. Institutional and

national systems have been promoted in different countries to monitor and evaluate research activities, including periodic assessment of scientific output (Cappelletti-Montano *et al.*, 2021). Similarly, the use of bibliometric analysis provides a historical overview of the most significant articles in a specific field and highlights the changing focus of a discipline over time (Kim *et al.*, 2020).

One of the indexes that can be utilized to evaluate the impact and visibility of a scientific publication is the number of citations that the article receives. Although citation count is not a holistic indicator of impact, it can give an indication of the merit of a scientific work. Studies have shown that other factors can contribute to the citation count of a document. These include characteristics related to an article's authors, publishing journal, and the article itself (Antoniou *et al.*, 2015; Falagas *et al.*, 2013; Khan *et al.*, 2017; Onodera and Yoshikane, 2015; Shekhani *et al.*, 2017). Notwithstanding, citation counts can be influenced by field-dependent citation practices and these vary across fields (Moed *et al.*, 1985). In many instances, the quality of a work determines its visibility, citation and impact on the scientific world. However, there can be situations where novel studies may not gain the expected traction because of submission in a journal with limited scope and/or readership, poor assembling of manuscripts, closed access, or simply inappropriate title. Overall, a manuscript that does not capture the attention of other researchers will not be cited and has the potential of getting lost in the pool of publications (Hafeez *et al.*, 2019).

Over the years, to reduce incidences and impact of foodborne illnesses, interest has grown in scientific research on food safety. As a scientific discipline, food safety draws from various academic fields, including microbiology, chemistry, engineering and others. Early studies on food safety mainly focused on reactive research on issues concerning the outbreak of food-related illnesses such as typhoid and paratyphoid fevers, pulmonary tuberculosis, and milk-borne diseases, with little emphasis on proactive investigations. Since then, research in food safety has transitioned from classical methodologies to advanced technologies and is well established in medical, pharmacological, and microbiological fields. Research and publications on food safety have expanded over the years. A recent study categorized food and safety-based research into the following nine groups: (1) food additives, (2) microorganisms and viruses, (3) contamination in foods (food contaminants), (4) poisons, (5) natural toxins and mycotoxins, (6) novel foods and genetically modified foods, (7) risk communication, (8) pharmacology, including drug metabolism, and (9) toxicology (Yamazoe *et al.*, 2021). This shows the vastness of the field and indicates the area of research focused, notably microbial contamination of foods and surge in food safety issues related to natural toxins and mycotoxins. This could be attributed to the growing concerns about pesticide residues in foods and increasing regulatory alterations to ensure microbial food safety. Thus, it is imperative to quantitatively measure, analyze, characterize and compare existing publications in the field of food safety. This analysis would aid in understanding the research direction, recent developments and impactful literature within the field, and, in turn, would inform policy decisions, capital expenditure, legislation and industry practices.

Although bibliometric analysis has been used to examine various research fields (Mattos *et al.*, 2021; Peng *et al.*, 2021; Zhang *et al.*, 2019), only one publication has focused particularly on food safety governance (Shen *et al.*, 2021). However, to the best of our knowledge, no citation analyses have examined publications on food safety. Thus, this study represents the first comprehensive scientometric analysis of the most cited publications in the field of food safety. It provides a contemporary overview of the most cited scientific articles on food safety, the associated affiliations and publishing journals, and the characteristics influencing their citation scores. Also, the collation of articles published from 1950 to 2020 allows us to comprehensively examine any short-term trends that may exist over time, making it different from other bibliometrics studies.

Database generation

Relevant articles related to food safety used in this study were retrieved from the Web of Science database. A basic search was conducted in March 2021 using the following specific keywords—"food intoxication," "food safety," "safe food," "food poisoning," "contaminated food," "food infection," "unsafe food," "harmful food," or "microorganisms in food"—in the "Topic" search tab to retrieve a broader collection of literature which mentioned these keywords in the title, abstract and keywords of searched papers. Retrieved documents were further filtered to select only English language research articles. Although Scopus and Google Scholar also provide citation and bibliometric data, Web of Science was chosen because of its accessibility and comprehensive coverage, with a collection of over 6,500 journals across over 150 disciplines (Birkle *et al.*, 2020; Šubelj *et al.*, 2014). All retrieved articles were categorized using Web of Science tools: country of origin, top publishing institution, publishing journals and research domain. Two independent researchers screened the articles to verify that all articles were relevant to food safety.

Article Ranking

The 100 top-cited research articles published between 1950 and 2020 were selected and ranked according to

their citation count. Research outputs were further ranked based on average citations per year of publication (citation intensity) up to the year 2021. This was determined as the number of citations divided by the number of years since publication. This helps to minimize bias, as the older an article is, the higher the number of citations, thus skewing the citation count in favor of older articles. On the other hand, this may increase the relevance of newer articles that garnered many citations in the first few years of publication and which over the years may not be as relevant as the highly cited older publications. All articles were exported to the HistCite Software (version 12.03.17) and Microsoft Excel (2016) for vetting to ensure articles were related to the topic and avoid repetition. Full texts of the top 100 articles were obtained and grouped according to the central research theme. Finally, VOSviewer software (version 1.6.8) was used to visualize authorship collaborations, institution collaborations, co-occurrence of keywords and co-citation of documents within the top-cited 100 articles. The VOSviewer software visualizes these relationships by creating bibliometric network maps and exploring the linkages within published data (Van Eck and Waltman, 2010). The generated bibliometric network maps help highlight the trend in research and how publications have evolved within the field of study over the investigation timeline. The detailed methodology employed in the collation and bibliometric analysis of published articles is outlined in Figure 1.

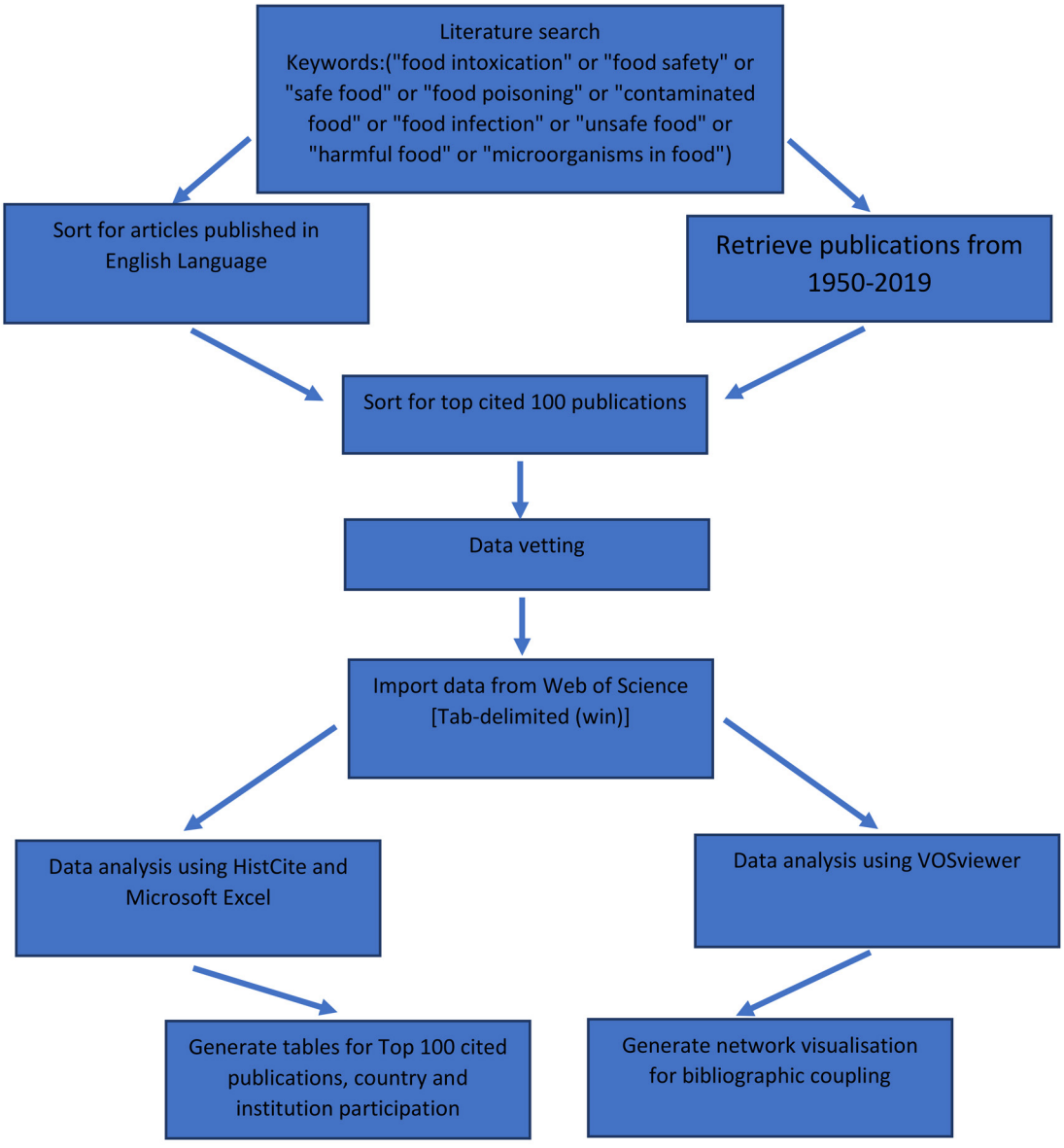

Figure 1. Data retrieval and analysis flowchart for the top 100 most cited papers on food safety.

Inclusion criteria

Articles were selected only after they met the following inclusion criteria:

- Original research articles (reviews were excluded)
- Published in English language
- Published between 1950 and 2020
- Contained any of the search keywords in the title, abstract or keywords.
- Studies that investigated the presence of or factors that contributed to hazards in foods, assessed microbial pathogens in foods, studied the impact of microorganisms and other contaminants in foods, the impact of unsafe foods on consumers, approaches to make food safe, food safety surveys, consumer perception of food and food policies.

Top-Cited Articles on Food Safety

A total of 29,449 publications were retrieved from the Web of Science database, including 22,221 research articles, 3,174 reviews, 3,345 proceeding papers and 912 book chapters. Others included editorial material, meeting abstracts, early accessed papers and letters. The most cited 100 research articles are shown in Supplement File 1. The highest cited article received 1,183 citations and was published in *Environmental Pollution* in 2008 (Khan *et al.*, 2008). The article studied the health risks associated with heavy metals in contaminated food crops irrigated with wastewater. The authors reported a substantial build-up of heavy metals in wastewater-irrigated soils in Beijing, China, highlighting that both adults and children consuming food crops grown in wastewater-irrigated soils ingested a significant amount of heavy metals which posed a risk to public health and safety. Although this article received the highest number of citations, it was not the article with the highest citation intensity when the year of publication was taken into consideration. The publication with the highest citation intensity was a report by the European Food Safety Authority (EFSA, 2017), which reported on the trends and sources of zoonoses, zoonotic agents and food-borne disease outbreaks. This article was published in 2017 and received a total of 645 citations (citation intensity of 161.25).

All top 100 studies were published between 1988 and 2017, and the the highest number of top-cited articles was published in 2008. Interestingly, the list of top-cited articles was dominated by 21st-century articles compared to older articles (20th-century articles), which ought to have had a higher number of citations as citation counts are expected to increase over time. Similar findings were reported by Shen *et al.* (2021), who found that the top-cited articles in the fields of food safety governance and management were from recent years compared to the earlier articles, with higher citations recorded by articles published between 1999 and 2019. This growth can be attributed to serious food safety and public health incidents that occurred in recent years. Furthermore, there is greater interest in food safety because of breakthroughs in scientific processes for the identification of microbial and nonmicrobial contaminants in foods, thus spurring more interest toward investigation and identification of foodborne diseases. Over the years, rapid and easy-to-use technologies, including hand-held spectral scanners and lateral flow assays, have been deployed in both laboratory and field for food analysis. These user-friendly approaches have made food safety investigations easier and more frequent, which, in turn, has lead to higher research output within the field (Qin *et al.*, 2017; Raeisossadati *et al.*, 2016).

Classification of Publications

The 100 top-cited articles discuss different aspects of food safety as categorized in Figure 2. The majority of articles focused on the outbreak of foodborne illnesses, followed by enumeration and identification of contaminating foodborne pathogens and the consumer awareness, perception, and attitude toward food safety-related issues.

Foodborne illnesses and contaminating microbial pathogens in foods are important food safety risks with growing global significance. Annually, there are 600 million reported cases of foodborne diseases, resulting in 420,000 deaths, of which about 30% of these occur in children aged less than 5 years (WHO, 2022a). This high magnitude of foodborne illnesses caused by microbial agents, including bacteria, fungi, parasites, toxins, and mycotoxins, and the potential of these organisms contaminating foods at any stage of the food production process or food chain lead to research interest in this sphere. Overall, more than 200 diseases are caused by foodborne microbial pathogens, and range from mild diarrhea to various cancers (WHO, 2022b). Interestingly,

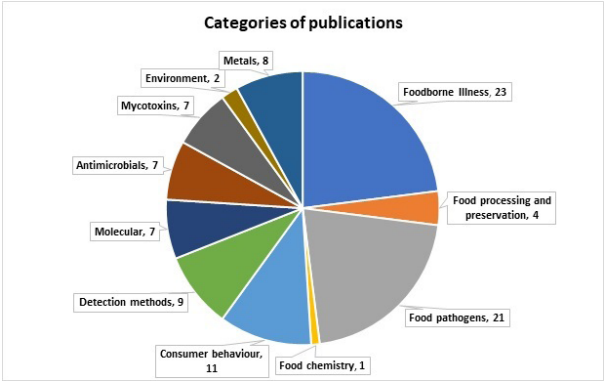

Figure 2. Categories of publications for the 100 top-cited papers on food safety.

the subject category of consumer awareness, perception and attitude toward food safety-related issues had a relatively good number of publications as shown in Figure 2. This suggests a growing consumer interest and awareness of food safety-related issues. Similarly, the subject categories of the use of state-of-the-art detection methods, heavy metals, mycotoxin, and contaminant analyses were also among the top-cited publications. This indicates the broad nature of the top-cited researches, and the fact that all aspects of food safety, including those which were previously not visible or prominent, are currently gaining traction. These findings indicate the interdisciplinary/multidisciplinary nature of food safety research that can help researchers identify the most influential contributions to the field of food safety, leading to ideas for the future endeavors and collaborations. Of the top-cited publications, some of the most remarkable include Scallan et al (2011), which focused on major agents of foodborne illnesses in the United States, the European Union's summary of the sources and trends of zoonoses and zoonotic agents (EFSA, 2015, 2017), the global and regional estimates of disease burdens (Kirk *et al.*, 2015), environmental studies on heavy metals (Khan *et al.*, 2008; Sharma *et al.*, 2007; Toth *et al.*, 2016), and microplastics in bivalves (Van Cauwenberghe and Janssen, 2014). These studies have gained remarkable traction in the recent decade.

Journal contribution to the top 100 publications

The 100 top-cited papers were published in 48 journals. The number of articles per journal ranged from 1 to 10, with 17 journals having two or more publications, as shown in Table 1. The 2021 journal impact factor of contributing journals was obtained from Clarivates Journal Citation Reports (JCR) using Web of Science access. The majority of top publishing journals had a high impact factor (between 1.581 and 10.500), which showed relevance, visibility, coverage and impact of articles published in them (Garfield, 2006).

The *Applied and Environmental Microbiology* and the *International Journal of Food Microbiology* published the largest number of articles (10). This was expected as the scope of these two journals encompasses food spoilage, foodborne infections and contaminations, these being core topical areas of food safety research. However, the highest number of citations (2,499) was recorded by the *EFSA Journal* (impact factor = 3.480) whereas the highest average citation per document was by *Environmental Pollution* (860). The journal with the highest impact factor was *Clinical Infectious Diseases* (impact factor = 20.999). However, this journal published only two of the highly cited papers but received 727 citations. The *Journal of Food Protection* had the lowest impact factor at 2.755 and published five articles in the 10 top-cited publications. From the data obtained in this study, there is no relationship between the number of publications in a journal and the journals impact factor. This indicates that researchers publishing in the field of food safety focus not only on the impact factor but also on the influence of a journal and its scope in their discipline. Also, the average number of citations for each article was not correlated with the journal's impact factor. A similar trend was observed between the number of top-cited studies and journal impact factors in the top 100 papers on vaccinology (Zhang *et al.*, 2019). Similar findings were observed in a bibliometric study on long non-coding ribonucleic acid (lncRNAs), in which only 18.86% of all publications appeared in journals with an impact factor of 3.00 and above (Miao *et al.*, 2017). This occurrence indicated that even across disciplines, most researchers focused not only on the impact factor of a journal but on the journal's influence/scope of relevance in their discipline when choosing journals for publishing their research. However, the bibliometric analysis of food safety governance research from 1999 to 2019 found a linear relationship between the top eight scholarly journals and their impact factors (Shen *et al.*, 2021). Our study does not support the theory that the number of publications and citations are positively correlated to the impact factor. Thus, the value of impact factor of a journal is not an effective predictor of citations received by an article.

Visualizations of the 17 journals involved in publishing the top-cited 100 articles are shown in Figure 3, revealing the co-citation association of articles published in them. Similar to the trend reported in Table 1, the *Applied and Environmental Microbiology* had the highest link strength, with connections to the following nine journals: *Foodborne Pathogens and Diseases*, *Clinical Infectious Diseases*, *Journal of Food Protection*, *Journal of Applied Microbiology*, *Epidemiology and Infection*, *Journal of Clinical Microbiology*, *International Journal of Food*, *Systematic and Applied Microbiology*, and *Journal of Infectious Diseases*. Similarly, the strongest coupling between two publication sources was between *Applied and Environmental Microbiology* and *Clinical Infectious Diseases*, underlining the pivotal nature of publications in these two journals to retrieve food safety-related information. Three journals, *Food Policy*, *Environment International*, and *Environmental Pollution*, were not linked to other publications, showing that although the articles published in them were highly cited, food safety was not the main scope of these journals.

Country contribution to research

A total of 42 countries were involved in the top 100 publications. The country with the highest number of

publications in the field of food safety within the top-cited 100 publications was the United States (n = 20), followed by the United Kingdom (n = 15), Italy (n = 9) and The Peoples Republic of China (n = 9). Other top contributing countries were Canada, Germany, Australia, the Netherlands, Denmark, Switzerland, Belgium, Spain, Japan, New Zealand, South Korea, Brazil, and France. A total of 20 countries (not listed) contributed only one article to the top 100 publications. Table 2 shows countries involved in the publication of a minimum of three articles. This trend is consistent with previous bibliometric analysis conducted in the areas of dental health, vaccinology, and long non-coding RNAs (Mattos *et al.*, 2021; Peng *et al.*, 2021; Zhang *et al.*, 2019).

The pronounced influence of the United States may be attributed to its large number of scientific research institutions and abundant research funds (Zhang *et al.*, 2020). It may also be due to the broader influence and ability of researchers to attract an audience and collaborations. It is interesting to note that despite the numerous food safety incidences all over the world, especially in developing countries, the top 16 countries having at least three publications were from developed countries. This is interesting because developing countries have a higher burden of food safety-related issues and outbreak of foodborne diseases. This paucity of publications from developing countries may be related to the several challenges facing researchers from these regions, including lack of funding and infrastructure, to conduct research and inadequate policy frameworks. However, with the multinational scope of food safety research as evidenced in this study, in the future, there would be space for growth in the quality and quantity of food safety research conducted in developing countries.

Figure 4 presents a visualization of the linkages among the top 16 publishing countries in food safety. The level of contributions by the country is indicated by the size of the country node, while their relationship with other publishing countries is highlighted by the thickness of the linking lines to the partnering countries. These indicate the strength of collaboration among the countries (Van Eck and Waltman, 2010). These countries are divided into three clusters of collaboration. The highest collaborating country was the United States, with 15 links (15 publications among the top 100 were published by US authors in collaboration with other countries). The strongest collaboration was between the United States and Switzerland and between the United States and the Netherlands. Similarly, there was a strong collaboration between Switzerland and the Netherlands. The high contribution of research by the United States could also be attributed to increased monitoring of food safety issues and newer regulations and policies that have revolutionized the sector following repeated outbreaks of foodborne illnesses across the country (Dewey-Mattia *et al.*, 2018). One such regulation was the Food Safety Modernization Act (FSMA) which laid down rigorous guidelines for food operators within the United States to follow (US Food and Drug Administration (USFDA), 2018). This has had the effect of greater awareness of food safety issues and increased research output, especially in the area of developing novel technologies for food processing, including radiofrequency processing, use of antimicrobial peptides, supercritical carbon dioxide, ultrasound, cold plasma,

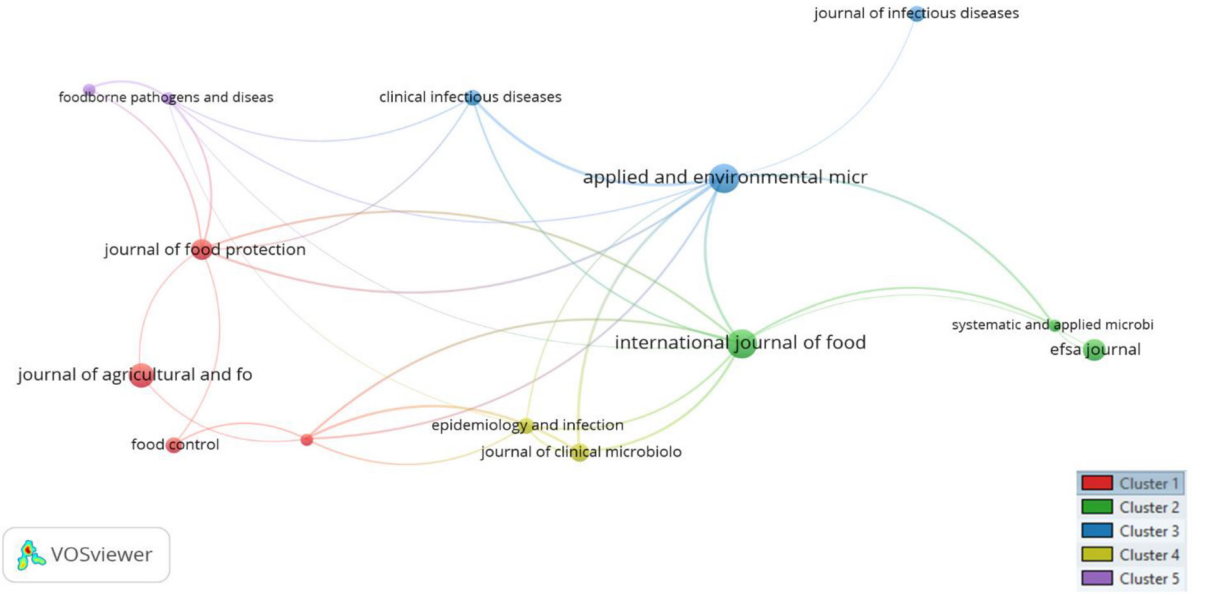

Figure 3. Bibliographic coupling of publication sources for the top 100 most cited papers on food safety.

Table 1. Publication by journals for the top 100 most cited papers on food safety.

S. No.	Journal	Impact factor (2021)	Publications	Citations	Average citation
1.	Applied and Environmental Microbiology	5.005	10	2,070	207.00
2.	International Journal of Food Microbiology	5.911	10	1,868	186.80
3.	Journal of Agricultural and Food Chemistry	5.895	7	1,175	167.86
4.	EFSA Journal	3.480	6	2,499	416.50
5.	Journal of Food Protection	2.755	5	967	193.40
6.	Journal of Clinical Microbiology	11.677	4	1,054	263.50
7.	Clinical Infectious Diseases	20.999	3	413	137.67
8.	Environment International	13.352	3	858	286.00
9.	Epidemiology and Infection	4.434	3	667	222.33
10.	Food Control	6.652	3	426	142.00
11.	Journal of Infectious Diseases	7.759	3	1,212	404.00
12.	Environmental Pollution	9.988	2	1,720	860.00
13.	Food Policy	6.080	2	342	171.00
14.	Foodborne Pathogens and Disease	3.788	2	598	299.00
15.	Journal of Applied Microbiology	4.061	2	382	191.00
16.	PLOS Medicine	11.613	2	727	363.50
17.	Systematic and Applied Microbiology	4.064	2	287	143.50

Table 2. Country participation in the 100 top-cited papers on food safety.

S. No.	Country	Publications	Citations
1.	USA	33	8,613
2.	UK	15	4,045
3.	Italy	9	2,886
4.	China	9	2,647
5.	Belgium	6	2,045
6.	Japan	6	1,795
7.	Spain	6	865
8.	Switzerland	6	1,661
9.	The Netherlands	5	1,283
10.	Canada	4	1,198
11.	France	4	759
12.	Australia	3	887
13.	Austria	3	437
14.	Denmark	3	1,034
15.	New Zealand	3	764
16.	South Korea	3	602

and *sous vide* processing for elongation of the shelf-life of foods (Anumudu *et al.*, 2021; Hart *et al.*, 2021; Jeong *et al.*, 2020; Onyeaka *et al.*, 2021, 2022; Varilla *et al.*, 2020) as highlighted in previous reviews.

Contribution of institutions to research

A total of 215 institutions contributed to food safety-based research. The highest number of articles (10) was published by the Center for Disease Control and Prevention (CDC), while USFDA published six articles. A total of 11 institutions had three or more publications, as presented in Figure 5. Of note is that the top institutions from which publications emanated were in the United States, showing that the core of food safety-based research was conducted in America. This could be attributed to the large number of institutions in that country, Gross Domestic Product (GDP) and funding availability (Man *et al.*, 2004). Although ranking of institutions usually resembled country rankings, some vital distinctions were found in the present study. Among the 11 institutions that had three or more publications, the United States-based institutions were six, having a total of 30 publications, followed by Belgium-based institutions, having a total of eight publications, while China, Italy and the Netherland had three publications each. Centers and institutions located in developing countries did not significantly contribute to the 100 top-cited papers, probably because of limited access to information, gaps in professional networking, language barrier (Fenton *et al.*, 2002) and insufficient funding. Furthermore, the FSMA, which was passed by the US government in 2011, placed more stringent regulations on the maintenance of food safety, with a focus on employing preventive rather than reactive approaches to food safety. The FSMA mandate that all food manufacturers must be FSMA-compliant by 2024 (USFDA, 2020) has increased interest and funding in food safety research, with a corresponding increase in research output within the country. Within the United States, the National Institute of Food and Agriculture (NIFA) allocated a total of $4.3 billion to food and agriculture-based research between 2019 and 2021 (US

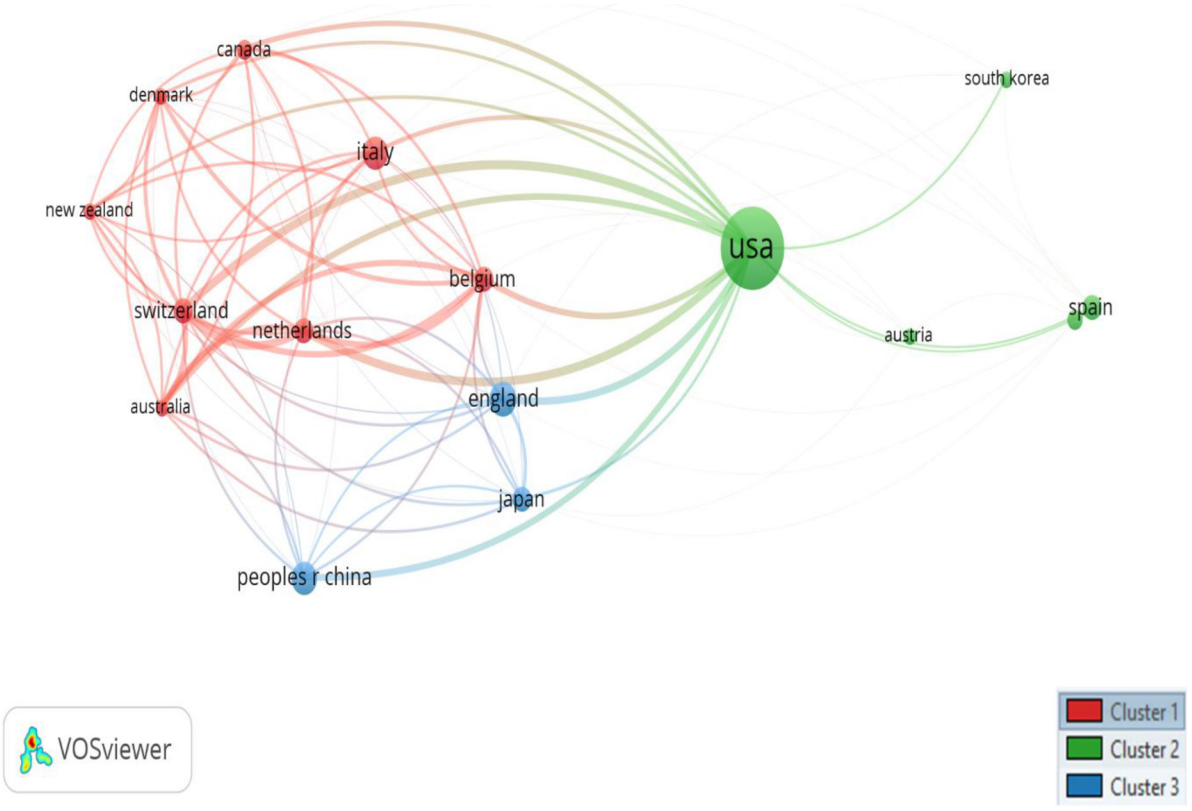

Figure 4. Network visualization of bibliographic coupling (collaboration) among publishing countries of the 100 top-cited publications on food safety.

Department of Agriculture [USDA], 2019, 2020, 2021). In addition, research has shown that countries, such as the United States, with a high GDP tend to allot substantial investments to scientific investigation and employ more senior researchers (Moon *et al.*, 2017). Thus, the GDP and the number of research institutes in the United States could be major contributors to the large research output from that country.

Occurrence of Keywords

A total of 732 keywords were used in the 100 top-cited articles. Of these, 27 occurred for a minimum of five times. The most often applied keywords were: food safety (16), *Salmonella* (10), food (9), identification (8) and surveillance (8). Co-occurrence of keywords as visualized in Figure 6 indicates the keywords that were used in association with one another and this helped to identify relevant keywords for effective retrieval of published literature within this field. The spread of the keywords also indicated the direction of research in the field. The keywords were grouped into two clusters (red and green) based on their association and usage. In the green cluster, the keyword "*Salmonella*" had the highest link strength and was linked to 22 other keywords. This was followed by "monitoring" connected to 16 other keywords. In the red cluster, "*Listeria monocytogenes*" had the highest link strength, connecting to 17 other keywords, followed by "food safety" (11 connections). *Salmonella* sp. and *Listeria monocytogenes* are two of the most important pathogens with regard to microbial foodborne contamination, with most outbreak of foodborne diseases and product recalls associated with these bacteria (Ehuwa *et al.*, 2021; Shamloo *et al.*, 2019). An understanding of recurring keywords within a research field is vital for scientific bodies and young researchers when choosing future research work, retrieving published literature and publishing articles more effectively (Loonen *et al.*, 2008).

Advances in Food Safety Research and the Future Perspectives

The majority of research focus in the area of food safety has been on microbial contamination and metabolites in foods. Recent issues related to chemical contamination of foods, including pesticides and the use of unauthorized preservatives, have highlighted the need to broaden the scope and focus of food preservatives. Research toward this new area is growing, with efforts geared toward the detection of contamination above the maximum residue

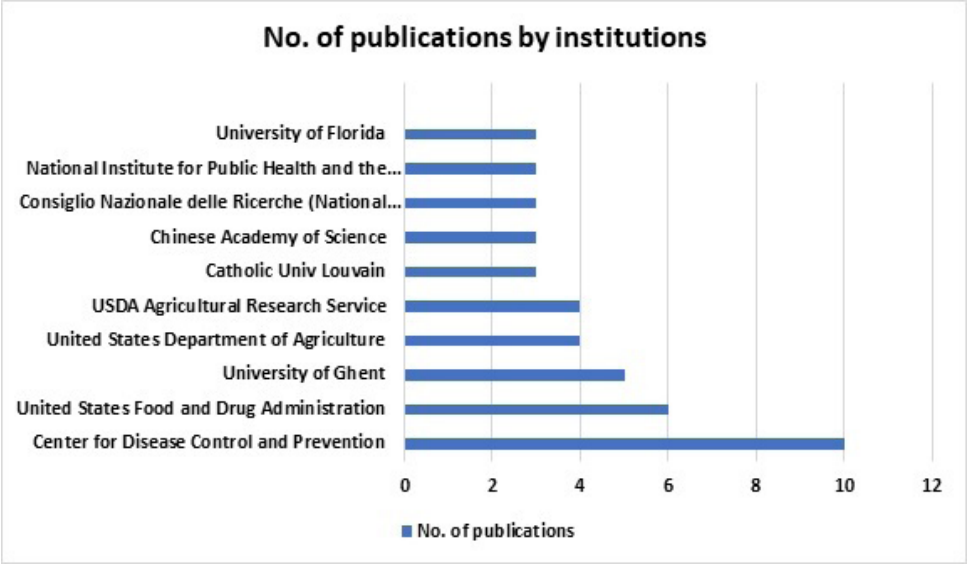

Figure 5. Institution participation in the 100 top-cited papers on food safety.

limits (MRLs). This spans from high-*performance liquid chromatography*–mass spectrometry (HPLC-MS) methods for detecting organochlorines in food items, such as honey (Alghamdi *et al.*, 2020), to the use of more rapid and user-friendly immunoassays and biosensors, such as gold nanobiosensor (AuNP), that are employed in the measuring of common pesticide dichlorodiphenyltrichloroethane (DDT; 1,1-(2,2,2-trichloroethane-1,1-diyl) bis(4-chlorobenzene)) in different food matrixes (Lisa *et al.*, 2009). Other approaches which are employed for detecting pesticides and chemical contaminants in foods include Surface-Enhanced Raman Spectroscopy (SERS), effective in the detection of mixed pesticides and residues in foods and is validated for fruit juice, milk and rice (Alsammarraie and Lin, 2017; Logan *et al.*, 2022). The use of SERS and surface plasmon resonance (SPR) for assurance of food safety is growing, and it is imperative that the technology is improved continually to become more rugged, portable, and cheap with minimal sample preparation (Huang *et al.*, 2020). Chemical contaminants and pesticides in food are an important food safety concern. These could be from anthropogenic source or occur naturally (Thompson and Darwish, 2019), and irrespective of their mode of entrance into food and the food supply chain, they have far-reaching health implications. These can range from numerous forms of cancers to hepatic disorders, cardiovascular diseases, and neurological and reproductive disorders (Rather *et al.*, 2017). Furthermore, the consumption of such contaminated foods by mothers can affect the child, resulting in low birth weight, immunodeficiency and stunting (Currie *et al.*, 2013). These adverse health effects could be debilitating, and thus it is important to channel food safety research toward development of validated methods for the analysis of multiple chemical contaminants in varied food matrixes.

Similar to chemical contaminants in foods, food frauds or economically motivated adulteration of foods is a growing concern within the food sector. Food frauds not only affect consumer confidence in foods with huge economic consequences in lost earnings but also pose a potent food safety risk. Over the years, the far-reaching health consequences of food frauds and their effects on food safety have been highlighted. Major incidences, such as melamine in milk scandal, in which pet foods and infant formula were fraudulently fortified with the organic compound to improve its value resulting in thousands of infant hospitalizations and deaths (Chan *et al.*, 2008; Xiu and Klein, 2010), has highlighted the fatality of food frauds. In recent years, reports have come out of various cases of food frauds, which span from substitution to addition frauds and mislabelling. This is exemplified in European horse meat scandal and the addition of Sudan red dyes in spices (Spink and Moyer, 2011; Spink *et al.*, 2019). Indeed, almost all food products can be adulterated and the perpetrators of food frauds have become smarter, evading conventional methods used for fraud detection. Thus, to combat food frauds, novel approaches for their detection has to be continually standardized to keep up with the menace. Food fraud incidences such as mislabelling and region of origin fraud, as is rampant in some food items, including rice, wine and honey, can be detected and prevented using inductively coupled plasma atomic emission spectroscopy (ICP-AES) to detect the elemental fingerprint of food product, thus differentiating them from species cultivated in other regions (Chung *et al.*, 2015). Similarly, other technologies, such as Fourier

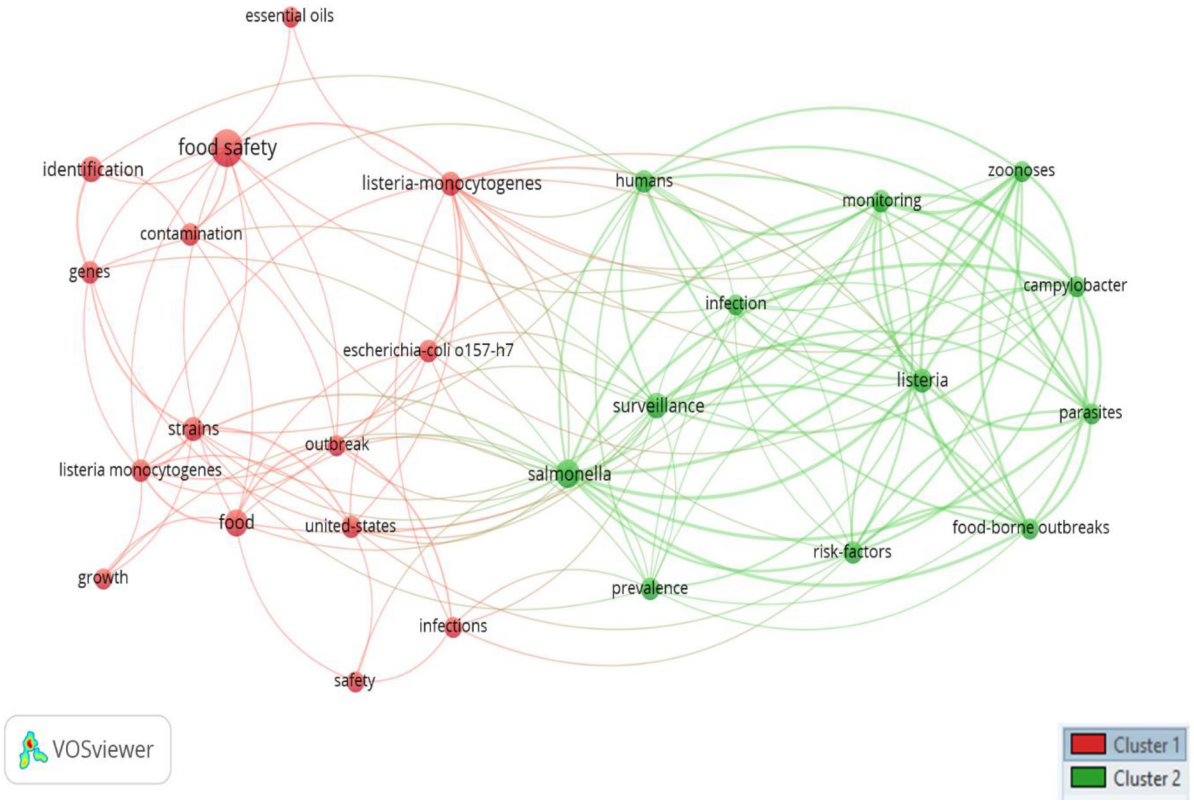

Figure 6. Co-occurrence of keywords used for a minimum of five times in the 100 top-cited papers on food safety.

Transform Infra-Red (FTIR) spectroscopy, species-specific mitochondrial (mt)DNA analysis, Nuclear Magnetic Resonance (NMR) and other methods, have been employed to test the authenticity of different food matrixes, including meat, cheese, milk, milk products and others (Jung *et al.*, 2010; Lerma-García *et al.*, 2010; Mortensen *et al.*, 2006; Reed *et al.*, 2007). The challenge with using current methods of detecting food fraud is that they require specialist knowledge, are expensive and not readily available, and need elaborate sample preparation. Thus, for detection and reduction of food frauds and assurance of food safety, more robust user-friendly, cheap and rapid methods need to be developed, and this should guide the focus of research in the field.

Limitations of Study

One of the most important limitations of this study was that bibliometric analysis was not able to assess the validity or level of scientific evidence reported by analyzed publications (Yeung, 2018). A highly cited article may not necessarily have high scientific quality, and the number of citations received by a publication depends on several factors, which are beyond the scope of this study. Furthermore, the current bibliometric review was biased toward articles published in English only. There could be relevant and impactful publications in other languages as well but were not considered in this review. In addition, it must be noted that the first author's affiliation determined location of the country of the paper, and collaborative research groups could include researchers from different institutions and countries; thus, the country of origin of a paper was not very definitive. Finally, over time, the number of citations of each publication changes; thus, the 100 top-cited articles within this field of analysis would also change. Despite these limitations, we believe that being the first citation-analysis in food safety, our findings would contribute to understand trends in food safety publications.

Conclusion

We identified and analyzed the 100 top-cited publications in food safety, classifying them according to focus of research, year of publishing, publishing journals, country of contribution to research, institutions' contributions to research, and occurrence of keywords. These data provided insight into the most impactful studies related to food safety. Thus, this would aid researchers and organizations to enhance their understanding regarding the trends and influential contributions to food safety research and foster scientific evidence for

their decision-making processes and ideas for the future study. Furthermore, advances and the future perspectives in food safety, relevant to stakeholders within the food industry, were identified; especially the use of novel food processing technologies which when incorporated into the food chain system would ensure wholesomeness of foods, microbial safety and food security. Overall, this study highlighted that research focused on food safety was growing rapidly globally and developed across several fields, including biotechnology, microbiology, food processing and preservation, consumer studies and policy development. Food safety publications have traditionally emphasized on microbial contamination of foods and food processing and preservation to reduce microbial spoilage and foodborne illnesses. There is a dearth of research articles in the areas of chemical contamination of foods by pesticides and other chemical residues and food fraud detection and prevention studies. Thus, the future research efforts must be geared toward approaches to detect these contaminants in foods and strategies toward preventing food frauds using scientific tools to access food fraud vulnerabilities and detect adulterated foods.

Conflict of Interest

The authors declared no conflict of interests.

Author Contributions

The conceptualization and designing of this research was done by Helen Onyeaka and Christian K. Anumudu. Research methodology was done by Christian K. Anumudu. Software and analysis was performed by Chioke A. Okolo and Christian K. Anumudu. Original draft was prepared by Christian K. Anumudu, Helen Onyeaka and Olumide Odeyemi. Review and editing were done by Christian K. Anumudu, Amara Anyogu and Anthony P. Bassey. Visualization was done by Christian K. Anumudu and Olumide Odeyemi, and project administration was handled by Helen Onyeaka. All authors read and agreed to the published version of the manuscript.

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