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Mapping the knowledge structure of a gluten-free diet: a global perspective

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Abstract

Background A gluten-free diet (GFD) has become one of the most popular eating plans and is essential for managing gluten-related medical conditions, signs, and symptoms. Therefore, we performed a bibliometric analysis of the scientific literature on the GFD to describe the research landscape.

Methods The Scopus database was searched for publications on the GFD from 1952 to 2021. A bibliometric analysis of the data was performed. VOSviewer software was used to perform visualization analysis, co-occurrence analysis, and publication trends in GFD.

Results A total of 3,258 publications were retrieved. In terms of publications, Italy ($n=468$, 14.36%) led in the number of publications, followed by the USA ($n=398$, 12.22%) and Spain ($n=274$, 8.41%). The retrieved documents earned an average of 22.89 citations per document, for a total of 74,560 citations. Since 2001, there has been a gradual growth in the number of articles published, going from 23 to more than 370 in 2021. Using the mapping terms in the title/abstract a minimum of 50 times, 291 terms were divided into two main clusters: '*adherence to a gluten-free diet in celiac disease*' and '*improvement of the nutritional and sensory quality of gluten-free products.*'

Conclusions Over the past six decades, there has been a growing need for gluten-free bakery products and a noticeable increase in related publications. This study indicates that the "*improvement of the nutritional and sensory quality of gluten-free products*" will remain a hotspot in this research field for upcoming years.

Keywords Gluten-free diet, Scopus, VOSviewer, Bibliometric, Global

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Introduction

According to the World Health Organization (WHO), a healthy diet is the best way to protect against malnutrition, cardiovascular diseases, diabetes and some types of cancer [1]. In addition, various worldwide dietary guidelines have reported that a healthy diet should be balanced and varied. However, some medical conditions, food allergies, or intolerance require a special diet to be considered healthy, such as the diet of Dietary Approaches to Stop Hypertension (DASH) for hypertensive patients, a renal diet for chronic kidney diseases, and a gluten-free diet (GFD) for intolerant patients or other medical reasons. These examples exclude any food components that could harm some people [2].

A GFD requires complete gluten exclusion, a protein complex soluble in ethanol in food products such as wheat, rye, barley, and triticale. There are many naturally available gluten-free (GF) food products, such as vegetables and fruits, dairy products, eggs, fish, and meat. In addition, GF alternatives manufactured specifically for wheat-based foods can be used as a GFD [3, 4].

Many conditions require treatment with a GFD, including allergies and intolerances such as gluten sensitivity, wheat allergy, celiac disease (CD), and others. Allergies occur as an immunologic reaction in individuals upon ingestion of wheat proteins; CD is a chronic autoimmune disorder triggered by gluten ingestion, resulting in histological changes in the small intestine due to the autoimmune reaction. Individuals with CD experience malabsorption, other gastrointestinal and extraintestinal symptoms [5, 6]. Strict adherence to the GFD is the only effective first-line treatment for CD that leads to duodenal mucosa healing along with the resolution of CD symptoms and signs of malabsorption of CD [6]. GFD is also an interesting therapeutic option for preventing and treating type 1 diabetes, depending on many promising animal studies. Gluten has multiple effects on the gastrointestinal tract, affecting the composition of the microbiota, inducing enteropathy in type 1 diabetes, and increasing intestinal permeability, all of which can be improved using a GFD [7].

Other studies shed light on the possible effect of the use of a GFD with probiotics in patients with major depressive disorders depending on the fact that a diet free of gluten has great potential to reduce the severity of depression symptoms in gluten-related disordered subjects [8]. Furthermore, supplementing a combination containing probiotics and a GFD might be crucial to inhibiting the immune-inflammatory cascade, which can regulate the central nervous system and digestive tract functions in patients with major depressive disorder [9].

While a GFD is recognized as productive for numerous conditions, patients must receive guidance and education about diet from qualified professionals. This is especially important due to the tendency of some variations of this diet to be high in carbohydrates and lipids while lacking in essential vitamins and fiber [10]. Furthermore, individuals adopting a GFD might encounter challenges related to excessive weight gain and obesity, as they often consume energy-rich gluten-free products [11]. Some gluten-free food items include quinoa, brown rice, almond flour, chickpea pasta, and gluten-free bread. Consequently, the food industry continuously expands its offerings by introducing innovative cereal-based gluten-free options. Unfortunately, a notable portion of gluten-free products falls short when compared to their gluten-containing counterparts, particularly with regard to nutritional composition and sensory attributes. Nutritionally, gluten-free breads tend to lack essential macronutrients and micronutrients such as protein, iron, calcium, and vitamins. This deficiency can lead to nutritional inadequacies for individuals with celiac disease [12–18].

However, it is important to acknowledge that not all gluten-free products are equal, and some may contain high levels of sugar or unhealthy fats [19]. Therefore, it is advisable to carefully review product labels and opt for items that are rich in nutrients and crafted from whole, unprocessed ingredients [20].

In recent years, the GFD has received substantial interest in a range of clinical research fields, including those indicated above, and an increasing number of studies are being published on the topic [21–25]. Therefore, we predicted that there might be numerous hotspots and research focuses in the area of the GFD. However, only a few attempts have been made to comprehensively evaluate the CD area's scientific output and current condition from a global perspective [26–29]. As a result, it is extremely important to shed light on the current state of GFD research and its application on a global scale, as well as prospective research trends and hotspots.

The bibliometric technique is the best method to analyze specific research trends that affect a given subject over time and to compare the contributions made between countries, institutions, and journals [30, 31]. Therefore, our bibliometric study of the literature on this topic will help to solve research gaps and increase understanding of the most recent viewpoints of the GFD. Thus, bibliometrics were performed to investigate potential focuses within this area of research for a thorough analysis of the present state of global GFD research using data from Scopus. Overall, a bibliometric analysis can offer insightful information about global research patterns and the organization of the knowledge base surrounding gluten-free diets. This can be aided by making wise choices about the direction of

research and the distribution of resources for researchers, decision-makers, and other stakeholders.

Materials and methods

Search strategies and data collection

A bibliometric approach was applied. SciVerse Scopus was used to carry out the current study. Scopus is the most popular and authoritative database of research publications and citations, containing publications from journals with the highest global impact. The bibliometric indicators used in the current study were the same as those used in previously published studies [32–34]. To improve the accuracy of the retrieved data, the search was restricted to the title and abstract of publications in the Scopus database because if extended to all fields of search, such as keywords or the full text of publications, many irrelevant publications would be obtained (i.e., false positive data). Scopus does not consider keywords as authors. Instead, Scopus uses various algorithms to match documents to relevant keywords, which can sometimes lead to the generation of false-positive results. In addition, Scopus also uses indexed keywords such as "EMTRE drug terms," "EMTREE medical terms," and "Medline keywords." These keywords are pre-defined by Scopus and can limit the search results to a specific field, but they can also lead to false positives if the search terms are too broad or not relevant to the research question. Using this approach will result in a considerable improvement in the level of specificity achieved, while the level of sensitivity may suffer slightly as a result. "Gluten-free" was used as a search term to search Scopus titles for all prior years up to 31 December 2021. We chose the keyword "gluten-free" because we are more interested in gluten-free as a concept than related terms. The productivity of scientific research beyond 2021 was omitted from the analysis because this time was still available for new journal issues. All data extraction was performed on a single day (4 August 2022) to avoid daily Scopus updates. The search strategy was validated for the absence of false positive documents by scanning the abstract of the top 500 cited documents in the retrieved literature.

Bibliometric analysis

We conducted bibliometric analysis from the following aspects: countries' contribution to publications, citations, and H-Index, growth trends of publications, types of publications, and contributions of institutions, funding agencies, and journals.

Visualization analysis

VOSviewer software version 1.6.8 was used to map the retrieved literature [35–37]. VOSviewer was used to display and develop a network of terms derived from titles and abstracts. The terms were simultaneously separated into clusters based on co-occurrence analysis and color-coded by time course. Furthermore, an average appearance year was established to evaluate emerging topics and detect a developing trend.

Results

Description of publications

Based on an analysis of the Scopus database, 3,258 GFD-related documents published between 1952 and 2021 were retrieved. Research articles ($n=2514$, 77.16%) constituted the majority of the retrieved documents, followed by reviews ($n=237$, 7.27%) and letters ($n=121$, 3.71%). Other types of documents included 11.84% ($n=386$).

Growth trends of publications

The first article on a GFD was published in 1952, entitled 'Gluten-free diet in idiopathic steatorrhoea: report of a case' [38]. Before 2001, this research area received little attention from researchers. Since 2001, there has been a gradual growth in the number of articles published, going from 23 to more than 370 in 2021 (Fig. 1).

Active countries and research collaboration

Authors from 91 different countries contributed to the retrieved documents. The top ten active countries are shown in Table 1. The top ten countries contributed approximately 60.93% ($n=1984$) of the documents retrieved. Italy ($n=468$, 14.36%) was the leader in the number of publications, followed by the USA ($n=398$, 12.22%), Spain ($n=274$, 8.41%), and Brazil ($n=204$, 6.26%). The mapping of the research collaboration of the leading active countries showed that the USA, Italy and Spain had the strongest research collaboration with other countries (Fig. 2).

Top ten active institutions

Table 2 shows the top ten active institutions in research on the GFD. The top ten countries contributed to approximately 9.82% ($n=320$) of the retrieved documents. Again, institutions from the European Union dominated the list. However, the *Universita degli Studi di Milano*, an Italian research institute, was the main active institution (n=79, 2.42%), followed by the *University College Cork*-Ireland ($n=75$, 2.30%), the *Universidad de Valladolid*-Spain ($n=61$, 1.87%) and *CSIC—Instituto de Agroquimica y Tecnologia de los Alimentos IATA*-Spain ($n=60$, 1.84%). The top ten list included two institutions from Italy, Spain, Finland, and Poland.

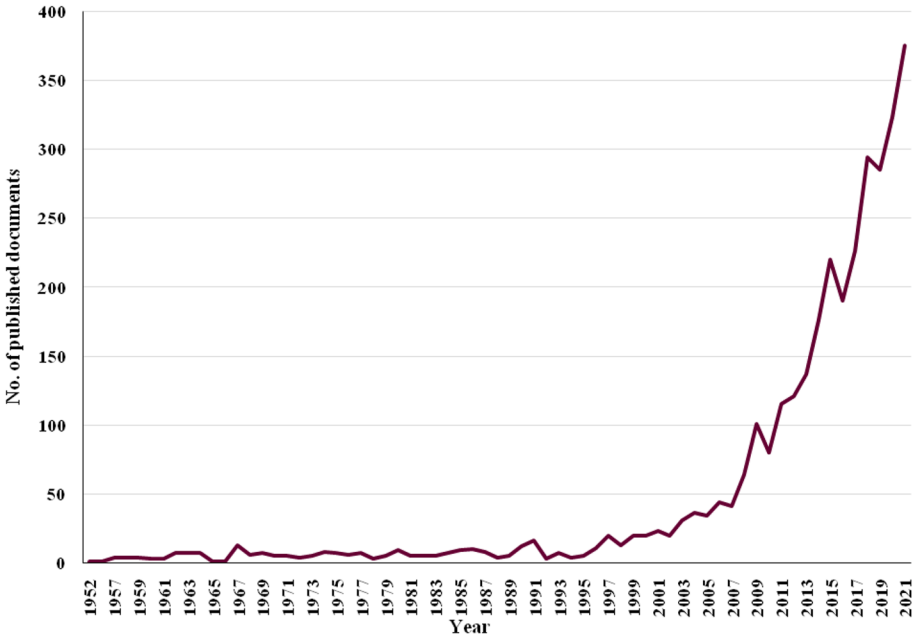


Fig. 1 The global number of publications related to the gluten-free diet from 1952 to 2021

Table 1 The top 10 productive countries/regions involved in a gluten-free diet from 1952 to 2021

Ranking	Country	No. of documents	%
1st	Italy	468	14.36
2nd	United States	398	12.22
3rd	Spain	274	8.41
4th	Brazil	204	6.26
5th	Poland	198	6.08
6th	United Kingdom	184	5.65
7th	India	120	3.68
8th	Turkey	115	3.53
9th	Germany	109	3.35
10th	Canada	102	3.13

Analysis of research funding agencies

Table 3 lists the top ten funding agencies in terms of GFD publications. The *European Regional Development Fund* (EU) funded a large number of publications ($n=67$; 2.06%). The *European Commission* (EU) came second ($n=56$; 1.72%), followed by the *Ministerio de EconomÃa y Competitividad* (Spain) ($n=46$; 1.41%).

Journal analysis

We identified the ten most productive journals in this field (Table 4). *Nutrients* ranked first in the number of publications ($n=104$, 3.19%), followed by *Lebensmittel-Wissenschaft & Technologie* ($n=80$, 2.46%) and the *International Journal of Food Science and Technology* ($n=69$, 2.12%).

Citation analysis

The retrieved documents earned an average of 22.89 citations per document, for a total of 74,560 citations. 105 was the H-index of the retrieved documents. Five hundred forty-two of the retrieved documents did not have any citations, but 143 of the documents received 100 or more citations. In terms of the number of times they were cited, the top ten articles received a total of 4,214 citations [39–48]. There was a wide range in the total number of citations for these GFD publications, from 257 to 936 (Table 5).

Co-occurrence term analysis

The terms in the title/abstract were used a minimum of 50 times, and of the 41,738 terms used, 291 terms were divided into two main clusters: the green cluster focused on 'adherence *to a gluten-free diet in celiac disease*,' while the red cluster focused on the results of '*improvement of the nutritional and sensory quality of gluten-free products*' (Fig. 3).

Future research direction analysis

Each term in Fig. 4 was colored differently by VOSviewer based on the average frequency with which it appeared in all the retrieved publications. Overlay visualization revealed that the yellow group represented recent research in this field, while the blue

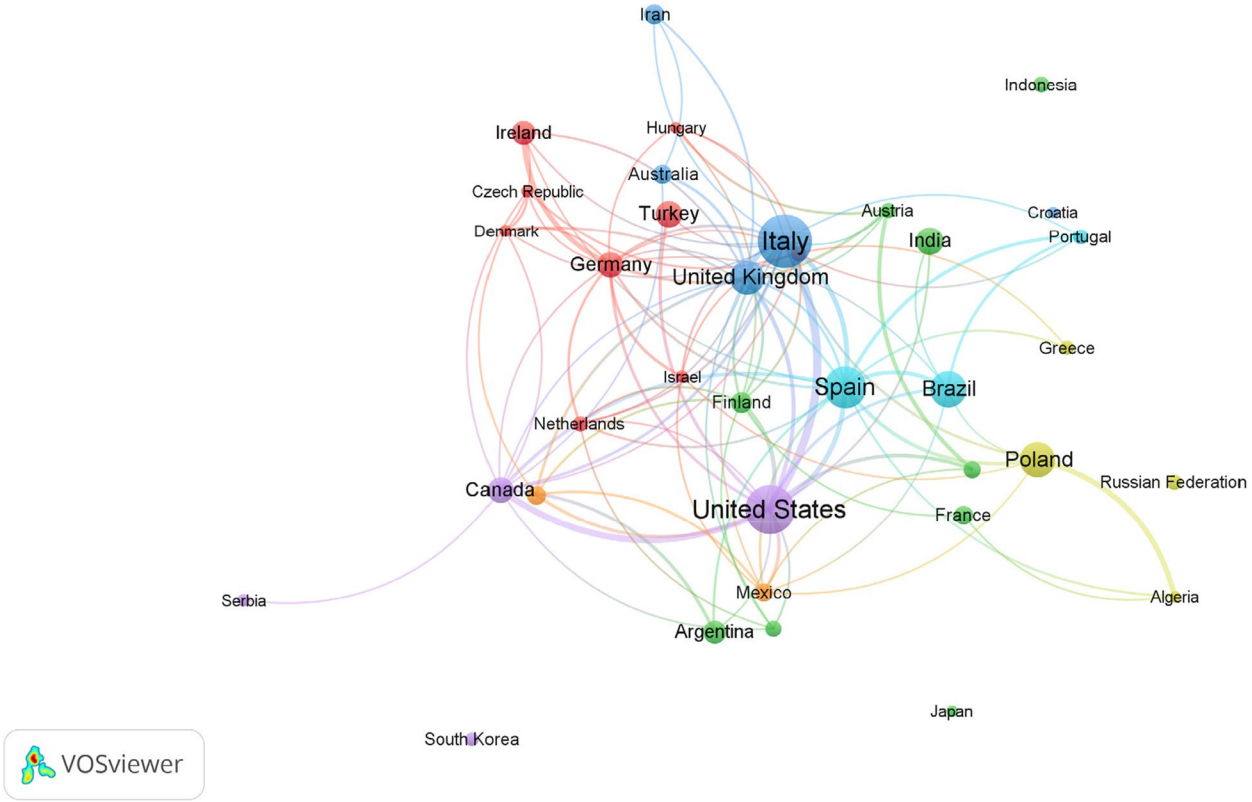


Fig. 2 International research collaboration among the main active countries (20 documents *per* country was established as a threshold ($n = 36$). The thickness of the connecting line represents the strength of research collaboration, whereas the node size is a relative representation of the research output

Table 2 The top 10 productive institutions involved in the gluten-free diet from 1952 to 2021

Ranking	Institute	Country	No. of documents	%
1st	*UniversitÃ degli Studi di Milano*	Italy	79	2.42
2nd	*University College Cork*	Ireland	75	2.30
3rd	*Universidad de Valladolid*	Spain	61	1.87
4th	*CSIC—Instituto de Agroquimica y Tecnologia de los Alimentos IATA*	Spain	60	1.84
5th	*Consejo Nacional de Investigaciones CientÃficas y TÃ©cnicas*	Argentina	45	1.38
6th	*Tampere University*	Finland	44	1.35
7th	*UniversitÃ degli Studi di Napoli Federico II*	Italy	39	1.20
8th	*University Hospital of Tampere*	Finland	36	1.10
8th	*University of Life Sciences in Lublin*	Poland	36	1.10
10th	*Institute of Animal Reproduction and Food Research of the Polish Academy of Sciences*	Poland	35	1.07

cluster represented relatively older research. Before 2014, the primary focus of this field was *"adherence to a gluten-free diet in patients with celiac disease."* The *"improvement of the nutritional and sensory quality of gluten-free products"* was focused on later (after 2014), reflecting the most recent research advances.

Discussion

In this work, we used bibliometric analysis to illustrate the global research landscape of the GFD for all previous years. There were 3,258 items in total. Research on GFDs has blossomed and attracted the world's attention, particularly in Italy, the United States, and Spain.

Table 3 The top 10 funding agencies involved in the gluten-free diet from 1952 to 2021

Ranking	Funding agencies	Country	No. of publication	%
1st	*European Regional Development Fund*	European Union	67	2.06
2nd	*European Commission*	European Union	56	1.72
3rd	*Ministerio de EconomÃa y Competitividad*	Spain	46	1.41
4th	*CoordenaÃ§Ã£o de AperfeiÃ§oamento de Pessoal de NÃvel Superior*	Brazil	43	1.32
5th	*National Institute of Diabetes and Digestive and Kidney Diseases*	USA	42	1.29
5th	*National Institutes of Health*	USA	42	1.29
7th	*Conselho Nacional de Desenvolvimento CientÃfico e TecnolÃ³gico*	Brazil	41	1.26
8th	*Consejo Superior de Investigaciones CientÃficas*	Spain	43	1.32
9th	*Generalitat Valenciana*	Spain	19	0.58
10th	*Consejo Nacional de Ciencia y TecnologÃa*	Spain	18	0.55
10th	*FundaÃ§Ã£o para a CiÃªncia e a Tecnologia*	Portugal	18	0.55

Table 4 The top 10 journals involved in gluten-free diets from 1952 to 2021

Ranking	Journal/source title	No. of documents	%	IF [a]
1st	*Nutrients*	104	3.19	6.706
2nd	*LWT—Food Science and Technology, formerly known as Lebensmittel-Wissenschaft & Technologie,*	80	2.46	6.056
3rd	*International Journal of Food Science and Technology*	69	2.12	3.612
4th	*Journal of Cereal Science*	68	2.09	4.075
5th	*Foods*	66	2.03	5.561
6th	*Food Manufacture*	63	1.93	NA
7th	*Journal of Food Science and Technology*	58	1.78	3.117
8th	*Food Chemistry*	57	1.75	9.231
9th	*European Food Research and Technology*	54	1.66	3.498
10th	*Journal of Pediatric Gastroenterology and Nutrition*	53	1.63	3.288

[a] 2021 Journal Citation Reports™ (Clarivate, 2022)

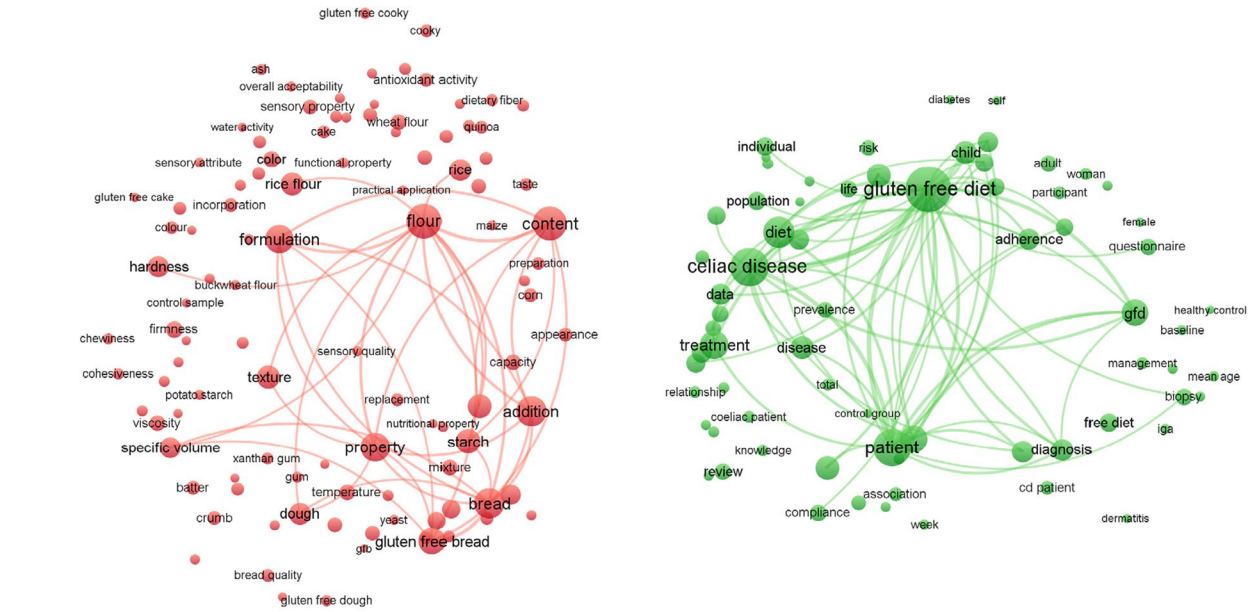
We identified a group of notable contributors, including institutions, journals, and funding agencies. Trends and hotspots in the field of research were outlined, and future developments were forecast.

The list of the ten most prolific countries published in the GFD includes countries unfamiliar with the ranking of scientific productivity in other disciplines [49–52]. Specifically, existing statistics revealed that Italy had been the leading contributor to GFD research, possibly because Italy has a rapidly expanding economy, which generates more finances to conduct research [53], contributing to the rise in GFD-related publications. In addition, Italy ranks first in the consumption of pasta and for pasta quality worldwide. Whole-grain pasta, along with bread and other starch from cereals, is an important food in Italy because it is the foundation of the Mediterranean diet inspired by the eating habits of people who live near the Mediterranean Sea. Pasta is also a part of Italian culture and its gastronomic history. Eating pasta meets both the nutritional and hedonistic and social needs linked to food. Therefore, manufacturers put more effort into researching how well GF products in supermarkets meet the needs of celiac people in terms of variety, prices, and safety to ensure adequate intake of nutrients and fiber necessary for well-being [54], which may explain why more research has emphasized the GFD over that time in Italy.

Increasing the allocation of financial resources toward research on GFD requirements can yield many substantial advantages for a particular geographic area. Enhanced financial support allocated toward study endeavours can facilitate a more comprehensive comprehension of gluten-related diseases, encompassing celiac disease and non-celiac gluten sensitivity. Consequently, this might offer prospective benefits and advantages. Understanding this concept is of utmost importance to achieve an exact diagnosis, effective therapy, and sustainable illness management [55, 56]. Furthermore, the provision of increased research funding has the potential to facilitate the advancement of sophisticated diagnostic

Table 5 Top 10 publications on a gluten-free diet with the most citations (up to 4 August 2022)

Ranking	Authors	Title	Year	Source Title	Cited by
1st	Holmes et al. [43]	"Malignancy in coeliac disease—Effect of a gluten free diet"	1989	*Gut*	936
2nd	Lazaridou et al. [45]	"Effects of hydrocolloids on dough rheology and bread quality parameters in gluten-free formulations"	2007	*Journal of Food Engineering*	664
3rd	Gallagher et al. [48]	"Recent advances in the formulation of gluten-free cereal-based products"	2004	*Trends in Food Science and Technology*	518
4th	Alvarez-Jubete et al. [47]	"Nutritive value of pseudocereals and their increasing use as functional gluten-free ingredients"	2010	*Trends in Food Science and Technology*	388
5th	Vazquez-Roque et al. [42]	"A controlled trial of gluten-free diet in patients with irritable bowel syndrome-diarrhea: Effects on bowel frequency and intestinal function"	2013	*Gastroenterology*	345
6th	Gallagher et al. [44]	"Crust and crumb characteristics of gluten free breads"	2003	*Journal of Food Engineering*	299
7th	Thompson et al. [46]	"Gluten-free diet survey: Are Americans with coeliac disease consuming recommended amounts of fibre, iron, calcium and grain foods?"	2005	*Journal of Human Nutrition and Dietetics*	275
8th	Hall et al. [39]	"Systematic review: Adherence to a gluten-free diet in adult patients with coeliac disease"	2009	*Alimentary Pharmacology and Therapeutics*	274
9th	Rubio-Tapia et al. [41]	"Mucosal recovery and mortality in adults with celiac disease after treatment with a gluten-free diet"	2010	*American Journal of Gastroenterology*	258
10th	Wahab et al. [40]	"Histologic follow-up of people with celiac disease on a gluten-free diet: Slow and incomplete recovery"	2002	*American Journal of Clinical Pathology*	257



VOSviewer

Fig. 3 Cluster map based on analysis of terms appearing in titles or abstracts. The size of the circle indicates the occurrences of the terms, and the different colors indicate the variety of clusters. The map was created using VOSviewer software version 1.6.18

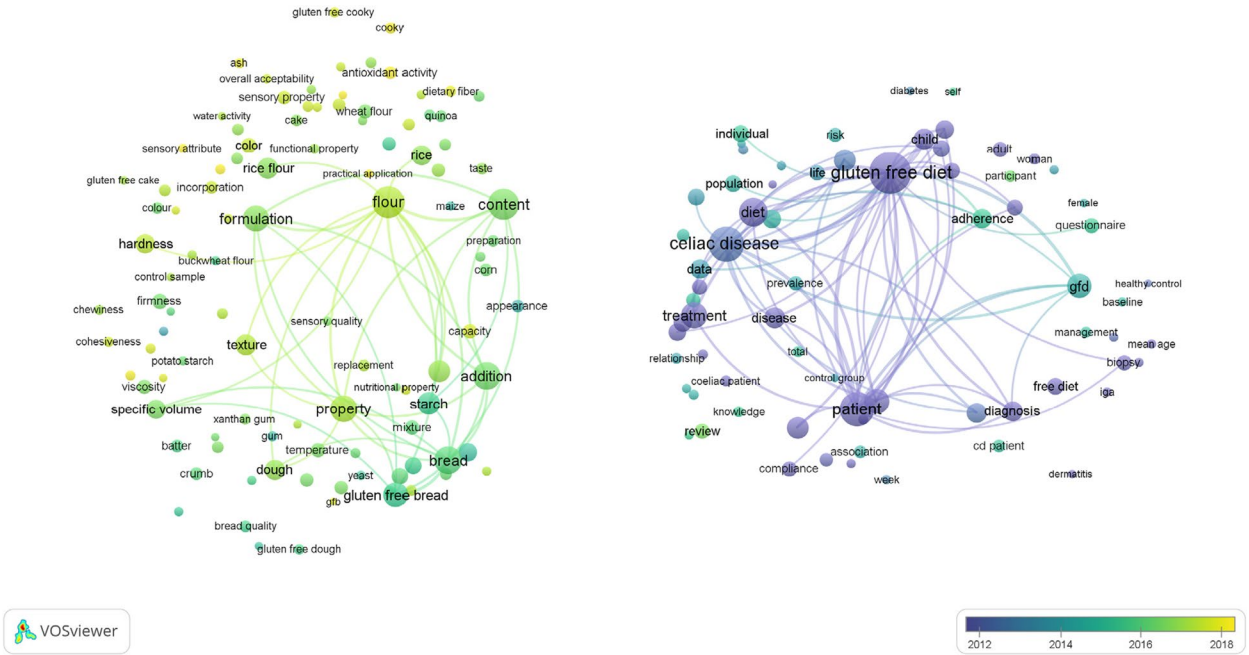


Fig. 4 A network visualization map of the analysis of terms in titles based on their frequency of appearance. Blue represents earlier occurrences of the terms, while yellow represents later occurrences. The map was created using VOSviewer software version 1.6.18

tools, biomarkers, and tests that can effectively detect and intervene in individuals who are at risk of developing gluten-related diseases [57, 58]. Additionally, allocating resources toward research endeavors would contribute to a more comprehensive comprehension of gluten-related diseases, including celiac disease and nonceliac gluten sensitivity [59]. Additionally, it is worth noting that regions with a greater incidence of gluten-related diseases may encounter a substantial burden on their healthcare systems [60]. The allocation of resources toward research endeavors has the potential to deliver better preventative techniques, therefore justifying the total burden of these illnesses on the well-being of the general population. Additionally, it has the potential to facilitate the implementation of focused public health initiatives, endorsing the implementation of suitable eating practices and the cultivation of better lifestyle preferences [61]. The proficiency possessed by individuals can catalyze fostering innovation, facilitating cooperation, and promoting the flow of information, therefore enhancing the region's standing within the respective domain. Additionally, it has the potential to foster collaborations among academia, healthcare institutions, and industry, thereby facilitating the advancement of state-of-the-art therapies, diagnostic tools, and dietary products. Furthermore, research funding can contribute to educational initiatives to enhance public knowledge regarding gluten-related diseases, their associated symptoms, and the significance of proper dietary management [62]. This enables individuals to make well-informed decisions regarding their health. Additionally, this bibliometric study has the potential to facilitate the development of evidence-based dietary recommendations for individuals affected by gluten-related conditions [27, 63]. Furthermore, the research findings derived from this bibliometric study can contribute to the existing pool of scientific knowledge on a global scale, potentially resulting in significant advancements in the comprehension of autoimmune disorders, gastrointestinal health, and nutritional science that extend beyond gluten-related diseases [3, 64].

The terms that are used in the title, as well as the abstracts, represent the primary focus themes. The co-occurrence of GFD terms is an essential indicator that shows the trending subjects and advancements in a research field. The research on GFD can be broken up into the following aspects based on the terms: (1) 'adherence *to a gluten-free diet in celiac disease patients*'; and (2) '*improvement of the nutritional and sensory quality of gluten-free products.*'

One of the main hot topics in our study was '*adherence to a gluten-free diet in patients with celiac disease.*' Strong research evidence indicates that all celiac patients should follow a strict GFD for life. Patients with CD should avoid permanently ingesting food or other substances containing wheat, barley, or rye, as

a small amount of these substances will trigger the immune system reaction and damage the small intestine. Therefore, monitoring dietary changes should become part of routine celiac follow-up [65]. Despite diet being the only treatment for CD, a diet regimen can be difficult to maintain for economic, palatability, and social reasons. Specifically, diet can act as a source of bullying, isolating patients from social life and reducing their quality of life. Therefore, many researchers highlight the importance of joining patients with multiple support groups and encouraging the provision of 'alternate diets' in social settings and supermarkets as a key to adherence to a GFD [66]. On the other hand, a GFD cannot be considered a healthy diet for those who do not have CD, as it is low in fiber, protein, iron, folate, and other B vitamins [67]. Hence, all those confirmed to have CD should be referred to dietitians for education and to limit exposure to gluten cross-contact in home and restaurant settings [68, 69].

Our research concluded that adherence to a GFD in patients with CD is among the hot topics globally, even though little is known about CD patients and adherence to a GFD in low- to middle-income countries. Therefore, different types of research are needed on this underestimated important issue [70, 71]. A GFD is required as part of the treatment for CD; however, much research is being done on alternative pharmacological treatments due to the high psychological load associated with such a diet [72].

Another hot topic is the '*improvement of the nutritional and sensory quality of gluten-free products*'. This issue occurred as a major hotspot in our investigation since gluten-free food is essential for consumption by people with celiac disease, gluten intolerance, or wheat allergy, while the related products are those that do not contain gluten, a protein found in wheat, barley, and rye. Regular bread and bakery are the major parts of meals worldwide, while regular bread flour has been reported to have the highest amount of gluten [73]. Gluten is essential to provide structure and elasticity to the product; therefore, GF bakery products are considered a great challenge, as they are often unattractive, undesirable, unavailable, and approximately 160% more expensive than regular products [74, 75].

Patients on a gluten-free diet may face sensory challenges, including issues with palatability, texture, and appearance of gluten-free foods. Clinicians should encourage patients to discuss these issues and provide guidance to overcome these barriers by suggesting recipes or alternatives that may improve the sensory experience of the diet [76]. In addition, the study suggests that there is a need for the development of high-quality, nutritious, and palatable gluten-free products. Clinicians and dietitians could provide feedback to manufacturers to develop products that meet the specific nutritional needs of patients while also addressing the sensory challenges they face [77, 78].

In the last seven years, there has been an increase in the demand for GF products, which has required the production of high-quality and nutritious GF baked goods using a variety of available substitutes, such as almond and coconut flour, which are rich in protein, healthy fats, and fiber and are considered a friendly choice for diabetic patients due to their low glycemic index [16, 77, 79]. This has improved the quality of life for patients with gluten sensitivity [16, 67]. Brown rice flour is also a good alternative, rich in micronutrients, fiber and complex carbohydrates that can provide sustained energy [14]. Pseudo grains include amaranth, quinoa, which are high in protein, especially with essential amino acids, minerals such as iron and magnesium, and fiber [80], and buckwheat, which is rich in fiber, protein, micronutrients and antioxidants [17]. Corn, montina, millet and teff flour have also been used as possible base ingredients. In addition, alternative hydrocolloids, enzymes, and fiber sources have been used to give superior properties [81].

Overall, gluten-free foods such as rice, corn, fruits, vegetables, legumes, beans and peas and GF products can be a healthy addition to one's diet, especially if they are consumed as part of a balanced diet that includes all food groups with a variety of nutrient-rich meals. However, GFD products remain challenging across the board and contain fewer sensory and nutritional ingredients than regular products. Therefore, producing affordable and high-quality GF products and labeling gluten are urgent issues that need to be considered in low- and middle-income countries to manage this public health problem related to gluten disorders [77, 82].

It would be very helpful to have a thorough bibliometric analysis of the most cited papers, as this would shed light on the future development direction in this field. Due to the clinical importance of GFD and the significance of highly cited publications, we conducted a qualitative and quantitative study of the ten GFD articles that garnered the most citations. This was done in light of the importance of GFD and highly cited articles. Our objective was to improve researchers' understanding of research quality and trends, facilitate more effective use of classic publications on the GFD, and serve as a reference for future research in this area. The most-cited publication out of 936 total citations was "Malignancy in celiac disease—Effect of a gluten-free diet, " written by Holmes et al. and published in *Gut journal* in 1989 [45]. The findings of this study have shown that celiac patients who have been on a GFD for five years or more have no increased risk of developing cancer at all sites compared to the general population. However, the risk of mouth,

pharynx, and esophagus (relative risk = 22.7, $p = 0.001$) and lymphoma (relative risk = 77.8, $p = 0.001$) increases in those who follow a GF or normal diet. In addition, a significant inverse correlation existed between increased GFD use and the morbidity rate. The findings suggest that a GFD may protect against celiac disease malignancy and further support the recommendation that all patients follow a strict GFD for the rest of their lives [45].

The article that was second in the list of citations, which was entitled 'Effects of hydrocolloids on dough rheology and bread quality parameters in gluten-free formulations', had a total of 664 citations; it was published in the *Journal of Food Engineering* in 2007 and was written by Lazaridou et al. [45]. This study thoroughly investigated various technological parameters and formulations to produce high-quality GF bread. In recent years, interest in GF bread has increased [18, 83–85]. As a result, many different types of flour and starches, as well as a number of additives such as gums, enzymes, and soybean proteins, have been used to mimic the viscoelastic characteristics of gluten and improve the structure, texture, acceptability, and shelf life of GF bread.

The article with the third-most citations, titled "Recent advances in the formulation of gluten-free cereal-based products", was published in 2004 in *Trends in Food Science and Technology* by Gallagher et al. [48]. It received a total of 518 citations. This article provides an overview of the prevalence of celiac disease and recent developments in creating GF products through the utilization of hydrocolloids, starches, gums, and other innovative ingredient processes [48].

Strengths and limitations

This is the first study to identify and evaluate the properties of documents related to GFD. The bibliometric analysis conducted by VOSviewer is more comprehensive and objective than the traditional literature review. However, when interpreting our findings, certain limitations must be considered. First, world regions with journals that are not indexed in the Scopus database will be underrepresented. As a result, the presence of false negative results remains a possibility. A second limitation is the list of active countries and institutions, which must be carefully interpreted due to overlap in publications, research networking, and self-citations. Third, there is an inherent flaw in the fact that we only included publications on gluten-free in the article title. Our previous experience has shown that including search items in the abstract has a much lower sensitivity [49, 50, 52, 86]. It would have only found a small number of additional papers, if any at all. This is something that we should have avoided. If we do not place any constraints on including phrases from the abstract in our search query, we will receive many articles that do not pertain to the topic we are interested in.

Conclusions

This study provided a comprehensive bibliographic analysis by reviewing research published over 60 years on the GFD from a global perspective using bibliometric analysis. The study has revealed that the majority of studies are related to research articles, and our findings demonstrated significant advances in GFD research and several hot topics during the previous decades. Italy supplied the most works, followed by the United States and Spain. Institutions from the European Union dominated the list with the most funded agencies. Diet is the only remedy for CD and is difficult to maintain; therefore, 'adherence to a gluten-free diet in celiac disease' has been found to be the most frequent occurrence issue, followed by '*improvement of the nutritional and sensory quality of gluten-free products*,' which has gradually become the focus of GFD research. These findings may provide valuable indications for future research paths and scientific decision-making in this domain. The study highlights the importance of continuing research in this field. Clinicians may need to stay up-to-date with the latest research to provide patients with the most accurate and current information regarding gluten-free diets.

Abbreviations

GFD	Gluten-free diet
GF	Gluten-free
WHO	World Health Organization
DASH	Dietary Approaches to Stop Hypertension
CD	Celiac disease

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Authors' contributions

Zyoud SH designed the study, collected the data, analyzed the data, made major contributions to the manuscript's literature search and interpretation, and drafted the manuscript; Shakhshir M contributed to the conceptualization and methodology of the study, was involved in the interpretation of the data, contributed to the manuscript writing, and made revisions to the initial draft; Abushanab AS, Koni A, Hamdallah M, and Al-Jabi SW were involved in the interpretation of the data, contributed to the manuscript writing, and made revisions to the initial draft; all authors provided a critical review and approved the final manuscript before submission.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article. In addition, other data sets used during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Because the current study did not include any human interaction, it does not require the permission of the Ethics Committee.

Consent for publication
Not applicable.

Competing interests
The author declares that he has no competing interests.

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