CFD Letters 17, Issue 7 (2025) 216-226

CFD Letters

Journal homepage:
https://semarakilmu.com.my/journals/index.php/CFD_Letters/index
ISSN: 2180-1363

Computational Fluid Dynamics Approaches in Quality and Hygienic Production of Foods: A Review of Critical Factors

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ARTICLE INFO

Article history:
Received 11 October 2024
Received in revised form 22 November 2024
Accepted 28 December 2024
Available online 31 January 2025

Keywords:
Computational Fluid Dynamics; quality; hygienic production food

ABSTRACT

The quality and cleanliness of the Product are the main focus in the food industry. Computational Fluid Dynamics (CFD) makes it possible to design and optimize production equipment, as well as maintain the quality and cleanliness of food production. Research on this matter is important to test the initial stages of using CFD in food production. Therefore, this research aims to conduct a theoretical study and analysis of research developments regarding CFD in Food Production and its impact on the quality and level of food hygiene. This research uses bibliometrics supported by theoretical analysis. The research procedure consists of (i) determining the study topic, (ii) collecting publication data, (iii) processing article text and bibliometric data, (iv) visualization of bibliometric data mapping, and (v) analysis of bibliometric data visualization results. The search keywords used were "Computational Fluid Dynamics" AND "Food Production". The research results show that the first journal-type CFD in food production appeared in 2006 and will most often occur in 2022. The results of bibliometric data mapping show that the word "simulation" is a word that has a high number of connections and appears in several nodes. Apart from that, in writing articles on this theme, 14 countries were involved. CFD plays a role in helping maintain the quality and cleanliness of food production through simulating several food production processes.

1. Introduction

In the food industry, production process efficiency is very important to increase productivity and reduce production costs. Computational Fluid Dynamics (CFD) allows manufacturers to design and optimize production equipment so that it can operate more efficiently and consistently [1,2]. The design of production equipment such as ovens, grills, and mixers play a key role in determining the final quality of the product. CFD allows manufacturers to simulate the design of the equipment, ensuring even heat distribution, optimal fluid flow, and efficient processing times. Apart from that, CFD also helps in maintaining product quality. Product quality is an important factor and is the main focus of the food industry. Through the use of CFD, manufacturers can better understand how

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https://doi.org/10.37934/cfdl.17.7.216226

parameters such as heat distribution, fluid flow, and ingredient mixing can affect the final quality of the product, including taste, texture, and nutritional value. Food hygiene and safety are top priorities in the food industry. In this case, the role of CFD is to design ventilation systems [3], optimize airflow, and minimize the risk of microbial or other particle contamination in the production environment.

In addition to product quality and cleanliness, CFD helps design production spaces and equipment. This can help ensure the sterile conditions necessary to prevent the growth of unwanted microorganisms. Uneven temperature distribution or inefficient cooling processes can affect food quality and safety. CFD helps in understanding airflow patterns and temperature distribution around cooling or freezing equipment [4]. Currently, there have been several previous studies that discuss the use of CFD in the food sector, such as research on the application of computational fluid dynamics to improve plant production systems [1], simulation of food drying processes [5], applications in drying spray food products [6], and CFD modelling applied to the ripening of fermented food products [7]. However, there has been no research that has conducted a Critical Factor review through bibliometric analysis of CFD in Food Production research. Therefore, this research was carried out to conduct a theoretical study and analysis of research developments regarding CFD in Food Production and its impact on the quality and level of food hygiene.

2. Methodology

This research aims to review previous research regarding the use of the Computational Fluid Dynamics (CFD) approach to the quality and cleanliness of food production. We use bibliometric analysis methods supported by theoretical analysis. A quantitative approach is used to demonstrate data visualization based on bibliometric principles. We carried out five research stages consisting of:

i. determining the study topic
ii. collecting publication data
iii. processing article text and bibliometric data
iv. visualization of bibliometric data mapping
v. analysis of bibliometric data visualization results.

In this research, we use the data provided by Scopus and mapping visualizations produced through computational processing in the VOSviewer application. Detailed information for installing and using the software (VOSviewer) and the step-by-step process for processing bibliometric data are described in our previous research [8].

Data retrieval from the Scopus database (https://www.scopus.com/). All data was obtained on November 10, 2023. The keywords used to search for article data were “Computational Fluid Dynamics" AND "Food Production". Data searches were limited to articles of the journal type and in English. We did not specify the year of the study. 15 related articles were found from 2006 to 2023. Article mapping visualizations were made in 3 types, namely network, density, and overlay visualizations based on the relationships between existing items. Data mapping is carried out on text data or terms found in article data. Data mapping based on text data found 607 terms or keywords that matched. The terms found are selected again based on the number of times they appear at least 3 times. Therefore, the number of terms used in the mapping analysis is 20 terms.

3. Results

3.1 Number of Article Publications and Citations Per Year

Figure 1 shows the publication history based on the number of articles regarding Computational Fluid Dynamics Design (CFD) in Food Production to maintain food quality and hygiene. Based on the results of the data search, it is known that the first journal-type publication regarding CFD in food production was in 2006. The number of publications per year is still relatively small, namely in the range of 1 to 3 articles—description of the number of publications each year based on the number of documents. In 2006 1 document was found, and from 2007 to 2009 no published documents were found. In 2010, 1 published document was found, and in 2011 2 published documents were found. In 2012 and 2013 1 document was found. Meanwhile, in 2014 and 2015 no published documents were found in this field. In 2016 and 2017 1 document was found, and in 2018 2 documents were found. From 2019 to 2021, no published documents were found. In 2022 3 documents were found and in 2023 2 documents were found. These results indicate that most research regarding CFDs in food production will occur in 2022.

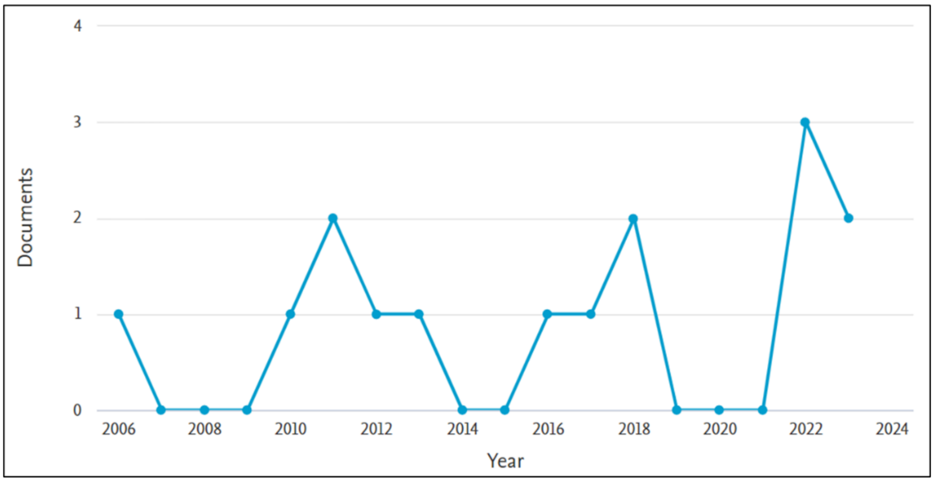

Fig. 1. Annual report publication

Based on the annual report on the number of publications, it can be seen that research regarding the use of CFD methods for food production is still relatively small. The use of CFD is considered to be able to help the food production process, especially in maintaining the quality and cleanliness of the production stage. CFD is a sophisticated tool used in various industries, including the food industry. CFD is used to simulate and analyse fluid flow, heat transfer, and mass transfer [9]. In the context of quality and hygienic food production, CFD can be applied to optimize processes, improve product quality, and ensure the highest hygiene standards [10,11].

In addition, CFD can be used to model and optimize heat transfer processes in food processing equipment such as heat exchangers, pasteurizers, and sterilizers [12]. Thermal processing simulation helps ensure food products are heated uniformly to meet safety standards and extend the shelf life of food. Another benefit of CFD is that it can also simulate fluid flow patterns during the mixing process in food production [13,14]. This helps in optimizing the mixer design to achieve homogeneous mixing and reduce processing time. in addition to understanding flow patterns, it can also prevent dead zones where contaminants may accumulate, thereby ensuring hygienic production. CFD helps in designing equipment that minimizes the risk of contamination and ensures uniform heat distribution during the sterilization process.

However, because the CFD analysis process requires high resources such as model validation and verification, CFD requires a suitable amount of experimental data that cannot be lacking. In addition, CFD requires large computing power. Model preparation for CFD simulations involves complex preprocessing processes, including geometry generation, meshing, and boundary condition determination. Mistakes in this stage can affect the final result. Therefore, there are still few researchers who use this CFD approach, especially in the field of food production. Despite the diverse challenges of using CFD, CFD itself is an invaluable tool in designing and understanding fluid flow processes [15]. A good understanding of model limitations and accuracy, as well as attention to validation of results with experimental data can help overcome some of these problems. The importance of CFD in food production, especially for maintaining food quality and cleanliness, is also shown by several previous research results [9,16].

Table 1 shows details of publication trends and the number of citations for articles regarding CFD in food production published in international journals indexed by Scopus. The number of citations can provide recognition to the author, support research arguments, and help build a strong foundation in writing a scientific work [17]. The development of citation ranking lists is an effort to highlight published works that have the potential to influence future research patterns. Apart from that, a list of quotation rankings is also presented in the hope that it can become a source of reading reference and inspiration for future researchers.

Table 1
Most cited articles

No	Title	Year	Cited	Ref
1	A CFD study on improving airflow uniformity in the indoor plant factory system	2016	75	[20]
2	Improving the thermal efficiency of a jaggery production module using a fire-tube heat exchanger	2017	21	[21]
3	Modelling and validation of the mechanism of pulsed flow cleaning	2013	19	[22]
4	Local analysis of cleaning mechanisms in CIP processes	2012	19	[23]
5	Evaluation of geometric symmetry condition in numerical simulations of thermal process of packed liquid food by computational fluid dynamics (CFD)	2010	19	[24]
6	Polycyclic aromatic hydrocarbons in a bakery indoor air: trends, dynamics, and dispersion	2018	7	[10]
7	Airflow inside an open ventilated system: Influence of operator's arms or moving conveyor	2011	4	[25]
8	Application of computational fluid dynamics simulations in the food industry	2023	3	[26]
9	Identification of microbial airborne contamination routes in a food production environment and development of a tailored protection concept using computational fluid dynamics (CFD) simulation	2022	3	[27]
10	Orientation simulation and image experiment for flexible biomass particle in wedge fluidization channel	2022	3	[28]
11	Computational fluid dynamics modelling of microclimate for a vertical agrivoltaics system	2023	2	[29]
12	CFD simulation of a co-rotating twin-screw extruder: Validation of a rheological model for a starch-based dough for snack food	2018	2	[30]
13	Evaluation of boundary conditions for CFD simulation of liquid food thermal process in glass bottles	2011	1	[31]
14	Experimental verification of the feasibility of the CFD approach in an air-knife	2022	0	[18]
15	Use of Sγ momentums for the modelling of tracer transport in homogeneous porous media	2006	0	[19]

Based on the data in Table 1, it is known that the number of citations for published articles regarding CFD in Food production has the highest number of citations, up to 75 times. Of the 13 articles, 2 articles do not have citations, namely the research article by Altay *et al.,* [18] which discusses the analysis of the use of wind blades with very different nominal values used for various purposes in industries related to food production. Altay *et al.,* [18] used CFD to model and design the wind blade. The second article that has not been cited is the research article by Coutelieris [19] regarding the use of droplet transport in the media "Sγ concept" applied in the CFD module for modelling transport processes that occur in a mixture of continuous water phases including discontinuous phases in the form of droplets. Meanwhile, the article with the highest number of citations is the article titled "A CFD study on improving airflow uniformity in indoor plant factory systems" written by Zhang *et al.,* [20] with a total of 75 citations. Experiments conducted by Zhang *et al.,* [20] regarding the development of a three-dimensional computational fluid dynamics (CFD) model developed and validated through simulation of a developing environment in a single-rack production system. Zhang *et al.,* [20] said that a better air circulation system was designed and proposed to help provide a dynamic and uniform boundary layer that could help prevent burns in lettuce production.

3.2 Mapping Visualization in CFD Research in Food Production

We mapped bibliometric data for CFD research in Food Production and analysed 3 types of visualization, namely network (see Figure 2), overlay (see Figure 3), and density (see Figure 4). Network visualization shows the connection between the terms found. The network visualization results show that the terms found are divided into 3 clusters, namely:

i. Cluster 1 in red consists of 9 items, namely application, CFD simulation, effect, food production, model, place, process, system, and work.
ii. Cluster 2 in green consists of 7 items, namely CFD, Computational Fluid Dynamic, Demand, Evaluation, Need, Numerical Simulation, and Study.
iii. Cluster 3 in blue consists of 4 items: addition, product, simulation, and use.

The visualization overlay shows the range of years the words were discovered. The visualization overlay shows that terms with a minimum number of occurrences of 3 times were found in articles with a research year range of 2014 to 2018. Meanwhile, the density visualization shows the number of occurrences of these words. The larger the node size and the brighter the colour in the density visualization, the more often the word is used [32,33]. These results show that the words CFD, use, Computational Fluid dynamic, and food production are the words that appear most frequently. These words appear most often because the article search keywords use the core words CFD, Computational Fluid Dynamics, and Food Production. This shows that the articles found are relatively related to the research theme to be studied.

Based on the results of bibliometric data mapping of articles regarding CFD in food production, it is known that the word simulation is a word that has a high number of connections and appears in several nodes. Data shows that many previous studies used CFD to carry out simulations in various aspects of food manufacturing. CFD can be used to model heat and airflow in ovens or other cooking equipment [34]. This helps in designing a system that can ensure even heat distribution across the surface of the food. In addition, in the roasting or frying process, CFD can help simulate heat and airflow patterns around food ingredients. In addition, CFD can also be used to design food cooling or freezing systems, such as refrigeration chambers or freezers [35,36]. Analysis of airflow and temperature distribution helps maintain food quality and safety. In making dough or food mixtures, CFD can help model fluid flow to ensure an even mixing of ingredients, thereby helping in designing efficient mixers. CFD can also be used to model sterilization or pasteurization processes [37]. This can be seen in the process of producing milk or food cans, helping to ensure that heat is distributed evenly and efficiently. CFD can help in designing production spaces and equipment by considering aspects such as air circulation, temperature distribution, and air cleanliness to ensure good sanitary conditions. CFD allows researchers to test complex scenarios that are impossible to recreate in the real world and ensure the highest level of accuracy for precision products, so that many previous studies have used the CFD method [38-46].

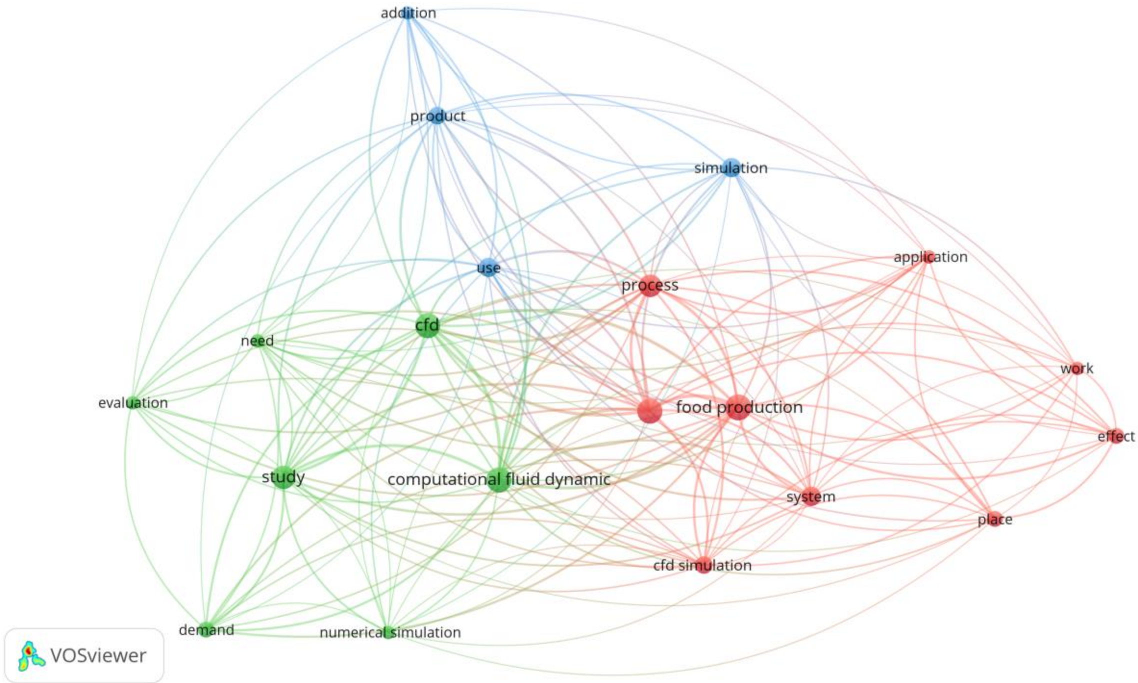

Fig. 2. Network visualization

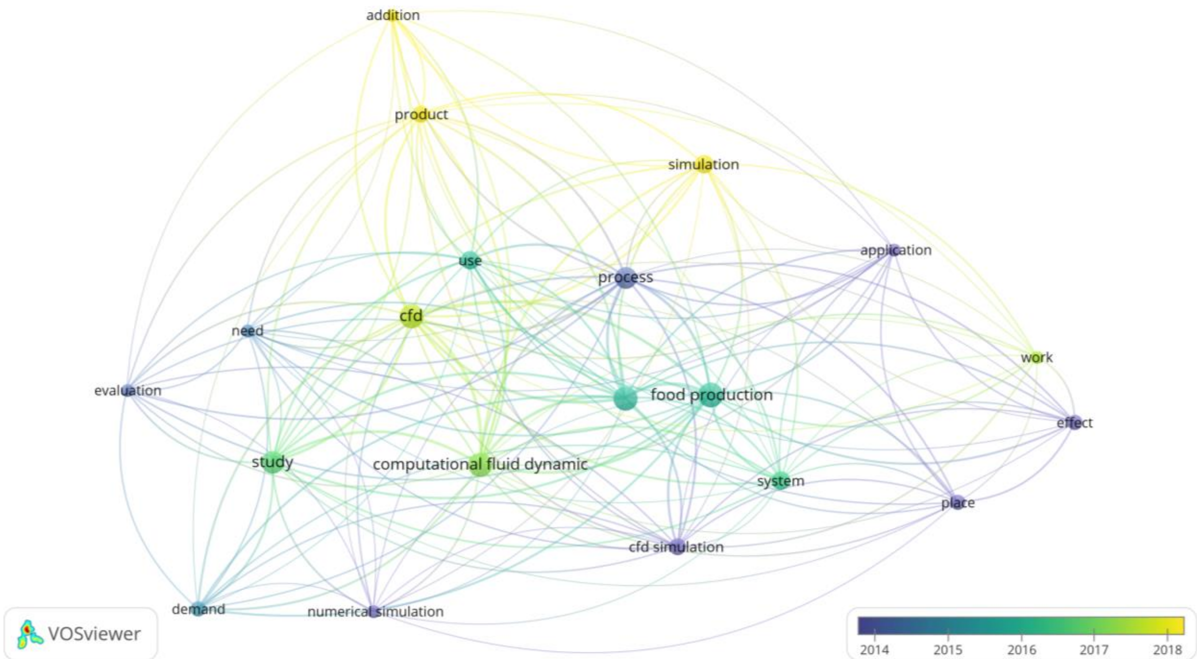

Fig. 3. Overlay visualization

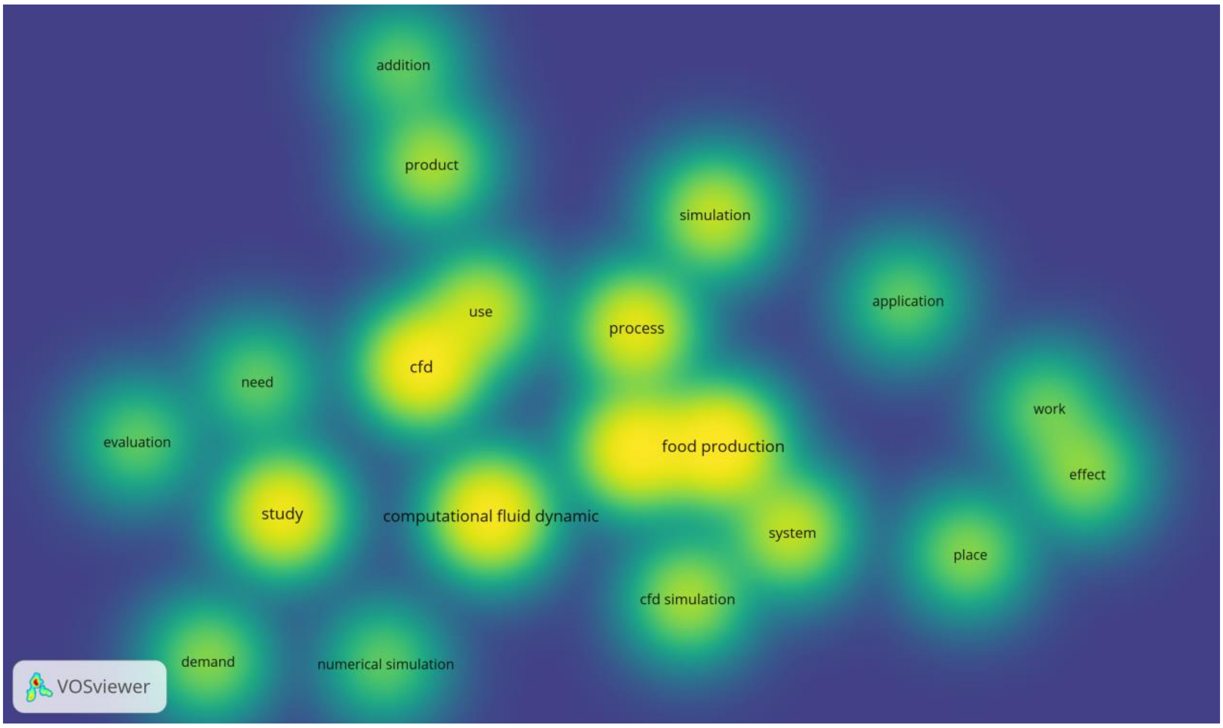

Fig. 4. Density visualization

3.3 Country Contribution

Figure 5 shows several countries of origin for researchers who have conducted research on CFD in food production. It is hoped that this information can motivate future researchers to conduct country references or conduct studies in that country regarding this subject. The countries involved in research on CFDs in food production are Germany, Brazil, Italy, Austria, China, France, Greece, Iraq, Peru, Poland, Spain, Sweden, Turkey, and the United States. Germany is the country that contributed the highest number of publications, namely 3 documents. Brazil and Italy are in the next position with 2 documents.

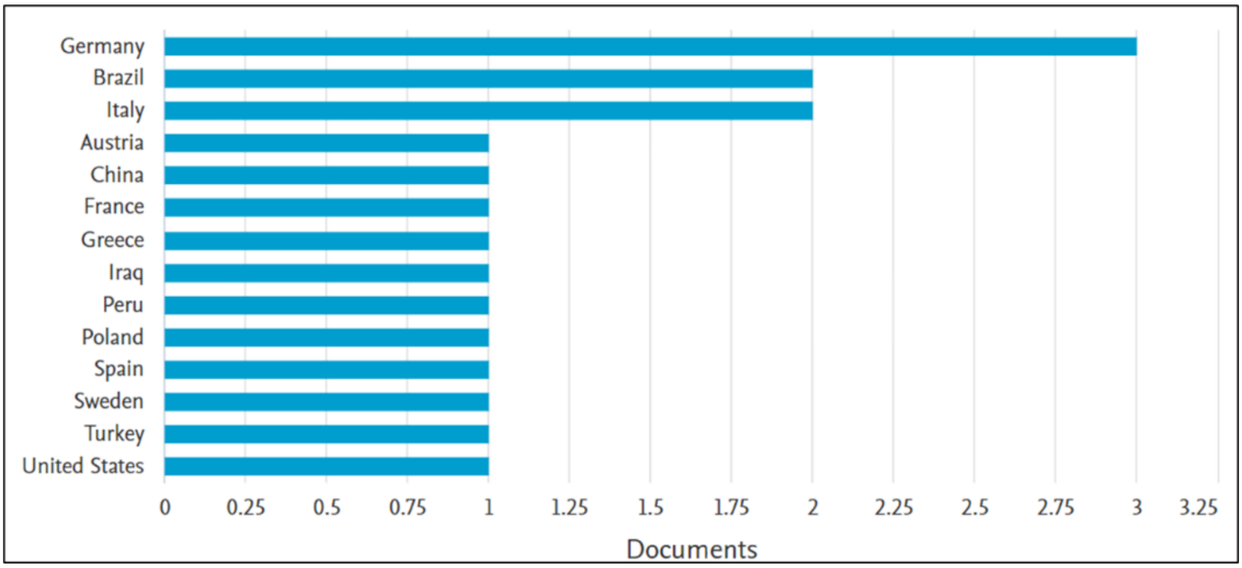

Fig. 5. County contribution

The application of CFD in food production faces several challenges that need to be considered by researchers and practitioners in the future. One of the main challenges is the complexity of modelling. The food production involves various phases, such as gas, liquid, and solid, which interact dynamically. Each phase has different fluid flow and heat transfer characteristics, so the CFD model must be complex enough to accurately represent these processes. In addition, the difficulty in obtaining valid and complete experimental data is also a major obstacle. Many processes in the food industry do not yet have sufficient data to support accurate CFD modelling, so the quality of the simulation can be affected. In addition, the limitation of computing resources is also a major challenge. CFD simulations require high computing power, which is often not available in many food production facilities, especially in developing countries or for small and medium-sized companies. Preprocessing processes such as geometry and mesh generation, as well as boundary condition determination, can be time-consuming and resource-intensive.

Therefore, the success of CFD applications often depends on the availability of sophisticated hardware and trained human resources, which may be a major challenge for many industries. To overcome these challenges, practical and innovative solutions need to be considered. One of them is to develop simpler and more efficient CFD models. For example, using semi-empirical models or dimensionality reduction approaches can reduce the computational burden while still providing valid results. Collaboration between academia and industry can also help improve access to better experimental data, thereby improving the accuracy of CFD models. In terms of resource constraints, the implementation of cloud computing or supercomputing can be a solution to overcome the problem of high computing power. In addition, providing training for workers in the food industry on the use of CFD can also accelerate the adoption of this technology in the wider sector.

4. Conclusions

We reviewed several relevant previous studies regarding the use of the Computational Fluid Dynamics (CFD) approach to the quality and cleanliness of food production. There are 15 related articles from 2006 to 2023. The first journal type CFD in food production appeared in 2006. The number of publications per year is still relatively small, namely in the range of 1 to 3 articles. Previous research has used CFD to carry out simulations in various aspects of food manufacturing. Based on several analyses carried out in this research, it can be seen that CFD has several roles in helping to maintain the quality and cleanliness of food production. CFD can help simulate several processes, so it can be a consideration for food manufacturing before proceeding to a larger stage. This study has limitations in that the analysis is based on 15 publications over a period of 17 years. We recommend further research to be able to analyse publications on the use of CFD in sports with a larger number of publications in order to produce comprehensive conclusions.

Acknowledgement
This research was not funded by any grant.

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