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ATMOSPHERIC COLD PLASMA TECHNOLOGY FOR MEAT INDUSTRY: A BIBLIOMETRIC REVIEW

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Abstract

Atmospheric cold plasma is an innovative, non-thermal technology. It has shown promising results for a broad range of food processing applications. On the basis of those facts, it has prompted growing attention in the scientific community. This paper reviews the literature generation trends surrounding the atmospheric cold plasma technology. A bibliometric analysis was carried out to objectively and analytically uncover the knowledge development in the atmospheric cold plasma technology within the context of meat processing. The research began with querying the Dimensions database for scientific articles published over the past two decades. A total of 105 papers were published during this period. The articles were examined according to several bibliometric metrics such as the year of publication, countries, institutions, sources, authors, and keywords frequency. The results of the bibliometric analysis revealed that researchers are very interested in studying the interface of the atmospheric cold plasma technology and meat processing. In the last couple of years, the number of publications on the topic has been growing. This is the first bibliometric investigation of the atmospheric cold plasma technology in the context of meat processing. To the authors' best knowledge, no similar analysis has been performed before. This paper provides researchers with a better understanding of topic developments. A better understanding can aid future research by closing present knowledge gaps. Hence, the paper provides the continuation of up-to-date technological discussions among researchers.

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Introduction

In the last two decades, a strong increase in interest in the atmospheric cold plasma (ACP) technology has been observed. This novel treatment process is becoming relevant for food processing and new applications are being researched daily. Consequently, in this period, the production of scientific publications has seen the exponential growth. The high rate of scientific production makes it difficult for researchers to remain current with everything being researched and published. Furthermore, the focus on empirical contributions has led to numerous and dispersed research streams [1]. All this results in the data being viewed in isolation, which prevents one from ever seeing the complete spectrum of research. There are several narrative reviews about ACP research as well [2–4]. A few of them are devoted to the particular uses of atmospheric cold plasma in meat processing [5–7]. However, a bibliometric review of publishing patterns in the general research field is still lacking. To our knowledge, a bibliometrics review of ACP research trends in meat processing applications is missing as well. Bibliometric reviews have the ability to introduce a methodical, transparent, and reproducible review process based on statistical measurements of the area and its scientific activity and to give the «overall picture» of existing research [8]. It is outside the scope of this journal and the author's intention to produce a general research field bibliometric review. However, a bibliometric review of research focused on meat processing applications would be beneficial. For scholars, it is valuable to have a deep understanding of the intellectual foundations of the research area and how it has developed. This is crucial for closing the entrance gap for new scholars, who frequently see conducting a thorough review of earlier research as a time-consuming and high-effort activity. Being a bibliometric review this article aims not to explore the advantages, limitations, physicochemical changes, nutritional quality and regulatory issues associated with the application of cold plasma on meat products but to provide a reader with the findings that will aid in area mapping and help steer the future research on meat processing applications of the ACP technology. The paper is structured as follows. Prospects of the atmospheric cold technology and research conducted on possible meat processing applications are discussed first. Then, a description of the study method is given, the review of the content evolution over time is presented and the potential limitations of the review are addressed. Finally, we explore the future and provide some thoughts about how the discipline might develop in the future in the conclusions.

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Atmospheric cold plasma

The major disadvantage of vacuum plasma is that it cannot be utilized to process most food materials, since it is only operating under vacuum and most food materials are not compatible with it [9,10]. Plasma operating under atmospheric pressure may provide a novel and highly reliable technique for sanitizing, preserving, and sterilizing food products. The application of ACP is envisioned primarily as a minimal food processing technique and as such should not compromise the protection of processed foods against microbial and chemical risks [11]. Many research papers and studies have concentrated on the use of ACP in food sterilization, microbial inactivation, and mycotoxin breakdown [12,13]. Only recently, investigations on ACP effects on specific products and food nutrients have been initiated. Firstly, effects on fresh produce were investigated and then research expanded to fruit and vegetable products, cereals and cereals products, and almost all types of food products [14–16]. Over the past fifty years, both meat production and consumption have increased, and it is expected that this trend will continue as the demand for animal proteins rises [17,18]. However, because meat and meat products are highly perishable, a variety of preservation and processing techniques have traditionally been used to retain their high quality and prolong their shelf lives [19,20]. In most cases, the application of ACP on meat has been executed as a direct exposure, used on the packaging matrix, or as a means for water treatment that will be used in meat products. This latter case is also termed the plasma-activated water technology but since water treatment also involves plasma excitation in gas for water activation and for the sake of simplicity of terminology throughout this paper, only the ACP term will be used. Numerous studies have concluded that ACP treatment improves the quality of meat [21,22]. Different reactive species constitute plasma, among them are nitrogen (long-lived species) which dissolves as nitrogen oxide (see Eq. 1) and forms nitric acid when water is present. Nitric acid then breaks down into nitrate and nitrite (see Eq. 2).

$$2NO_2 + H_2O \rightarrow HNO_2 + HNO_3 \leftrightarrow NO{-}2 + NO{-}3 + 2H^+ \quad (1)$$

$$2HNO_2 \rightarrow NO + NO_2 + H_2O \quad (2)$$

Plasma-activated brine was utilized by Inguglia et al. to cure beef jerky [23]. According to their findings, air plasma formed more nitrites in the brine solution than N_2 gas plasma, with a residual nitrite concentration of between 26 and 180 ppm. This nitrite depletion is a result of nitrite direct interaction with the proteins in meat. However, they found out that the texture and lipid oxidation of beef jerky were unaffected by this nitrite reaction. Additionally, treatment of the jerky with air ACP, which is regarded as a potential disinfectant on the meat surface, results in a notable decline in the overall population of *Listeria innocua* to 0.85 $\log_{10}$ CFU/g. A significant reduction, ranging from 2.3 to 5.3 log CFU/cm^2, in *Salmonella* Typhimurium was achieved by using CAP in combination with peracetic acid (PAA) in a range of 100 to 200 ppm on the poultry meat, while CAP alone reduced the microbial load by 0.6 to 2.3 log CFU/cm^2 [21]. Furthermore, several studies showed that employing any combination of gas in ACP decreased meat spoilage caused by bacterial contamination [24]. The water activity in meat products is also affected by modifications to the gas mixture. When 25% O_2 and 75% Ar gas combination was used in ACP, a reduction in the water activity (a_w) was seen at an a_w of 0.71 [25]. Low a_w has been proven to be crucial for stopping bacterial development in meat products.

Bibliometric method

Growing attention has been devoted to the bibliometric study of the scientific literature, in recent years. The availability of online databases and the development of effective tools enable one to carry out analysis dealing with a specific domain of research. Since, the primary aim of this review is to examine the domain of the ACP technology in the meat processing domain, we conducted a bibliometric analysis. For this study, we chose to query the Dimensions database due to its certain advantages. The Dimensions database is the most inclusive. It captures the broader list of sources (i. e. journals), increasing our analysis horizon. Dimensions had over than 106 million publications by December 2019 [26]. That is around 30% more than comparable databases. Publications from prominent publishers such as Elsevier, Emerald Insight, Springer, and Taylor & Francis are included [27,28]. Moreover, this database includes publications from numerous small academy-led journals and publishing houses. Access to databases for scientometric purposes is free. Since the authors did not have access to other databases that need a subscription, it was also the only practical choice. The greatest weakness of our choice is incomplete affiliation data. As discussed earlier, the database in some cases lacks the identity of the author's affiliated institutions [29]. Alternative databases for retrieving bibliometric data could be used, for example, Scopus, Google Scholar, Microsoft Academics, Crossref, and Web of Science databases. But each of them also has a set of advantages and weaknesses, just like Dimensions have. In a recent large-scale comparison of bibliographic databases, the strengths and weaknesses of the different data sources are discussed [26].

Selection strategy

All data were extracted through a set of queries. Only bibliographic records published from 2001 to July 31, 2022 were retrieved. To maintain the academic nature and high quality of the literature, the search was limited only to peer-reviewed English-speaking journal articles. Each query was constructed of terms linked by Boolean operators. That way queries aimed to encompass all relevant search fields while still providing adequate selectivity. Hence, only results from the literature connected with our domain of interest would be returned.

The following search fields were defined:

- Keywords;
- Titles;
- Abstracts.

We added all terms that led to the improvement of search results. To identify all publications related to ACP in general, the first query was defined in the following form:

'' Plasma AND (cold OR nonequilibrium OR non-thermal OR non-thermal OR atmospheric OR corona OR "activated water" OR "treated water") AND (food OR cereals OR fruits OR dairy OR beverages OR milk OR meat OR egg OR beans OR fish OR insects OR oils OR nuts OR rice OR wheat OR maize OR barley OR corn OR quinoa OR sorghum OR oat OR juice OR snack OR spice OR "food protein" OR "edible seed" OR legumes OR coffee OR wine OR beer OR cheese OR clams OR juice OR salad OR berry OR flour OR spinach OR lettuces OR oyster OR shrimps OR sausage OR poultry OR pork OR beef OR lamb OR goat)''

To identify all publications related exclusively to the ACP application in food processing, the second query was defined in the following form:

''Plasma AND (cold OR nonequilibrium OR non-thermal OR non-thermal OR atmospheric OR corona OR "activated water" OR "treated water") AND (meat OR sausage OR poultry OR pork OR beef OR amb OR goat) ''

The information about the retrieved record was then exported into Microsoft Excel 2016. Then, several preprocessing methods were applied to improve the quality of the retrieved data:

- Detection of duplicate records;
- Spellings checks of authors' names;
- Screening of records for relevance.

Relevance of records was assessed on the basis of several requirements and all records were manually checked for compliance. The authors screened the titles and abstracts of articles and deemed them relevant if relevance requirements were satisfied. Requirements were defined to include a record in further analysis on the basis that a record was explicitly focused on the application of ACP in food/meat processing when it dealt with at least one of the following topics:

- Effect of treatment on food/meat characteristics (chemical, physical, sensory etc.).
- Effects of treatment on microbial decontamination in food/meat matrix.
- Effect of treatment on packaging material properties tested on food/meat.
- Effect of treatment on chemical decontamination of food/meat samples.

Similarly, requirements to exclude records from the further analysis were defined on the basis that a record was not explicitly focused on the application of cold plasma in food processing, its scope was broader:

- Literature review of several technologies, e. g. of all non-thermal technologies;
- Application of cold plasma in analytic techniques;
- Record was without overlap with Food Sciences categories, e. g. Physics, Materials, Medicine, Microbiology, Non-Food Biotechnologies.

We accepted the use of ACP in all its forms on samples. We also accepted the use of ACP to generate plasma-activated water, which was subsequently used to treat food/meat samples.

At the end of the data preparation process, from 3466 records returned by the first query we ended up with only 1259 articles that satisfied all inclusion conditions. Similarly, in the case of the second query, from 364 records returned we ended up with only 105 articles that satisfied all inclusion conditions.

Data loading and converting

Starting with our final set of records, we loaded the data (i. e., the selected records that matched the inclusion criteria) into an R data frame using bibliometrix [30]. Bibliometrix provides one of the most extensive sets of bibliometric analyses. Bibliometrix is suitable for practitioners through the Biblioshiny addon [31].

Analyses and results

General Information

The main information about the two obtained collections of records is presented in Table 1. In it, an overview of ACP in food processing and ACP with the intersection with meat processing is given. Development dynamics can be used from this overview to provide answers to the questions of this review, i. e. whether the ACP application in meat processing is similar to or differs from the ACP topic in general and what are the most prominent differences. What are the most prominent differences? There were 415 journals that published at least one document about ACP in food processing. Of these, only 44 journals published research articles about the application of ACP in meat processing. It can be easily noticed that published studies about ACP in meat processing are more recent, which is to be expected since it is a subset of ACP research. Looking at the authorship patterns, it can be noticed that only a small number of articles were written) by a single author. Considering the number of times an author appeared in the collection, an average co-authorship value of 5,4 authors per article was obtained for the ACP records. This value is closely matched with 5,28 authors in ACP focused on meat processing. This value can also be seen as a proxy for the average size of research teams.

In order to get insight into the internationalization of the researchers' collaboration, one should look at the values of international co-authorships. It can be seen that the research teams exploring ACP for meat processing appli-

cations are more diverse. This could also explain the notably higher values of the average citations per article and growth rate. Published research about ACP in meat processing should be characterized as more recent since it is only a subset of the ACP research. The timespan and the average age of articles can easily be used to confirm the expected, signaling that the the majority of articles had been written recently.

Table 1. Main information about the collection

Description	ACP — Meat	ACP
MAIN INFORMATION ABOUT DATA		
Timespan	2007–2022	2001–2022
Journals	44	415
Articles	105	1259
Annual Growth Rate %	18.02	15.45
Average Article Age	3.99	4.31
Average citations per article	31.34	26.66
AUTHORS		
Authors	346	4128
Authors of single-authored docs	1	24
Co-Authors per article	5.28	5.4
International co-authorships %	66.67	55.68

The number of articles published is an important indicator for determining whether a topic is attracting the attention of scholars. Analyzing the number of papers published can provide insight into whether the field has seen significant breakthroughs in its development. The foregoing is particularly true for a topic that is a subset of a parent topic. Figure 1 shows the year-wise distribution of articles published during 2001–2022. The earliest published article on the ACP topic dates back to 2001. The first research about the ACP application in meat processing appeared only six years later, in 2007.

ACP: The number of articles on the topic of ACP in general; ACP: Meat the number of articles on the topic of the ACP application in meat processing.

In the mid two thousands, the annual volume of published articles increased barely noticeable. This period averaged 12,1 articles per year. In the last decade, starting from 2012, the number of articles grew more prominently, reaching a value of 219 published articles in 2021, while in the first six months of 2022, 143 articles were published. Extrapolation from the described pattern suggests that the total number of articles in 2022 could also exceed that of the former year. Two main factors explain the observed growth. Firstly, through the maturation of the ACP topic, it is possible that the overall number of studies has increased exponentially, boosting also the number of submissions to the journals. Secondly, the development is fueled by the search for new technologies that provide minimally processed food products to answer the developing tendencies of consumers. However, according to the trend shown in Figure 1, there were no continuous year-by-year publications on the topic of ACP in meat processing after the first article had been published in 2007. In the following year, not a single article was published. This clearly indicates that topic started its development at this moment. In the course of development during the following years, the annual number of articles presented almost a stationary publishing trend. Only in 2019, 12 years after the first article had been published, a noticeable increase in the number of annual publications can be noticed. In that year, there were 19 articles published. After this noticeable peak of activity, we again observe the stationary publishing trend described in the former period. This is quite possibly due to the COVID — 19 pandemic events and the slowing down of research activities. Until sufficient time passes after COVID — 19 pandemic, it is difficult to deduce the reason for our observation with certainty. The above-mentioned numbers show that the topic has been attracting the attention of researchers. This suggests that the topic's concerns continue to have an impact on the academic world, implying that the topic has not been adequately addressed.

Highly contributive journals and articles

There are 44 relevant journals on the topic of ACP applications for meat processing. They represent almost one-tenth of the total number of journals, in which ACP studies were published. Each of the journals published one or more articles in this analyzed set. Figure 2 shows the most relevant journals considering the number of articles. The journal of *Innovative Food Science & Emerging Technolo-*

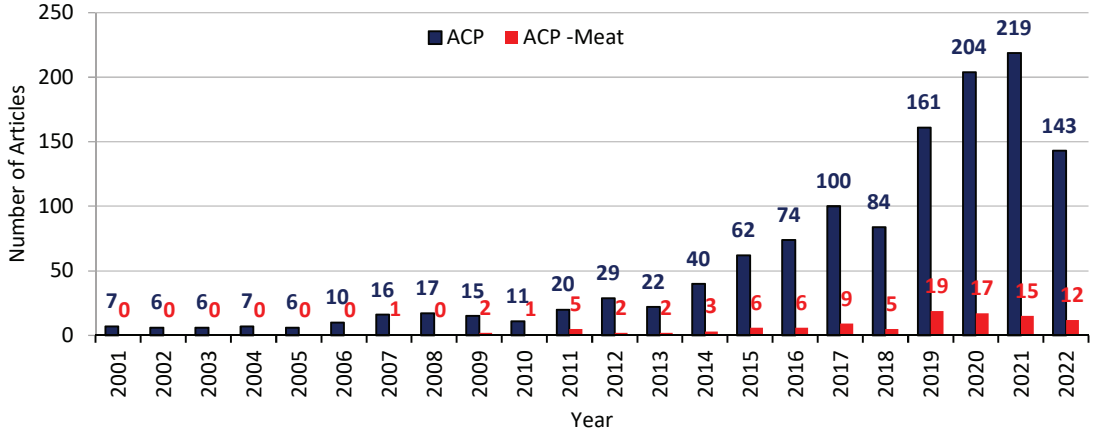

Figure 1. Year-wise distribution of scientific production in 2000–2022 timespan

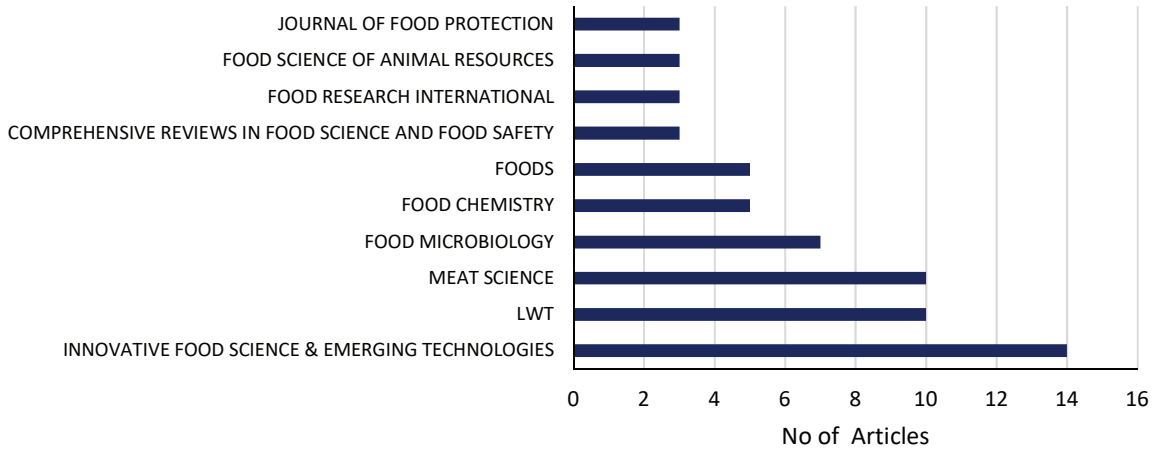

Figure 2. Highly contributive journals

gies is the top critical journal in the field, as it published 14 articles. The *LWT* journal is the second top journal with 10 articles and this number of articles is matched with the number of articles published in the *Meat Science* journal. These three journals are clearly playing a key role in publishing research on ACP in meat processing and hence the development of the topic.

The distribution of research output per journal supports Bradford's law, which says that there is a small set of key journals that account for a significant percentage of publications on the corresponding field or topic [32]. All listed journals involved in publishing articles on the topic of the ACP application in meat processing are well-established venues for publishing in food sciences, hence have adequate bibliometric indicators and professional prestige. This is indicates that the topic of ACP in meat processing is of interest to editors and that the research field is certainly one of the "hot" topics in development. In Figure 3 the most contributing articles to the topic are presented. The contribution was measured as the number of total citations those articles had received. In total, from all analyzed documents in our collection, only 5 articles had 100 or more citations. The most impactful article is an article by Noriega et al published in 2011 in the *Journal Food Microbiology*. This article is closely followed by the other three most impactful articles all published in the same journal and at approximately the same time. From that observation, we can easily extrapolate that the effects of ACP on microbiological safety are the main focus of the conducted studies and that the most important results are in the described line of research.

Authors and Co-authorship productivity

In Figure 4 authors' productivity is shown) through Lotka's Law. In total, there were 3084 unique authors. In accordance with Lotka's Law, 77.5% of authors wrote) just one article, 11.3% of authors wrote) 2 articles, 4.9 wrote) 3 articles, 3.2% authored 4 articles and etc.

In Figure 5, the top 10 countries were ranked by their count of articles published. The gray columns demonstrate the publication rate by corresponding author's country, wherein at least one foreign co-author exits. The black columns represent the number of articles by authors from the same country. These are called Multiple Countries publication (MCP) and Single Country Publication (SCP), respectively. South Korea, China and the USA are considered the top three most relevant countries. South Korea has by far the most international collaboration. Two North American countries, three European countries, three Asian countries, and one country each from Oceania and the Middle East are ranked as countries with the highest number of articles on the topic.

Researchers do not work in isolation, since they are members of a worldwide community working together to provide new insights and inspiration for new researchers to work on the same or related topic. International

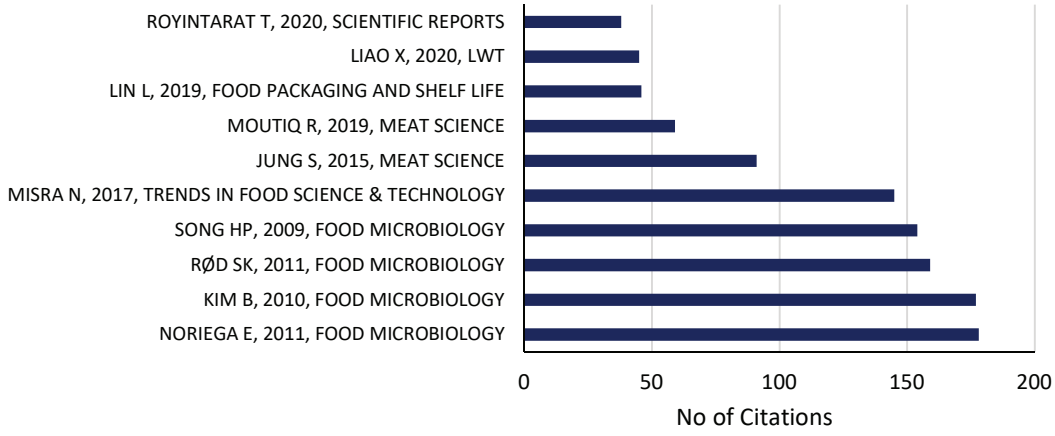

Figure 3. Most contributing articles

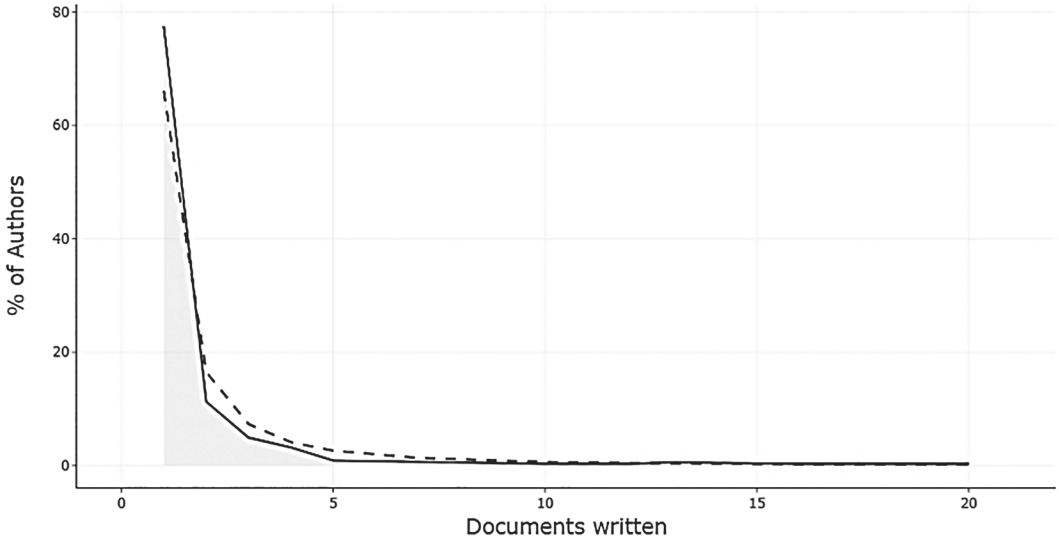

Figure 4. Authors productivity shown through Lotka's Law

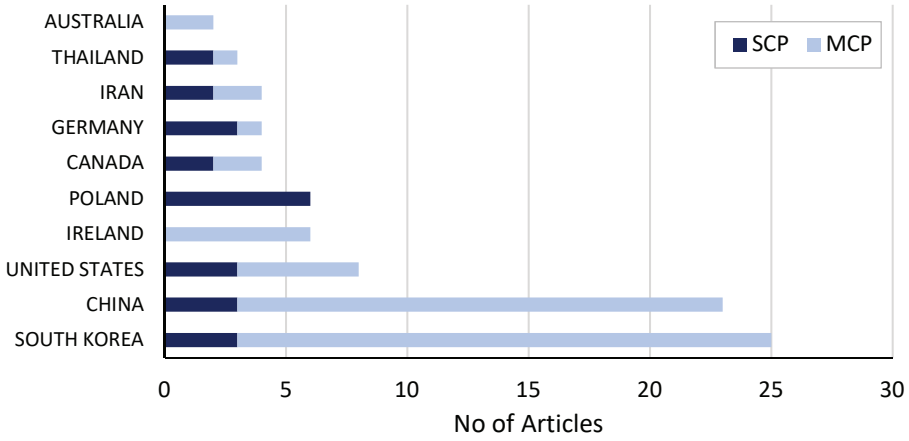

Figure 5. Top 10–Most productive countries (based on first author's affiliation).
SCP — single country publications; MCP — multiple countries publications

co-authored publications are frequently used as a measure to obtain a comprehensive picture of international collaborative works. Co-authorship is the final result of different scientific exchanges that facilitate the acquisition of science undertaken within a community of facts and ideas. It is worth noting that a country we refer to as the author's affiliation is a country indicated at the time of publication.

Keyword Frequency Analysis

The goal of keyword frequency analysis is to identify research hotspots and development trends based on the number of keyword occurrences. [33]. The keywords are derived from the publication's core content; therefore, if a keyword is frequently used in a certain knowledge domain, the topic it represents can be deemed to have garnered substantial attention from researchers and can therefore be regarded as a hotspot in the area [34]. Furthermore, keyword selection follows precise standards, as keywords are frequently used to identify research ideas, define the research field, restrict the scope of the investigation; synthesize research; and discuss the methodology or theory employed in a study [33]. As a consequence, we may find hotspots in certain knowledge fields by analyzing keywords based on their frequency and the meanings they express. Following this approach, we first extracted the most common keywords and conducted a content analysis referring to application of ACP in meat processing. Figure 6 displays the top 10 most often used keywords in our collection of articles.

Overall, all the most frequent keywords listed in Figure 6 suggest that the practicality of the ACP technology is explored mostly in the direction of its use for microbial decontamination of meat products. Beef and chicken meat are most commonly treated and analyzed. It is interesting to note that the most common keyword is nitrite. The importance of nitrite in meat products does not need elaboration. But how to explain its prominence when all other words are connected with microbial decontamination? Simply stated, every use of any other prominent keyword must be followed with the keywords nitrites. So great is its importance for the production of safe meat products. Besides that, outside of the theme of microbial decontamination, there is only one other important theme of the research. This theme is the use of the ACP technology to introduce nitrites into meat products. The process is explored as an easier and potentially more sustainable alternative to the traditional curing process.

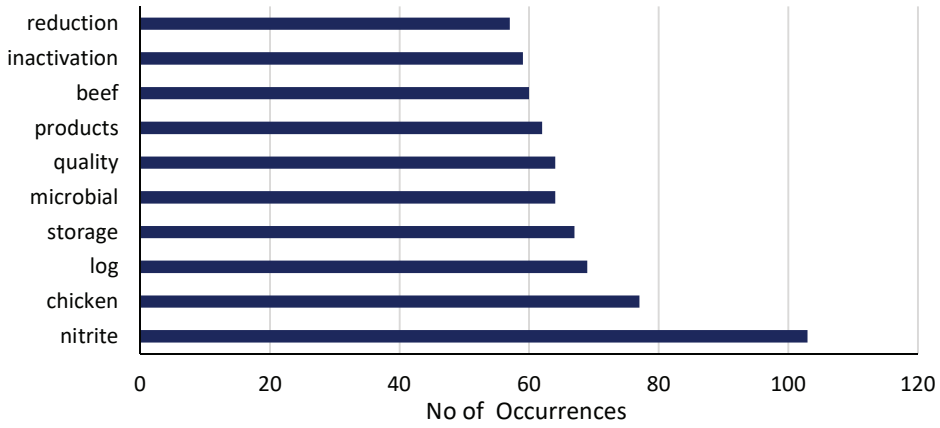

Figure 6. Top 10 most frequent keywords in ACP in meat processing research

Conclusions and Limitations

Science mapping is becoming a vital task for researchers from all scientific areas. As the number of publications continues to grow at an increasing rate and articles emerge with just fragments of knowledge, the process of collecting knowledge becomes exceedingly challenging. The definition of the intellectual structure and the research-front of scientific domains is crucial not only for research but also for policy-making and practice. Bibliometric analysis uses mathematical and statistical methods to evaluate research outputs. Although extensive empirical research has been carried out on the topic of the ACP application in meat processing, there is no study dealing with its bibliometric analysis. This work focuses on the bibliometric analysis of research at the interface of the ACP technology and meat processing through the literature from 2001 to 2022 queried from the Dimensions database. The number of articles has shown a clear increasing trend in the past decade. A great extent of collaboration among different countries, authors, and institutions has been already established. Core journals are identified as well as the list of ten most impactful articles on the topic.

Limitations of Study

This study has several limitations mainly related to the instrument of bibliometric analysis per se. Indeed, there are always false positive and false negative results in any bibliometric research. The first limitation of this study is the impossibility to generate a perfect and all-encompassing research query. The other limitation springs from the fact that the citation analysis represents an objective and quantitative measure of the research but does not provide information about research quality or its influence on the practice. Although we may hypothesize that the more citations an article receives, the greater the impact that article may have on the scientific community, we must be aware that there are many forms of citations. Besides mentioning and supporting, there is also contradicting citation which we could not isolate and quantify with the applied method. Considering all these limitations, the number of articles analyzed in this study might not exactly reflect the entire global research activity on the topic of ACP in meat processing, but the data presented likely provides significant insight into the evolving patterns over the last two decades.

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