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Cold Plasma Treatment of Rice: A Bibliometric Analysis

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ABSTRACT

The use of cold plasma (CP) technology in rice processing has gained global attention. A bibliometric analysis explored research trends, collaboration opportunities, and key concerns in the CP treatment of rice. The analysis aimed to highlight the substantial increase in scholarly publications since 2013. It focused on rice decontamination and storage improvement using CP treatment. The study revealed that China, India, and Thailand, leading rice-producing nations, were also at the forefront of CP treatment research. South Korean author Min, S.C., with six publications, made a noteworthy contribution. Most articles on CP treatment of rice resulted from domestic collaborations, but China and India actively engaged in global partnerships, indicating a growing interest in international research. These findings suggest an inclination towards fostering international collaborations in CP treatment of rice. Overall, this investigation contributes significantly to the academic community, offering insights into the current research landscape. The study also provides recommendations for future directions in managing CP treatment of rice. This bibliometric analysis serves as a valuable reference for scholars interested in the emerging CP treatment technology in the rice sector.

Keywords: *cold plasma; rice grain; food safety; bibliometric analysis*

INTRODUCTION

Rice is one of the world's most important staple foods, particularly in Asia, where it serves as a primary energy source for millions of people. According to the Food and Agriculture Organization (FAO), rice is the second most widely grown grain after corn and is the staple food for more than half of the world's population (FAO, 2021). However, the rice-consuming population eats starchy milled (white) rice with high glycemic index levels and little to trace amounts of dietary fiber (de Guzman et al., 2017). Thus, there is growing interest in a far better special rice type, brown rice, that is high in fibers, vitamins, minerals, and antioxidants that are preferentially in the aleurone layer of the rice bran but are otherwise lost upon milling. These bioactive compounds play an important role in promoting digestive health, reducing the risk of chronic disease, and aiding in weight management. The bran layer also contains B vitamins such as thiamine, niacin, and vitamin B6, which are important for energy metabolism and general well-being. In addition, brown rice is a good source of minerals such as magnesium, phosphorus, and potassium, which are essential for various physiological processes in the body (Fardet, 2010). The bran layer of brown rice is also home to antioxidants and phytochemicals such as phenols and flavonoids, which possess anti-inflammatory and disease-fighting properties (Wang et al., 2011). Incorporating brown rice into your diet can thus contribute to a balanced and nutritious meal. But the major challenge in sustaining the production and marketing of brown rice lies in ensuring its long-term viability, where if not stored properly, it will be more susceptible to molds and aflatoxin contamination as well as the risk of becoming rancid due to the high oil content in the bran of brown rice (Fisher et al., 2016). To counter these issues, fungicides and insecticides are employed; however, their use creates food safety worries, leading to allergic reactions or immunological reactivity in consumers. Cold plasma (CP) treatment is a promising postharvest technique widely applied to cereal samples, resulting in several benefits, including increased shelf life, enhanced seed germination rate, reduced cooking time, modified starch, microbe, and enzyme inactivation, and alteration of hydrophilic/hydrophobic properties (Sarangapani et al., 2018). In addition to food security, CP treatment can enhance rice grains' nutritional and functional qualities (Xia et al., 2019).

Plasma is generally created by introducing energy to a gas. This phenomenon allows the reorganization of the electronic structure of the gas molecules and atoms, producing excited species and ions (Tendero et al., 2006). Atmospheric pressure plasma (APP) is also generated by applying an electric field to a neutral gas, and the energy is transmitted to the gas electrons and neutral species by collision (Conrads & Schmidt, 2000; Tendero et al., 2006). The properties of plasma, in terms of electron density (ED) or electron temperature (T_e), change depending on the type of supplied energy and the amount of transferred energy. For APP-generated systems, ED and T_e lie along the ED and T_e ranges for glow discharge (ED 10^{14} to 10^{20} m^{-3}; ET 10^0 to 10^2 eV) and arc plasmas (ED10^{20} to 10^{30} m^{-3}; ET 10^{-1} to 10^1 eV (Kogelschatz, 2004; Taaca et al., 2022).

The influence of pressure on the plasma temperature is shown in Figure 1. Plasma can be classified as thermal plasma (LTE) or non-thermal plasma (non-LTE). This classification depends on the temperature of electrons and heavy particles (T_h). As pressure increases, the difference between T_e and T_h reduces. This phenomenon then reaches the LTE state (T_e=T_h), and the ED of plasma can rise to 10^{24} m^3. The T_e is greater than T_h for non-LTE plasmas. Hence, inelastic collisions are expected between electrons and heavy particles. These inelastic collisions induce the plasma chemistry for non-LTE plasma (Tendero et al., 2006). The standard temperature and pressure for APPs are represented as a black dot in the figure. Based on this, APPs are considered non-LTE and often referred to as cold plasmas or CPs.

Due to the extensive research on CP treatment in rice (Chandravarnan et al., 2022; Misnal et al., 2021; Starič et al., 2020; Xia et al., 2019), this paper aims to conduct a bibliometric analysis of scientific works published on this topic. Bibliometric analysis is a valuable tool in examining research trends in the CP treatment of rice, which could help determine the future direction of this area of research. This approach uses analysis and mapping techniques to measure and evaluate literature, including citations, authorship, keywords, and methodology (Fasogbon & Adebo, 2022). There have been several bibliometric studies that have been done on rice-related topics, such as rice farming (Ali et al., 2022), the effects of climate change (Yuan & Sun, 2022), and salt stress (Zhang et al., 2023). This work aims to use the bibliometric method to collate documents related to cold plasma treatment on rice, which have been primarily indexed by Scopus from 2013 to 2023, and with the help of VOSviewer, a bibliometric tool, further analyze the co-authorship network visualization of authors, organizations, and countries and co-occurrence network visualization of all keywords using VOSviewer.

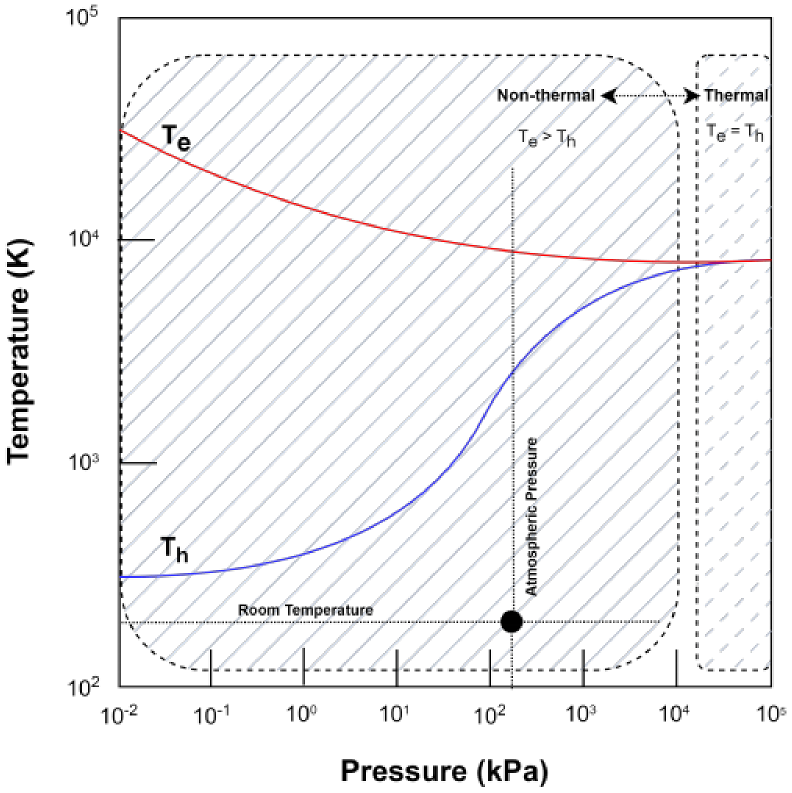

Figure 1. Influence of pressure on the plasma temperature (electron and heavy particle). T_e represents the electron temperature, and T_h is for the heavy particle temperature.

METHODS

For this investigation, bibliometric analysis was limited to Scopus-indexed publications from 2013 to 2023, accessed on April 30, 2023. The search terms" cold plasma" or "cold atmospheric plasma" and "rice" in the title, abstract, or keywords were applied. The search yielded 65 documents, and the data was exported in CSV format and imported into VOSviewer (version 1.6.19, Leiden University, Leiden, The Netherlands) to create a bibliometric map. Scopus is a comprehensive bibliographic data source that provides scientometric indicators for assessing the citation count and researcher performance (Pranckutė, 2021). According to Pranckutė (2021), Scopus has superior data sorting capabilities compared to PubMed and Web of Science. Scopus offers various features, such as an advanced search function for complex search queries and bibliometric data for tracking citations of articles published in scientific journals (Sweileh, 2020), and considers all document types and languages. The obtained data were tabulated, and the results were presented through tables and graphs using Microsoft Excel. VOSviewer is a tool for creating bibliographic maps that only includes one type of item, such as countries, organizations, authors, documents, or sources, linked by a single type of link. Items (also called nodes or vertex) are the objects of interest; a cluster is a group of items, while a network refers to a group of items with links. Items in the map have weight and score attributes, with a higher weight indicating greater importance for network and density visualization purposes. There are two standard weight attributes for links: the number of links on an item with other items, known as" links," and the total strength of the links of an item with other items referred to as "total link strength" (TLS) (van Eck & Waltman, 2010, 2017).

RESULTS AND DISCUSSION

Yearly Publication. As shown in Figure 2, the number of papers related to cold plasma treatment of rice significantly soared from 3 (in 2013) to a cumulative total of 65 (in 2023). This technology has shown promise in improving the safety and quality of food products, including rice. It has since become an improved alternative to chemical agents (pesticides, herbicides, and fertilizers) that can eliminate microbial pathogens and insect pests without affecting the rice grain quality. It has been found that cold plasma, a mixture of ionized gas, reactive oxygen, nitrogen species, free radicals, and electrons, is very effective at getting rid of microorganisms and can be used to decontaminate food surfaces and thus extend shelf life. This technique was employed for the degradation of mycotoxins, offering benefits such as the absence of chemical residue post-treatment, non-thermal characteristics, and preservation of the quality attributes of the food material (Chandravarnan et al., 2022; Mir et al., 2021). Applying cold plasma to grains (e.g., rice, wheat, corn, barley, and oats) significantly reduced the number of fungi, bacteria, and spores on the grain's surface (Kaur et al., 2020). Moreover, Misnal et al. (2021, 2022) suggested integrating cold plasma technology in the postharvest management of rice to prevent damage and/or spoilage, thereby increasing the value of rice. Besides microbial decontamination, CP treatment enhanced the rice grain and starch's functional, nutritional, and cooking properties. Interestingly, the two highest-cited articles by Thirumdas et al. (2016, 2017), 150 and 113 citations, respectively, focused on these attributes.

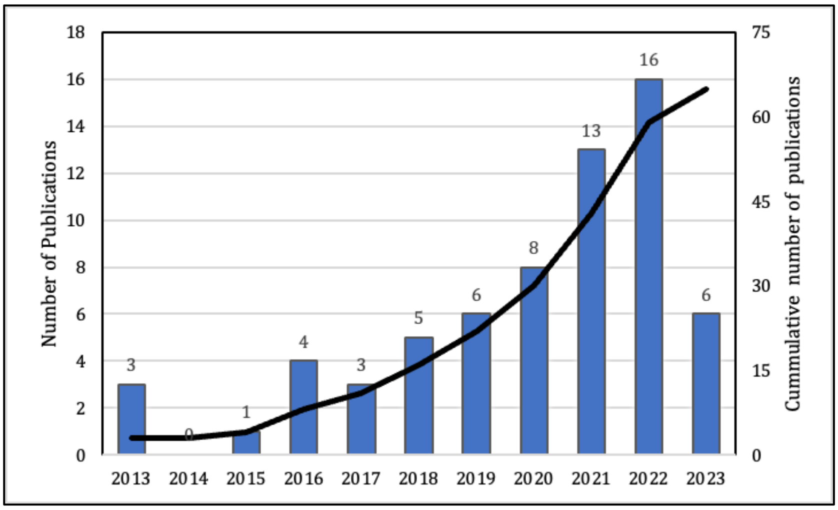

Figure 2. Annual Publication from 2013 to 2023

Countries/regions co-authorship analysis. Figure 3A displays the publication output of 20 countries between 2013 and 2023. India, China, and Thailand, the leading rice producers (Bin Rahman & Zhang, 2023), have the highest number of articles on CP treatment for rice, with 13, 12, and 11 documents, respectively. As per Statistica, India, China, and Thailand accounted for over 80% of global rice production in 2021-2022, producing 129.47, 148.99, and 19.88 million metric tons of milled rice, respectively. Additionally, rice is a staple food in South Korea and Iran, two countries that rank highly in publication activity. This indicates a shared interest among food scientists and agricultural researchers worldwide in utilizing CP to ensure the quality and safety of rice. While Figure 3B illustrates the country co-authorship network of CP treatment research from 2013 – 2023, having 20 items with 13 clusters. Each country is depicted by a circle whose size corresponds to the number of articles attributed to that country, indicating its activity level. A line is drawn between countries that share a collaborative relationship. The countries with the most documents, namely China, India, South Korea, and Thailand, are also the largest in item size. However, there is a lack of international collaboration among these countries within their respective clusters. Interestingly, India is involved in collaborative works with Brazil, Iran, and Saudi Arabia within Cluster 1. On the other hand, China has interacted with Egypt, Iran, the United

States, and the United Kingdom within Cluster 2. As a result, China and India are at the forefront of developing international collaborations and are likely to increase academic exchanges, promoting communication as well as diversification of perspectives in the academic community.

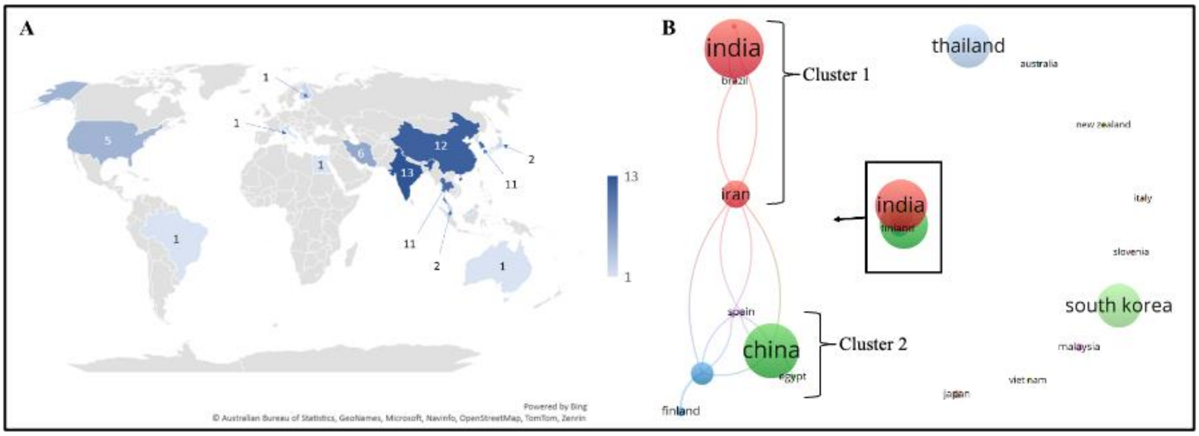

Figure 3. (A) Publication productivity by country; (B) The country co-authorship network of CP-treated rice research-related top papers.

Organizations co-authorship analysis. The co-authorship analysis indicates the level of communication between institutions and highlights the influential institutions involved (Reyes-Gonzalez et al., 2016). Table 1 presents the findings of the leading 11 organizations, out of 159, that have published at least two documents. The most productive countries, as depicted in Figure 3A, are India (5), South Korea (3), Iran (3), and China (2), and it is within these countries that the top organizations are located.

Table 1: Top organizations and institutes publishing papers with more than one publication in the field of CP-treated rice research.

Rank	Organization	Documents	citations	total link strength
1	Department of Food Science and Technology, Seoul Women's University (South Korea)	3	37	2
2	Center of Innovative and Applied Bioprocessing (Ciab) (India)	2	7	3
3	College of Food Science and Engineering, Northwest A&F University (China)	2	31	0
4	College of Grain, Oil, and Food, Henan University of Technology (China)	2	23	0
5	Department of Food Engineering & Technology, Institute of Chemical Technology (India)	2	263	2
6	Department of Medical Parasitology and Mycology, School of Public Health, Tehran University Of Medical Science (Iran)	2	5	4
7	Department of Microbiology, Science and Research Branch, Islamic Azad University, (Iran)	2	5	4
8	Dr. S. S. Bhatnagar University Institute of Chemical Engineering & Technology (Ssbuicet), Panjab University (India)	2	4	2
9	Institutes of Green Bio Science & Technology, Seoul National University (South Korea)	2	37	2
10	National Agri-Food Biotechnology Institute (Nabi) (India)	2	7	3
11	Plasma Physics Research Center, Science and Research Branch, Islamic Azad University (Iran)	2	5	4

VOSviewer software divided these 13 organizations into 7 clusters, as shown in Figure 4; the more prominent nodes represented the more influential institution in this field, while the distance and thickness of links represented the degree of cooperation among organizations. The list indicates that the three Iranian institutions have collaborative works within Cluster 1, while in India, there are two separate collaborations among the organizations located in Punjab (Cluster 2) and Mumbai (Cluster 3). Additionally, two organizations in South Korea have established a co-authorship network. According to these findings, these current co-authorship networks are restricted to the top publishing organizations within the country, indicating a limitation in their scope.

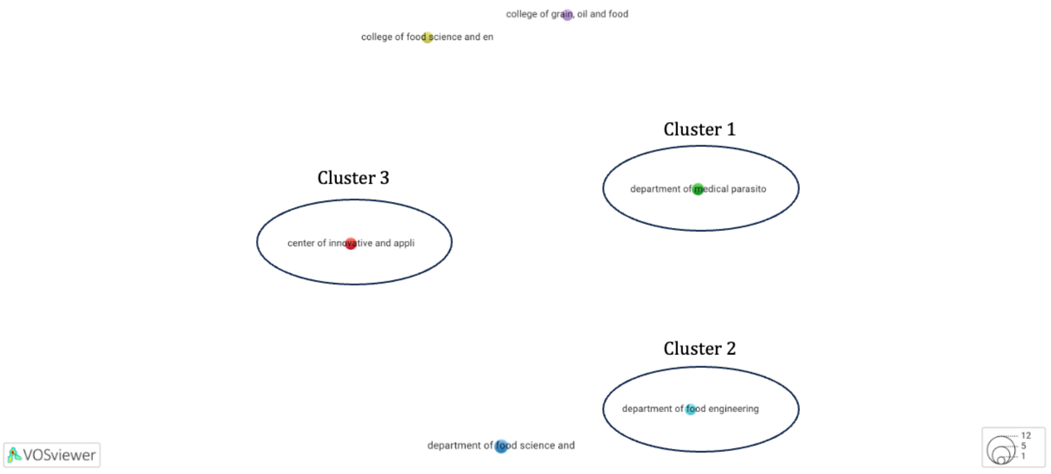

Figure 4. The co-authorship network among organizations of CP-treated rice research with at least two publications.

Author's co-authorship analysis. Working collaboratively on research can expand an author's network and increase their chances of gaining more visibility (Sjögårde & Didegah, 2022). Figure 5 illustrates the authorship network for CP treatment of rice, with prominent items indicating authors with more papers on this topic. This network map of the leading author's co-authorship reveals 252 items and 37 clusters, with larger clusters containing at least 14 items. The thickness and distance of links reflect the level of cooperation among authors. Most co-authorship networks are nationality-based, as indicated by the clusters. The red-highlighted Cluster 1 (in red) consists of at least 14 networks and comprises Chinese authors, while Clusters 2 (in green) and 3 (in blue) are Korean authors.

Table 2 presents the 15 most productive authors with at least three publications focusing on the CP treatment of rice out of 252 authors. Sea Cheol Min from Seoul Women's University (h index = 38) and Siwapon Srisonphan from Kasetsart University (h index = 9) are the most productive, with six publications each and citations of 59 and 135, respectively. Min's work primarily focuses on the effects of cold atmospheric plasma-treated water (Han et al., 2020) and in-package CP treatment (Lee et al., 2023) on the microbial decontamination of rice cakes, while Srisonphan's research focuses on the impact of CP on surface function, wettability, and rice seeds' germination (Khamsen et al., 2016; Srisonphan & Teerakawanich, 2018).

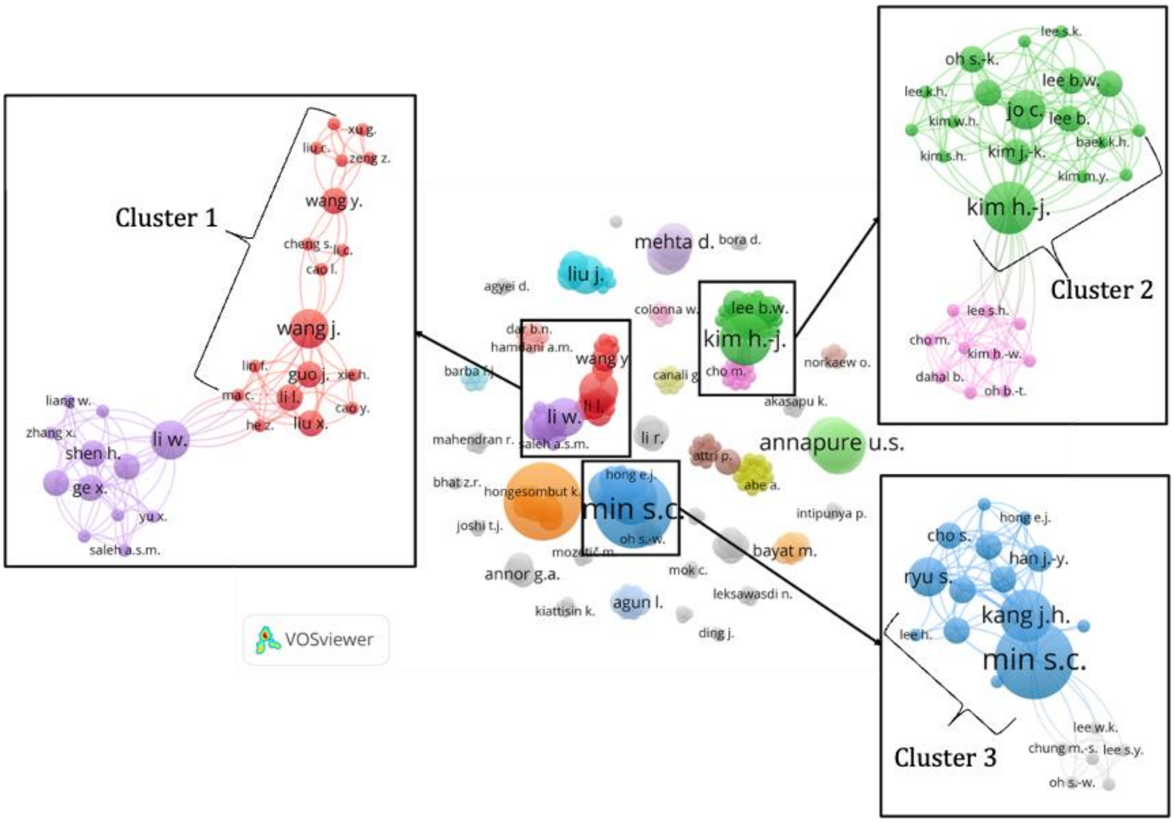

Figure 5. Network visualization map of top authors for CP-treated rice. The authors' first names have been reduced to their initials, and a minimum publication productivity of one paper was set as the threshold.

Table 2. The most prolific authors of CP-treated rice top papers with at least 3 publications

Rank	Author	Documents	Citations	Total link strength
1	Min S.C.	6	59	30
2	Srisonphan S.	6	135	14
3	Annapure U.S.	4	435	16
4	Deshmukh R.R.	4	435	16
5	Kang J.H.	4	53	20
6	Kim H.J.	4	112	35
7	Jo C.	3	104	25
8	Li W.	3	35	22
9	Liu J.	3	37	14
10	Mehta D.	3	9	13
11	Ryu S.	3	37	20
12	Shivhare U.S.	3	9	13
13	Thirumdas R.	3	346	12
14	Wang J.	3	9	16
15	Yadav S.K.	3	9	13

Keywords co-occurrence analysis. Keywords analysis is a crucial component of bibliometric analysis as it reveals the focus of researchers' interest in a particular research topic (Nordin et al., 2023). To explore the co-occurrence connection among keywords derived from research publications on the CP treatment of rice, a VOSviewer visualization map (Figure 6) was generated. After removing the duplicates, the visualization depicts 57 items categorized into five clusters, distinguished by their respective colors based on their co-occurrences. "Cold plasma" is positioned at the center of the map, being the most frequently occurring keyword in the analyzed articles. Cluster 1 (in red) pertains to using cold plasma in food safety and storage by decontaminating bacteria, mold, and yeast. Cluster 2 (in green) is focused on the effects of cold plasma on rice grain and starch's physicochemical and functional properties, including hydrophilicity, contact angle, texture, and gelation. Cluster 3 (in blue) emphasizes using dielectric devices/materials to generate cold plasma to enhance seed germination. Cluster 4 (in yellow) denotes instrumental techniques such as Fourier transform infrared spectroscopy and scanning electron microscopy to study the surface property of cold plasma-treated rice. Cluster 5 (in purple) represents the grain quality of brown rice. In general, this keyword co-occurrence visualization illustrates how cold plasma positively impacts rice grain quality and storage by facilitating microbial decontamination and detoxification.

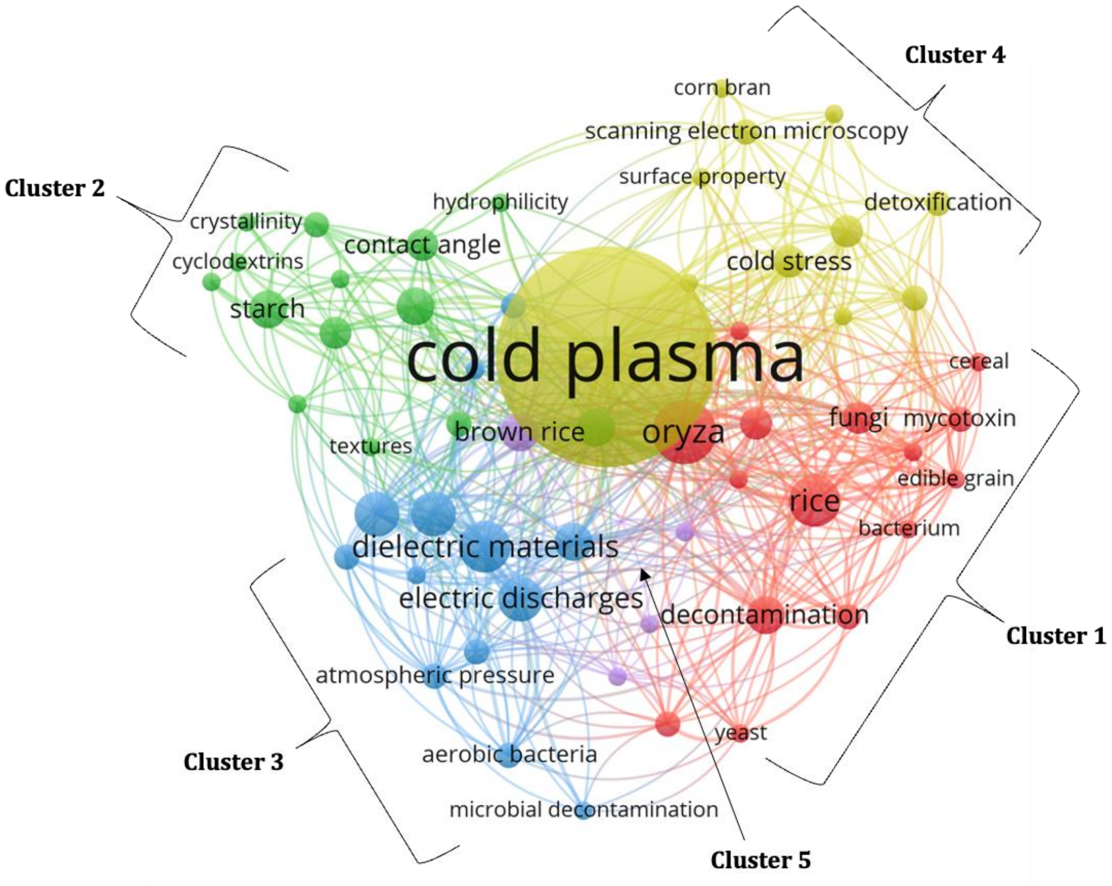

Figure 6. VOSviewer co-occurrence Network visualization mapping of most frequent all keywords (minimum of 3 occurrences) of CP-treated rice.

The most frequently cited articles. The research findings from 65 articles have been published across 46 different journal sources. Table 3 lists the top 13 journals that have received at least 20 citations. Among these, 11 journals are categorized under Quartile 1 rank, while the remaining two are listed under Quartile 2. The leading journal in terms of productivity and citation count is LWT (Lebensmittel-Wissenschaft & Technologie)- Food Science and Technology, which has published seven articles with a total of 344 citations. Agrifood science research journals make up

8 out of the 13 top journals. In terms of CiteScore and SJP, the leading journals Critical Reviews in Food Science and Nutrition and ACS Applied Materials and Interfaces have several citations related to the subject but are not necessarily at the top rank. Furthermore, this trend reflects a preference among authors to publish their work in food and agricultural science journals rather than in plasma or radiation-related journals.

Table 3. Top journal published CP-treated rice research with at least 20 citations during period from 2013 to 2023.

Rank	Journal	Document	Citation	CiteScore*	Highest percentile/ Research Field	SJR*	Quartile
1	LWT - Food Science and Technology	7	344	7.3	87%, 42/338, Food Science	1.06	Q1
2	Carbohydrate Polymers	2	186	16	98%, 3/154, Polymers and Plastics	1.61	Q1
3	Innovative Food Science and Emerging Technologies	3	124	9.7	93%, 24/338, Food Science	1.15	Q1
4	ACS Applied Materials and Interfaces	2	122	14.4	92%, 33/455, General Materials Science	2.14	Q1
5	Food Chemistry	3	92	13.1	97%, 8/338, Food Science	1.49	Q1
6	International Journal of Food Microbiology	2	77	9.4	92%, 25/338, Food Science	1	Q1
7	Plants	1	49	3.6	71%, 140/482, Plant Science	0.77	Q1
9	Food and Chemical Toxicology	1	46	10.2	95%, 6/123, Toxicology	0.81	Q1
10	Critical Reviews in Food Science and Nutrition	1	41	20.8	99%, 2/338, Food Science	1.75	Q1
11	Food and Bioprocess Technology	3	25	7.8	90%, 16/171, Safety, Risk, Reliability and Quality	0.99	Q1
12	Journal of Food Processing and Preservation	1	21	3	53%, 159/338, Food Science	0.42	Q2
13	ACS Agricultural Science and Technology	1	20	0.4	13%, 104/119, Agricultural and Biological Sciences	0.37	Q2

** CiteScore 2021 counts the citations received in 2018-2021*

***SCImago Journal and Country Rank 2021 is a portal that includes the journals and country scientific indicators developed from the information contained in the Scopus database (Elsevier)*

Table 4 lists the top 8 articles that have received at least 70 citations. The study by Thirumdas et al. (2017) has the highest number of citations, with 150. Their research aimed to investigate the impact of cold plasma treatment on the functional and rheological properties of rice starch using two different power levels (40 and 60 W). The reason for the high citation rate of this paper is likely due to its findings that cold plasma treatment of rice starch resulted in depolymerized and cross-linked rice starch chains, reduced gelatinization temperature, increased pasting properties, and induced fissures on starch granules. Most of the top articles regarding cold plasma (CP) treatment focused on its application for postharvest management. Specifically, these studies examined the effects of CP treatment on the physicochemical, functional, cooking, and textural characteristics of wholegrain rice in the form of both brown and parboiled rice.

Table 4. Top 8 highly cited articles with total citations more than 70 times.

Rank	Title	Authors	Source title	Year, Volume, Pages	Citations
1	Functional and rheological properties of cold plasma treated rice starch	Thirumdas R., Trimukhe A., Deshmukh R.R., Annapure U.S.	Carbohydrate Polymers	2017, 157, 1723-1731	150
2	Influence of low-pressure cold plasma on cooking and textural properties of brown rice	Thirumdas R., Saragapani C., Ajinkya M.T., Deshmukh R.R., Annapure U.S.	Innovative Food Science and Emerging Technologies	2016, 37, 53-60	113
3	Rice (Oryza sativa L.) Seed Sterilization and Germination Enhancement via Atmospheric Hybrid Non-thermal Discharge Plasma	Khamsen N., Onwimol D., Teerakawanich N., Dechanupaprittha S., Kanokbannakorn W., Hongesombut K., Srisonphan S.	ACS Applied Materials and Interfaces	2016, 8, 19268-19275	104
4	Evaluation of cold plasma treatments for improved microbial and physicochemical qualities of brown rice	Lee K.H., Kim H.-J., Woo K.S., Jo C., Kim J.-K., Kim S.H., Park H.Y., Oh S.-K., Kim W.H.	LWT	2016, 73, 442-447	99
5	Effect of low-pressure plasma on physico-chemical properties of parboiled rice	Sarangapani C., Devi Y., Thirundas R., Annapure U.S., Deshmukh R.R.	LWT	2015, 63, 452-460	89
6	Effect of low-pressure plasma on physico-chemical and functional properties of parboiled rice flour	Sarangapani C., Thirumdas R., Devi Y., Trimukhe A., Deshmukh R.R., Annapure U.S.	LWT	2016, 69, 482-489	83
7	Inhibition of Aspergillus flavus on agar media and brown rice cereal bars using cold atmospheric plasma treatment	Suhem K., Matan N., Nisoa M., Matan N.	International Journal of Food Microbiology	2013, 161, 107-111	77
8	Cold plasma treatment to improve germination and enhance the bioactive phytochemical content of germinated brown rice	Yodpitak S., Mahatheeranont S., Boonyawan D., Sookwong P., Roytrakul S., Norkaew O.	Food Chemistry	2019, 289, 328-339	74

Future Insights and Direction. As observed in the increasing publications from the decade, the implementation of cold plasma treatment is anticipated to increase in the future because it has demonstrated positive results in enhancing the quality and safety of rice. Here are some potential future developments regarding the use of cold plasma treatment in the processing of rice:

A. Different rice varieties can benefit from different cold plasma treatments, which can be tailored to enhance their quality and safety. Future studies can concentrate on figuring out the best treatment conditions for each rice type, considering elements like grain size, moisture content, and amylose concentration.

B. To improve the quality and safety of rice, CP treatment can be integrated with other techniques, including soaking, steaming, and drying. For example, combining CP treatment and soaking can enhance chickpeas' moisture absorption, which may help save cooking time and energy (Pathan et al., 2021).

Developing and commercializing efficient, safe, and scaled-up cold plasma systems for the food industry is essential (Laroque et al., 2022). Future research can concentrate on creating low-cost, effective cold plasma systems for processing rice that small-scale rice mills and farmers can employ. Cold plasma treatment is a burgeoning field of research with tremendous potential to improve the quality and safety of rice, making it a valuable tool in the food industry. This technology holds great promise in addressing issues in the rice business, including concerns surrounding food safety and nutritional deficiencies. As more research is conducted, there is a strong possibility that cold plasma treatment will emerge as a transformative solution that can help revolutionize rice processing and production. Continued advancements in this area could have far-reaching implications for the entire food industry, potentially opening new avenues for innovation and growth.

CONCLUSIONS

CP treatment of rice is an emerging technology that is continually developing globally. This bibliometric analysis demonstrates the rapid growth of this research field since the first known publication came out in 2013. Based on this analysis, the primary emphasis in the research on the cold plasma treatment of rice lies in two key areas: rice decontamination and storage improvement. The leading countries researching this field are also the top rice-producing countries – China, India, and Thailand. However, it is interesting to note that the most prolific author in this field, Min, S.C. hails from S. Korea, with 6 publications as of this writing. Furthermore, while strong collaborations have been primarily observed on a national level, China and India are actively pursuing increased international linkages. The findings in this study can serve as valuable references for researchers, guiding the future direction of this field. By analyzing publication and authorship trends, scientists can effectively identify research hotspots and potential opportunities for collaboration as well as address pertinent issues within the field.

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