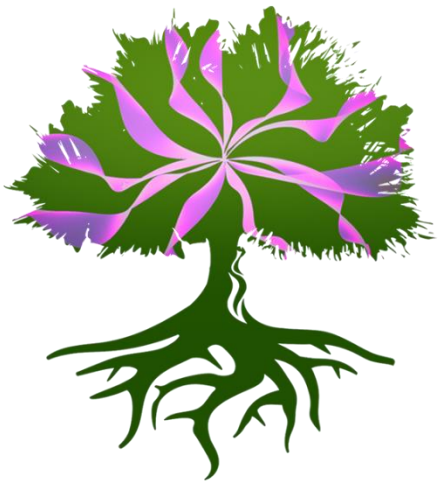

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European Cooperation in Science and Technology

Virtual Mobility grant

Bibliometric evaluation - Atmospheric and low pressure cold plasma technology for seed treatment

Grantee name: Kosta Spasić

03/10/2022 to 23/10/2022

Introduction

Worldwide growth of population, that is in general more educated than ever, and necessity for technological advancements in all spheres of life have fueled rapid increase in both scientific research and accumulated knowledge. The best way to quantify that effort is by the number of scientific publications. Generally speaking, rise in publications over time is following exponential curve. Due to already big and ever-growing pool of knowledge that is being disseminated through various articles, proceeding, chapters and whole books, reaching specific information is getting more and more difficult. That means that average researcher is more likely to omit data that may be crucial for his work either in planning phase or during analysis of his results.

Low temperature plasma is one of the research fields that is attracting attention of both scientists and industry. Due to the inherent nature of plasma, it is possible to achieve very different, even opposing, results just by changing parameters such are pressure, discharge power and frequency, working gas or mixture of gases, geometry of electrodes, etc. Possibility for application of low temperature plasmas and their effectiveness is currently researched in fields ranging from medicine and biology to metallurgy and textile industry. Relatively new but rapidly growing niche, that is of special interest for the Action, is the field of Plasma agriculture. Important part of that field is application of low temperature plasma in treatment of seeds.

One of the best ways to analyze certain field of research and to detect the most important institutions and scholars is by bibliometric review. As it is mostly based on number of publications and number of citations they collected over time, it also one of the most objective ways to asses impact of analyzed work. Additionally, it can help to pinpoint journals which are publishing the largest number of documents related to the field which can be very helpful to both young researches who need introduction into the field or to the experienced scholars who are preparing their results for publication.

This report is hence written as a bibliometric analysis of the work connected with plasma treatment of seeds at both atmospheric and low pressure. Hopefully, these results will contribute to Action goals as they would help to declutter and organize already published work of scholars in this field and they would also help in coordination of both future experimental work and selection of journals or conferences where those results would most likely stand out. Research time frame is selected to cover publications starting from 2003 up to today. Beside presentation of

the most relevant bibliometric results, special attention will be given to publications with the highest number of citations.

Selection and methodology

First step in any bibliographic research is selection of appropriate database. Currently most popular databases, with highest number of entries, are Google Scholar, Microsoft Academics, Crosreff, Web of Science, PubMed, ScienceDirect, Dimensions, Scopus, CORE, ScienceOpen, or Semantic Scholar. There are, of course, other scientific paper repositories but they are usually focused on publications that area dealing with more specific field of research, like biology or economy.

In order to be selected, database had to fulfill following requirements:

- Free to use – this requirement was crucial since author did not have access to repositories that are maintained by user subscriptions.
- Multidisciplinary –treatment of seeds with plasma usually requires expertise from scientists with various background like physics, biology and engineering.
- Up to date – in order to operate with correct bibliometrics, database had to be automatically updated in real time.
- Rich metadata – fields that are describing entry had to contain key words and abstract so that meaningful search can be performed and that most of the wrongly included entries (false positives) could be excluded.
- Possibility of data export – locally stored data makes data processing, creating of tables and graphs, much easier.

After initial survey two databases were singled out: Scopus and Dimensions. At the moment of this research Scopus claimed to have records of about 80 million documents while Dimensions boasted of about 130 million records. Both of them are equally user friendly while Scopus provides more data exporting tools.

Since we are dealing with very specific field of interest, search was performed in both databases. Requesting data have to be done through a query. In that sense Scopus is also a better choice because it allows query to be made through more than 20 categories like title, abstract, authors, affiliation and other information connected with entries. On the other hand, Dimensions have only 3 options available: full data, title and abstract or DOI.

Creating of proper query is the most important part of this analysis. It had to be done in a way that it would include the highest number of relevant entries but to exclude the most entries that are not of interest for this research. In this step it is important to note that perfect query does not exist and that certain number of both false positives and false negatives will always appear. After initial analysis of available literature it was concluded that query should be assembled in way that it would return results that are, as much as possible, fulfilling following conditions:

- Focused on treatments by plasma but to avoid treatments by lasers or chemicals.
- To be focused on treatment of seeds but to avoid treatment of other surfaces.
- To include all major seeds that are being treated.
- To include all plasma sources that are being used.

It was decided that questionary refers only to title, abstract and keywords (Scopus) or title and abstract (Dimensions). When all fields or full data was selected, both databases returned tens of thousands results most of which didn't have anything to do with treatment of seeds by plasma. Words that are added to query are selected in a way that would maximize number of relevant entries that are returned. Finally, both Scopus and Dimensions were queried as follows:

plasma OR discharge

AND

treatment OR treated

AND

seed OR seeds

AND

grain OR legumes OR lentils OR beans OR wheat OR wheat OR oat OR maize OR lupine OR soybean OR radish OR cucumber OR pepper OR lambsquarters OR "lambs quarters" OR cereal OR cumin OR basil OR rice OR tomato OR triticum OR sunflower OR rapeseed OR "rape seed" OR pine OR corn OR nastrutium OR okra OR hemp OR "cannabis sativa" OR buckwheat OR leucaena OR cotton OR poppy OR "paulownia tomentosa" OR pea OR quinoa OR asparagus OR sesame OR groundnut OR peanut OR mung OR spinach OR alfalfa OR broccoli OR fenugreek OR mustard OR barley OR coffee OR grape OR millet OR fruit

AND

cold OR nonthermal OR non-thermal OR "low-temperature" OR "room temperature" OR atmospheric OR "low pressure" OR low-pressure OR ccp OR icp OR "inductively coupled" OR "capacitively coupled" OR "parallel plate" OR non-equilibrium OR "nonequilibrium" OR "Surface Barrier Discharge" OR dbd OR "dielectric barrier discharge" OR radiofrequency OR "radio-frequency" OR rf OR "plasma bullet" OR "plasma needle" OR "surface discharge" OR "plasma jet" OR surfatron OR dscbd OR lpcp OR khz OR "Gliding-arc" OR glidarc OR capp

Both databases returned around 400 results. Due to aforementioned advantages Scopus, which provided 420 entries, was selected as database of choice. Due to the relatively low number of total results, checkup for false positives was performed manually. Most of the erroneous results were dealing with plasma activated water. They are excluded because seeds were not directly treated with plasma. Entries that were comparing two methods of treatment (direct and indirect) were included. Additionally, a lot of false positives appeared due to inclusion of keyword “ICP” as it is used to describe diagnostic tools such are ICP-MS and ICP-OES. After all non-compliant entries were excluded, total number of bibliometric units to be analyzed dropped to 288.

General Analysis

Basic information about collected data is presented in Table 1. There are 288 documents that are written by 157 authors, they are presented in 134 sources (journals, proceedings, books…) and those documents were cited, in total, 7103 times. Two papers did not have any country specified as a place they were created in but 286 other originated from 49 different countries. Interestingly, 43 of these documents do not have any citations at all. That means that, averaged across whole selection, there are 24.66 citations for each document. If non-cited documents were excluded, average citation reaches 28.2 per article.

Table 1. The most important data about document collection.

Description	Results
Documents	288
Authors	157
Citations	7103
Affiliations	160

Sources	134
Countries	49 (2 undefined)
Time span	2003-2023

Distribution of published documents for every year in 2003-2023 range is shown in Figure 1. In the beginning of the 2000s interest in this topic was low and there were only few articles published every year. Starting from the middle of the next decade, number of published documents have started to rapidly increase, reaching maximum of 58 published articles in 2021. In period starting from 2014 the highest relative increase happened in 2018, when there were 43.5 % more documents published compared to year before. Similarly, the highest increase in absolute numbers happened in 2020 with a rise of 13 documents year on year. Starting from year 2022 there is noticeable decline in number of published documents. Most probable reason are covid-19 mobility restrictions which were significantly hampering both cooperation between researchers and their ability to perform experiments.

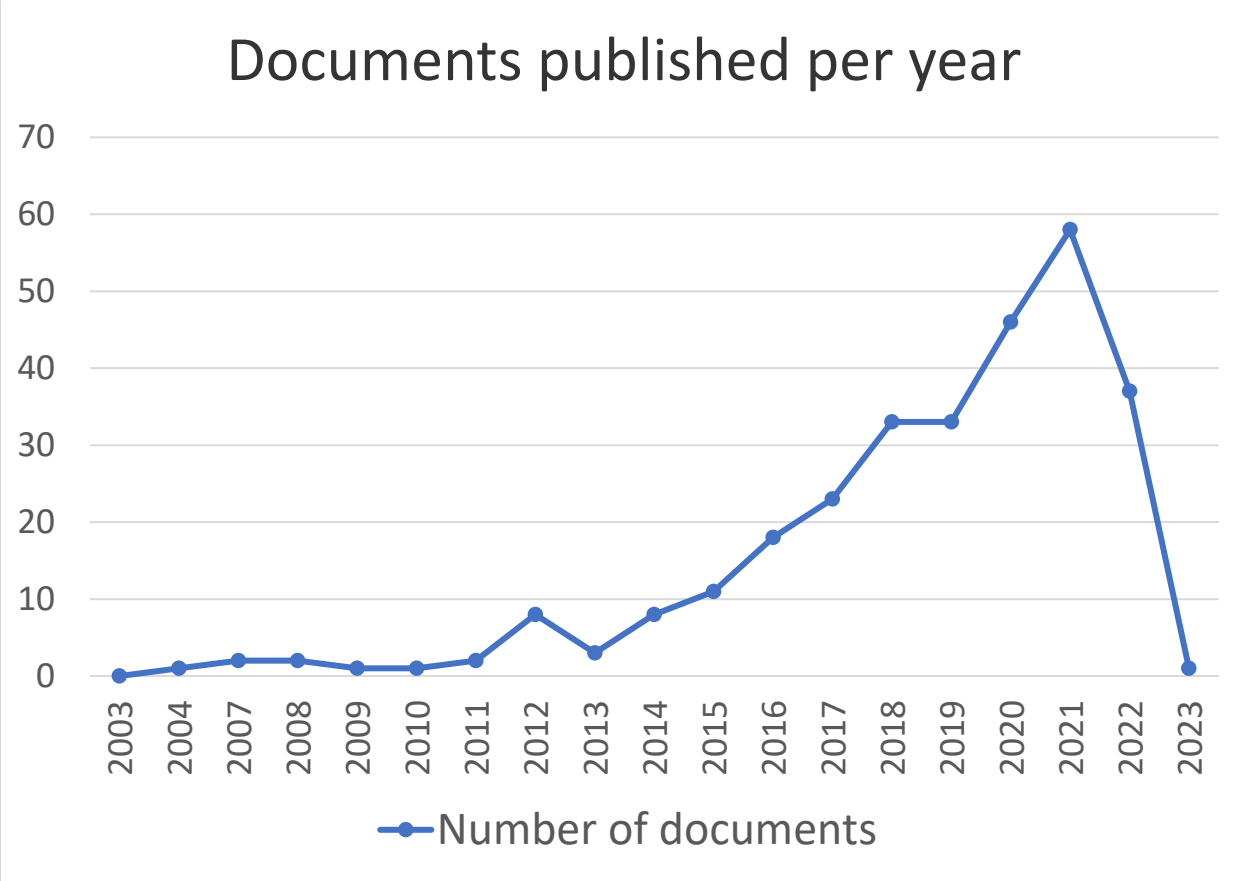

Figure 1. Number of documents published per year during 2003-2023 period.

Total citation of selected documents per year is presented in Figure 2. It is interesting to note that total of 7103 citations is made by 2091 document. That means that, in average, 3.4 documents from this list were cited per publication that is related to treatment of seeds by plasma. Following similar trend as total number of published documents, citations are starting to significantly rise during middle of 2010s. Up to year 2021 increase in citations is basically following exponential curve. The most significant relative rise happened in 2018 with 84 % increase, but in absolute numbers it happened in 2021 with 1920 citations which represents year on year jump of 744. As with total number of documents, probably due to the same reason, records for the last two years of examined period are significantly lower. It remains to be seen whether it is a sign that interest in this field of research is withering or it is really just a consequence of the aforementioned measures.

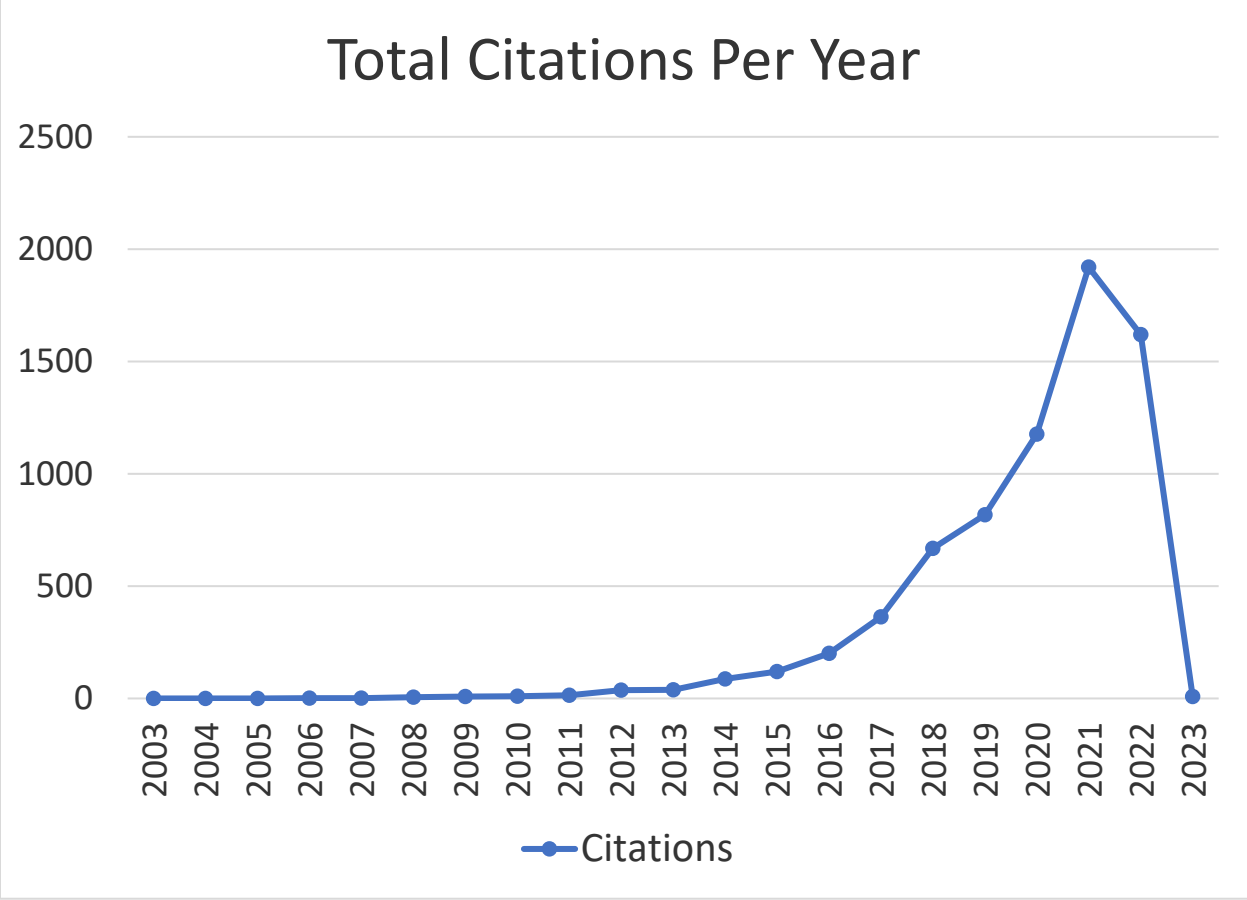

Figure 2. Total citations of documents per year during 2003-2023 period.

There is a statistical law which is usually used to describe productivity of authors in certain field, named Lotka's law. According to it, as described on NIST website, the number of authors making n contributions is about $1/n^a$ of those making one contribution. Productivity of authors encompassed by this research is not closely following Lotka's law, as it would be expected. Usually more than half of authors contribute with just one document. Surprisingly, in our list there are no authors that contributed with only one document. Out of 157 authors, 16 (10.2 %) of them contributed with at least 2 papers. Three papers were contributed by 63 authors or 40.13 %, 4 documents were signed by 36 (22.93 %), 5 by 19 (12.1 %), 6 by 7 (4.46 %) and 7 by 6 (3.82 %). Authors which signed 8 or more documents are belonging to top 10 contributors in this list. There are few possible reasons why this set of authors and their contributions deviates so strongly from this almost universal law:

- It may reflect peculiarities of the field of research.
- It may be connected to database (SCOPUS) algorithms and filtering.
- Statistical rules are less likely to hold on at small sample size.

Productivity of authors is shown in Figure 3 a). It is still noticeable that large part of documents is signed by only few highly prolific authors.

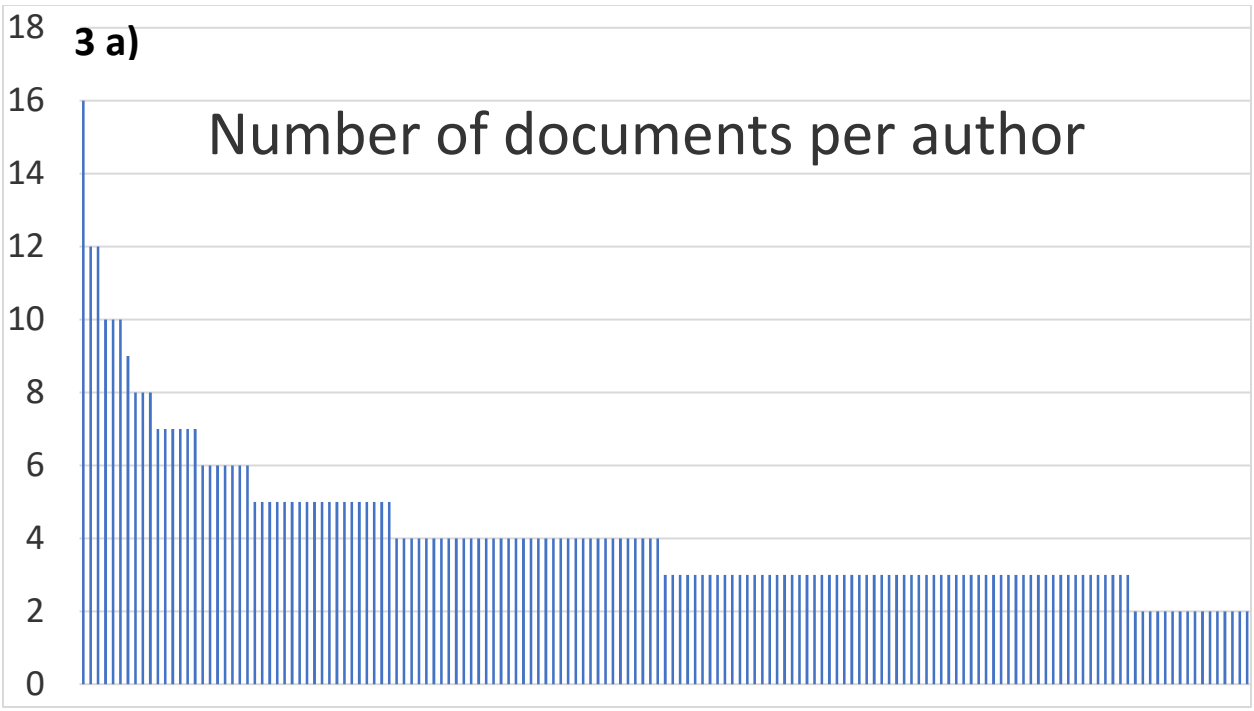

Figure 3. a) Distribution of documents per author.

Contribution of top 10 authors, in total number of documents, is shown in Figure 3 b). Author with the highest number of signed documents is Božena Šerá from Faculty of Natural Sciences at Comenius University in Bratislava. She signed 16 documents or 5.56 % of them. Only two other authors contributed more than 10 documents. Michal Šerý and Siwapon Srisonphan who are both signees on 12 documents or 4.17 % of total each.

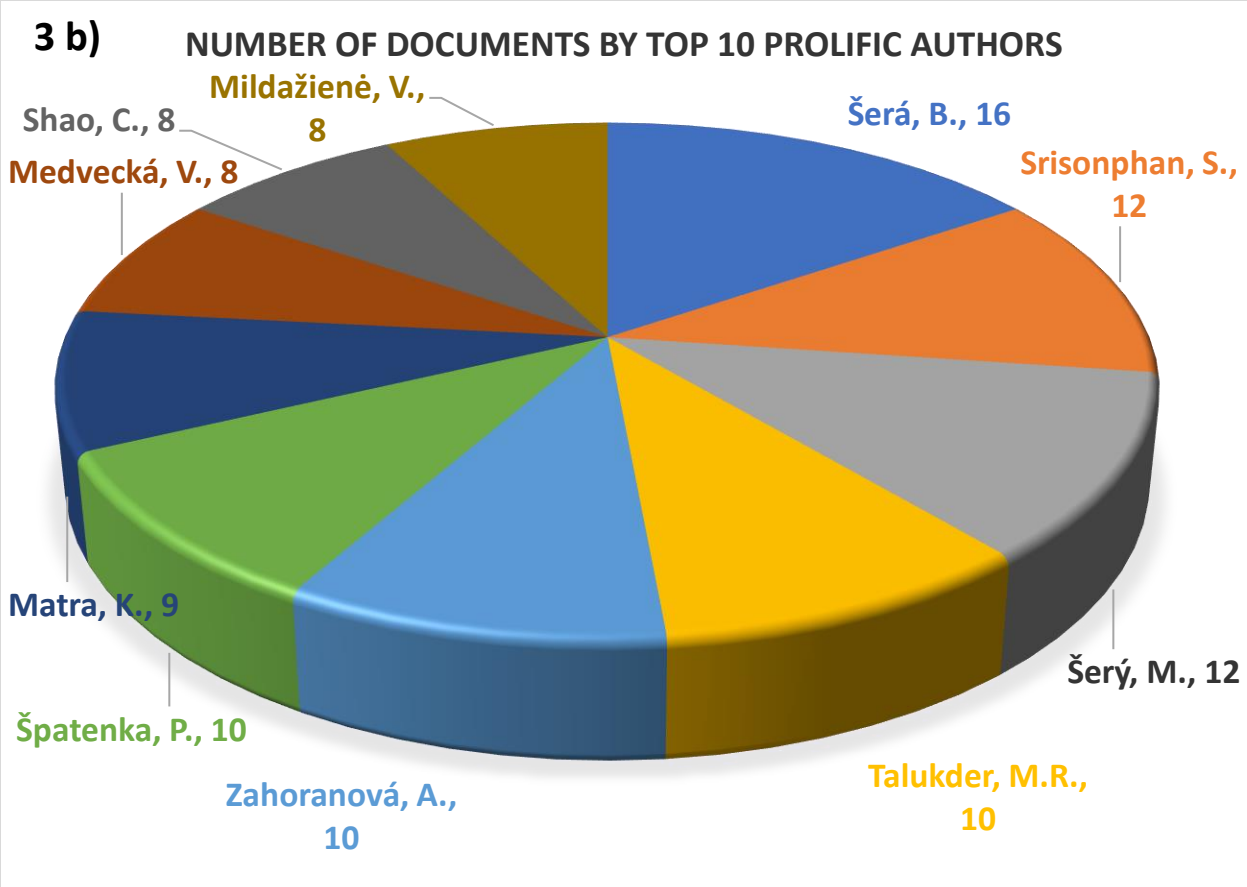

Figure 3. b) Number of documents written by top 10 most prolific authors.

Number of documents published by certain source is also following rapidly decreasing curve, but the one that is more similar to Lotka's law. Only one document is published by 88 sources or by 65.7 % of all sources in this list. Two documents are published by 23 sources or by 17,2 % of total, 3 by 7 (5.2 %), 4 by 5 (3.73 %), and 5 by only 1 source. Sources that published more than 6 documents are belonging to top 10 sources by number of documents and they are presented in Table 2. Distribution of published documents per source is shown in Figure 4.

Figure 4. Distribution of published documents per source.

Table 2. Number of publications in top 10 sources

Source name	Number of documents
Plasma Chemistry And Plasma Processing	24
Scientific Reports	17
Plasma Science And Technology	13
Plasma Processes And Polymers	10
Journal Of Physics D Applied Physics	9
Plants	9
Applied Sciences Switzerland	7
IEEE Transactions On Plasma Science	7
Food Chemistry	6
International Journal Of Molecular Sciences	6

Source that contributed the most to this list is Plasma Chemistry And Plasma Processing where 24 documents were published or 8.3 % of all documents. It is followed by Scientific Reports with 17 (5.9 %) and Plasma Science And Technology with 13 (4.5 %). Basically, all of the top 10 sources are dealing with either specifically plasma and its applications or they are requesting that submitted manuscripts are dealing with multidisciplinary issues. Structure of top ten contributing sources is hence very well reflecting the nature of this field, because

successful publication usually requires knowledge of experts from various backgrounds.

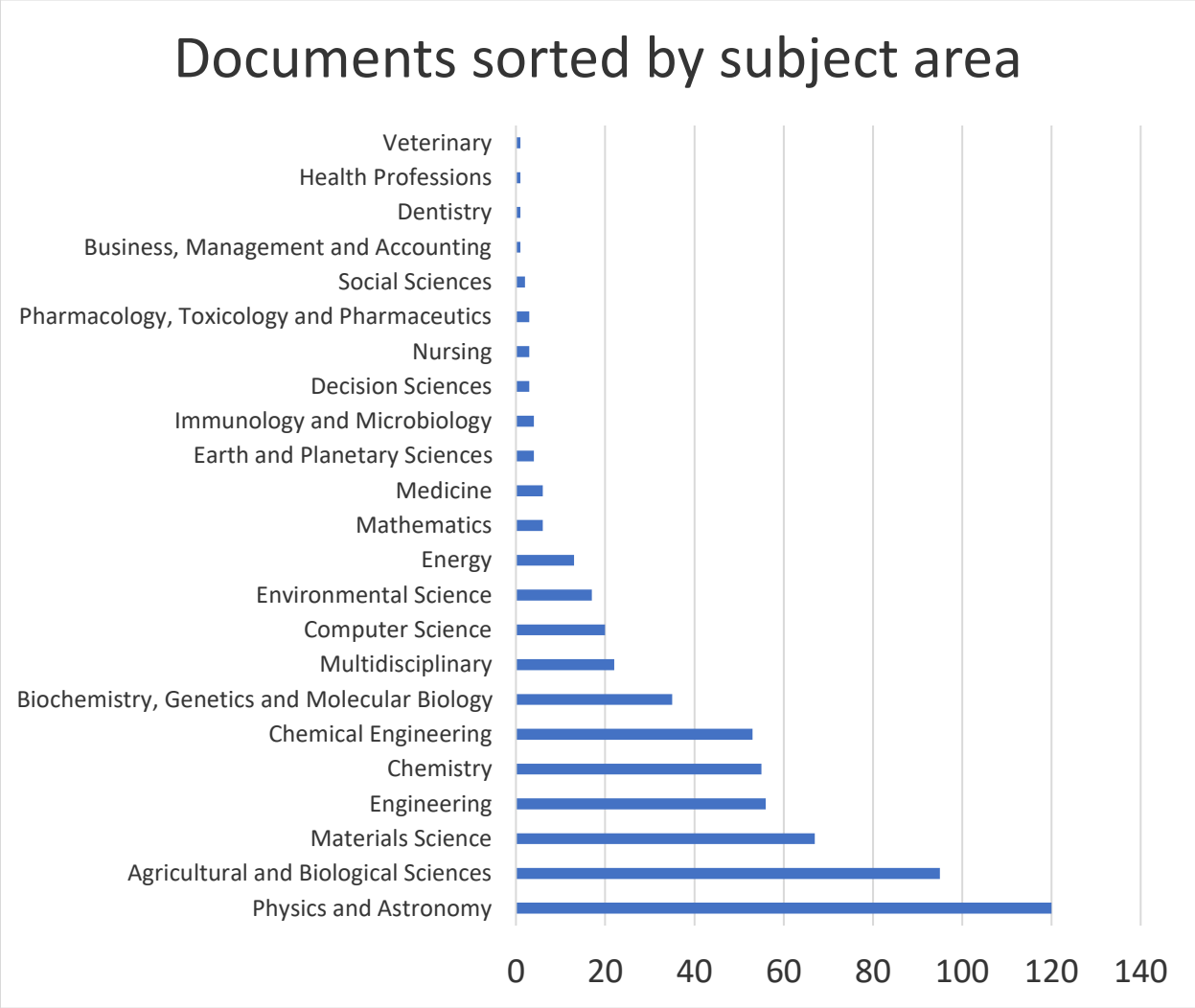

Figure 5. Distribution of documents by subject area.

Having in mind multidisciplinary nature of this field it is interesting to see distribution of documents by subject area shown in Figure 5. Obviously, each document can be categorized in more than one subject area. The most of them (120) were categorized as belonging to Physics and Astronomy. Interestingly, no other subject area is mentioning or implying either physics or plasma. Second most used category is Agricultural and Biological Sciences with 95 documents belonging to it. Third one is Materials Science and it was selected by authors of 67 documents. These

categories are closely followed by Engineering (56), Chemistry (55) and Chemical engineering (53).

Another way for document to be categorized and to be methodically searched for is by keyword. As with subject area, each document can be described by several key words. Authors of examined list of documents have used 160 different key words. It is important to note that some sources are allowing authors do define their own keywords while others are assigning them during process of revision. Top 20 most used keywords are shown in Table 3. In this selection word "plasma" was used 8 times while words directly connected to seeds are used 5 times. Among other less used keywords are also descriptions of type of plasma or working gas that are used like "Non-Thermal Plasma", "Nitrogen" or "Atmospheric Pressure Plasmas". Authors were also using keywords to specify treated seed (wheat, rice, barley…) or examined property of seed (Decontamination, Enzyme Activity, Wettability…). With that in mind, it is highly recommended that searching for documents is done through keywords.

Table 3. The most used keywords.

Keyword	Occurrence	Keyword	Occurrence
Seed	132	Plasma Gas	44
Cultivation	104	Cold Plasma	43
Plasma Applications	101	Plasma Gases	41
Germination	90	Plasma Treatment	36
Electric Discharges	77	Cold Plasmas	35
Atmospheric Pressure	58	Dielectric Devices	35
Seeds	56	Article	30
Seed Germination	47	Nonthermal Plasma	29
Dielectric Materials	45	Plasma	28
Plant Seed	44	Growth, Development And Aging	26

Mapping out researchers' interest about certain field, in a geographical way, can be helpful in planning of future cooperations. It is important to note that documents' country of origin is provided by database (SCOPUS) without further explanation of how it was selected. Since the number that is acquired by summing contribution from all countries is larger than total number of documents, multinationality of research teams is obviously taken into account.

As on many other similar lists, the most productive country is China with 42 entries. On the second place is also Asian country of Thailand with 31 entries. It is surprising to see small countries of Czech Republic (25) and Slovakia (20) to be ranked 3rd and 4th on this list. Obviously, plasma treatment of seeds is highly ranked priority among scholars from these two countries. They are followed by Iran, Japan, Russian Federation and South Korea which all have 14 entries. As shown in Table 4., among the countries with 10 or more entries are India (13), Romania (11), Bangladesh (10) and United States (10). Because there are lot of small European countries in total list of contributors, one can conclude that this research topic is disproportionally more important to researchers and institution on this continent compared to other parts of the world.

Table 4. The most contributing countries by number of documents.

Country of origin	Occurrence
China	42
Thailand	31
Czech Republic	25
Slovakia	20
Iran	14
Japan	14
Russian Federation	14
South Korea	14
India	13
Romania	11
Bangladesh	10
United States	10

Another insight into importance of this topic can be made if we look at the list of research sponsors as specified by authors. All of the most important sponsors (that funded work published in at least 5 documents) are shown in the Table 5., but it has to be taken into consideration that part of the documents didn't specify their sponsors. There are 14 entries in the list, 9 of which are foundations, agencies or ministries while other 5 are universities. The most generous was National Natural Science Foundation of China, managed by Chinese Ministry of Science and Technology, which funded research for 14 documents. On the second place is Slovak Research and Development Agency (Agentúra na Podporu Výskumu a Vývoja),

funded by Slovak Ministry of Education, Science, Research and Sport, which financially supported research published in 12 documents. Kasetsart University which is in Bangkok, Thailand, and has rich background in agriculture, financially supported making of 9 documents. According to their website, Kasetsart University and Kasetsart University Research and Development Institute are not the same entity so their contributions were not merged.

Table 5. The most important funding sponsors, sorted by number of supported documents

FUNDING SPONSOR	
National Natural Science Foundation of China	14
Agentúra na Podporu Výskumu a Vývoja	12
Kasetsart University	9
European Regional Development Fund	6
Universidad Tecnológica Nacional	6
Universidad de Buenos Aires	6
Agencia Nacional de Promoción Científica y Tecnológica	5
Consejo Nacional de Investigaciones Científicas y Técnicas	5
Fundamental Research Funds for the Central Universities	5
Japan Society for the Promotion of Science	5
Javna Agencija za Raziskovalno Dejavnost RS	5
Kasetsart University Research and Development Institute	5
Secretaría de Ciencia y Técnica, Universidad de Buenos Aires	5
Vedecká Grantová Agentúra MŠVVaŠ SR a SAV	5

During bibliometric analysis, success of a document can only be quantified by number of citations. Our collection would have h-index of 46, which means that 46 of documents were cited more than 46 times. Distribution of citations per article is presented in Figure 6. The most cited article “Cold Plasma: A novel Non-Thermal Technology for Food Processing”, published in 2015 in Food Biophysics was written by Thirumdas R., Sarangapani C. and Annapure U.S. Over the years it accumulated 289 citations. The second most cited article, with 269 citations, is titled “Decontamination of grains and legumes infected with Aspergillus spp. and

Penicillum spp. by cold plasma treatment". It was written in 2008 by Selcuk M., Oksuz L. and Basaran P. and published in Bioresource Technology. Following this criterion, in the third place is work by Li L., Jiang J., Li J., Shen M., He X., Shao H. and Dong Y., titled "Effects of cold plasma treatment on seed germination and seedling growth of soybean" with 246 citations. It was published in 2014 in Scientific Reports.

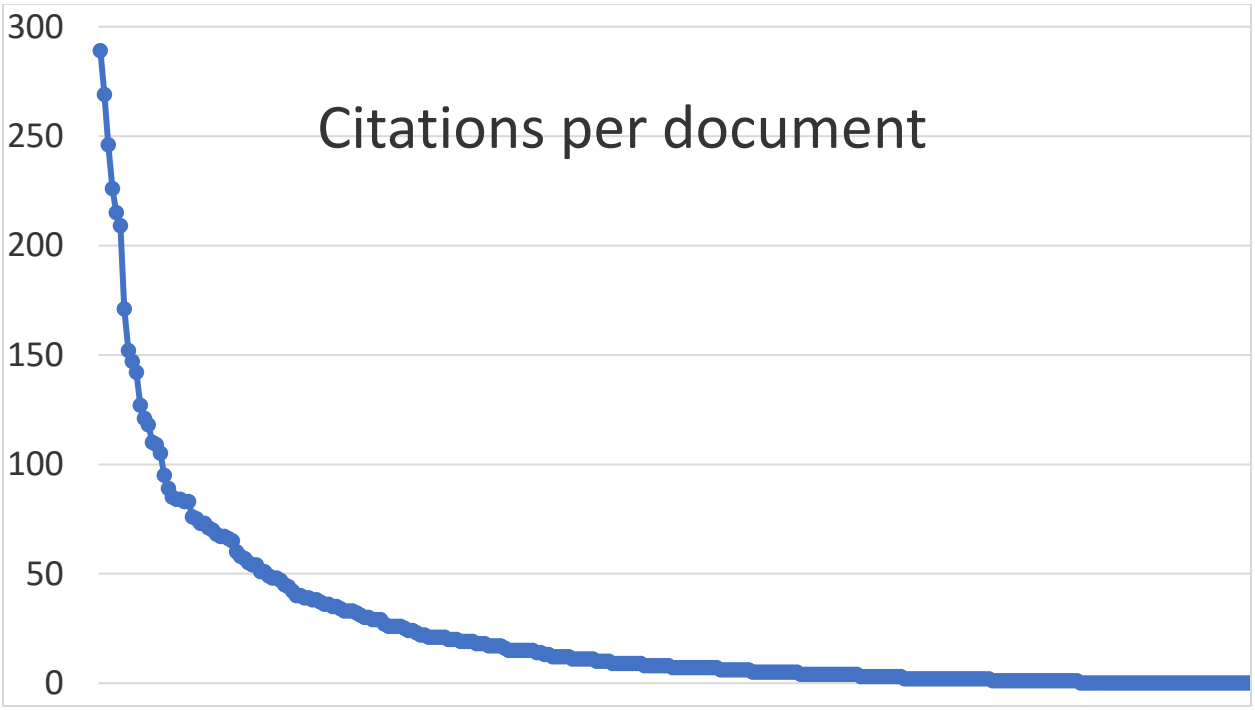

Figure 6. Distribution of citations per document.

Per year citation of these 3 most cited articles is presented in Figure 7. As in total citations for complete selection (Figure 2.), sharp decline is noticeable in years 2022 and 2023. Articles that are positioned as number 1 and 3, started to gain citations in year 2015 and in per-year citations, they both overcame document that is in second place in 2017 and 2018 respectively. Hence it can be expected that documents in 2nd and 3rd place will switch positions sometime in the future. These articles, on average got 32.1, 16.8 and 27.3 citation per year (sorted by total number of citations). If those citations are divided by number of authors of each of these documents, sorted in the same way, we get 10.7, 5.6 and 3.9 citations per author per year.

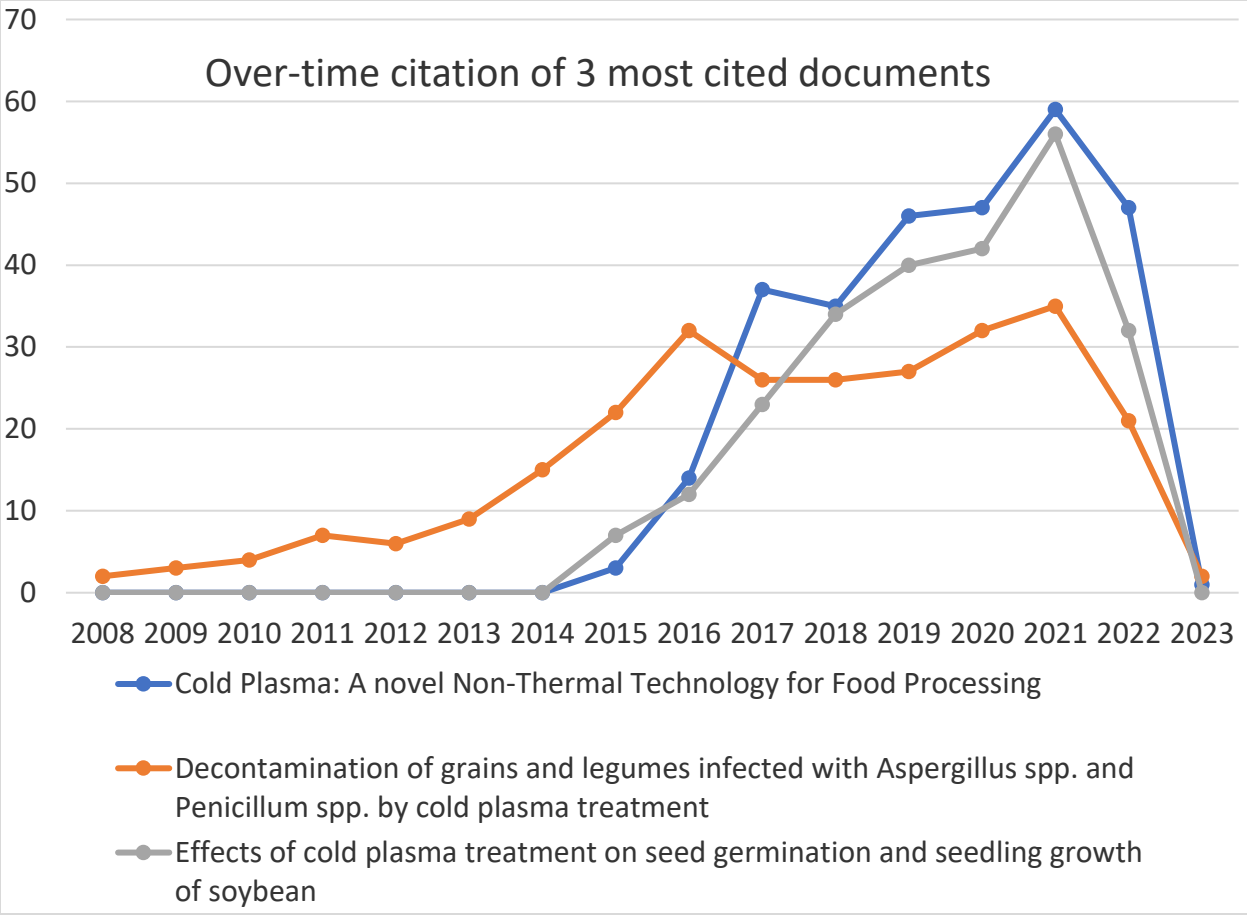

Figure 7. Per year citation of 3 of the most cited documents.

In this list, there is a total of 6 documents with more than 200 citations. In addition, there are 10 documents with citations between 100 and 200. In total, these 16 documents (5.6 % of all documents) have 2751 citation or 38.74 % of all citations. The list of all documents with more than 100 citations, with their title, publication year and total citations, is given in Table 6. Short overview of top 10 articles is given in Table 7. They are sorted by number of citations, starting from the most cited. In order to understand bigger picture about the state of the matter, the table provides information about the type of the reactor, pressure and gas that were used, seed that was treated and the trait of the seed they tried to influence.

Table 6. Titles and publication years of the most cited documents

Title	Year	Citation
Cold Plasma: A novel Non-Thermal Technology for Food Processing	2015	289
Decontamination of grains and legumes infected with Aspergillus spp. and Penicillum spp. by cold plasma treatment	2008	269
Effects of cold plasma treatment on seed germination and seedling growth of soybean	2014	246
Influence of plasma treatment on wheat and oat germination and early growth	2010	226
Cold radiofrequency plasma treatment modifies wettability and germination speed of plant seeds	2012	215
Enhanced seed germination and plant growth by atmospheric pressure cold air plasma: combined effect of seed and water treatment	2017	209
Effect of cold plasma treatment on seed germination and growth of wheat	2014	171
Effect of Low-Temperature Plasma on the Structure of Seeds, Growth and Metabolism of Endogenous Phytohormones in Pea (Pisum sativum L.)	2015	152
The effect of non-thermal plasma treatment on wheat germination and early growth	2015	147
Effect of Cold Atmospheric Pressure Plasma on the Wheat Seedlings Vigor and on the Inactivation of Microorganisms on the Seeds Surface	2016	142
Growth, anatomy and enzyme activity changes in maize roots induced by treatment of seeds with low-temperature plasma	2012	126
Effects of Atmospheric-Pressure N2, He, Air, and O2 Microplasmas on Mung Bean Seed Germination and Seedling Growth	2016	121
Cold plasma treatment enhances oilseed rape seed germination under drought stress	2015	118
Effect of seed treatment by cold plasma on the resistance of tomato to Ralstonia solanacearum (bacterial wilt)	2014	110
Germination of chenopodium album in response to microwave plasma treatment	2008	109
Interaction of cold radiofrequency plasma with seeds of beans (Phaseolus vulgaris)	2015	105

Table 7. Treatment conditions, treatment goal and type of seed used in top 10 cited documents

No	Type of reactor / Gas	Seed	Treatment goal
1	Review paper	Various	Germination
2	LP ICP 1 kHz / SF_6	Tomato, wheat, bean, chickpea, soybean, barley, oat, rye, lentil and corn	Decontamination (Aspergillus spp., Penicillium spp), germination
3	LP ICP 13.56 MHz / Helium	Soybean	Germination, growth, weight, wettability
4	Magnetron 2.45 GHz afterglow / air	Oat, wheat	Seedling size and weight, germination
5	LP ICP 10 MHz / air	Lentil, bean, wheat	Germination, wettability
6	AP DBD 1 kHz / air	Tomato, sweet pepper	Germination, plant growth
7	LP RF ICP / helium	Wheat	Germination, growth, yield
8	AP DBD (coplanar) 14 kHz / air	Pea	Germination, growth, phytohormones content
9	AP 50 Hz / air	Wheat	Growth, germination
10	AP DBD (coplanar) 14 kHz / air	Wheat	Decontamination (fungi), germination

The most cited article is actually not dealing with experimental work, but it is a review paper about plasma in food processing, including seeds. It is interesting to note that remaining documents, written about experimental work by authors, is almost equally divided between low pressure (LP) and atmospheric pressure (AP) plasmas. Generally, during treatments at atmospheric pressures researchers tend to use sources that operate at lower frequencies. In these top 10 articles they used kHz and 50 Hz sources. On the other hand, for treatments at low pressures authors mostly used radio frequency devices with an exception of magnetron that operates at 2.45 GHz. Another insight can be gained if we look at the type of plasma sources that were used. For atmospheric pressure treatments, DBD reactors were devices of choice while, almost exclusively, inductive coupling was used during treatments at low pressure.

While selecting plant species whose seed will be treated, scientists are led by various factors. Most often they chose locally grown commercial species used in agriculture. Therefore, it is of no surprise that majority of authors of top 10 cited documents used wheat as the seed of choice. Beside wheat, seeds of vegetables and cereals like tomato, oat or beans were also treated. There are various traits of seeds that could be

affected by exposure to plasma, but 100 % of documents presented in Table 7. were concerned about germination. In some of them it was the main cause for treatment while in others it was examined as a part of a broad test of how can plasma effect both seeds and their sprouts. Beside germination authors were interested in influencing growth of the young plants. For that purpose they were measuring root, shoot and leaf size, water intake (imbibition), plant mass, seed wettability (usually by measuring contact angle) or content of various compounds. Other than changing characteristics of seeds, plasma treatments are also used as a tool for decontamination of infected seed. In Table 7. there are two documents presenting research in which plasma was used in order to inactivate pathogenic fungi.

Scope and limitations of the analysis

Bibliometric analysis is reliant on database that is providing bibliometric data and on the available tools for processing that data. First problem is that all encompassing repository does not exists. That means that inevitably some documents will always remain omitted. Additional issues ensue while searching through database, because creation of perfect query is another impossible task. Careful preparation of query will certainly minimize both false positives and false negatives but, unfortunately, they could never be completely eliminated. And final limitation is that even though citations are the most objective way to measure the influence of some document on the scientific community they do not necessarily reflect quality of research.

With all the advantages and the limitations of bibliometric approach one can conclude that this analysis certainly does not include all of the scientific effort put into the plasma treatment of seeds, but that it does offer great insight into this dynamic and broad topic.

Conclusion

This report is written as an effort to classify and organize scientific results published on topic of plasma treatments of seeds at both atmospheric and low pressure. It is shown that interest in this field was rapidly increasing, in both number of published documents and citations, up to year 2021 after which both parameters are plummeting. It remains to be seen whether it happened due to research hampering measures against covid 19 or is this topic merged with larger fields of plasma

agriculture and plasma food processing. Besides that, report points to most prolific and influential authors and institutions in the field. It shows that equally important results are achieved at both pressures (atmospheric and low), while at low pressures the most cited results are made using ICP reactors. Authors are usually opting to treat seeds of plants that are important in agriculture, such is wheat. Interest in this field is present all around the globe but, considering population of countries or territories, it is most prominent in central Europe. In absolute numbers, China is leading country by number of produced documents. The most important journals for this research field were also singled out.

Considering all the limitations and advantages of bibliometric approach, this report can serve as an introduction into the research field or as starting point for writing papers or preparing an experiment. It can also be helpful for scientific networking since it points to the most influential authors and institutions.