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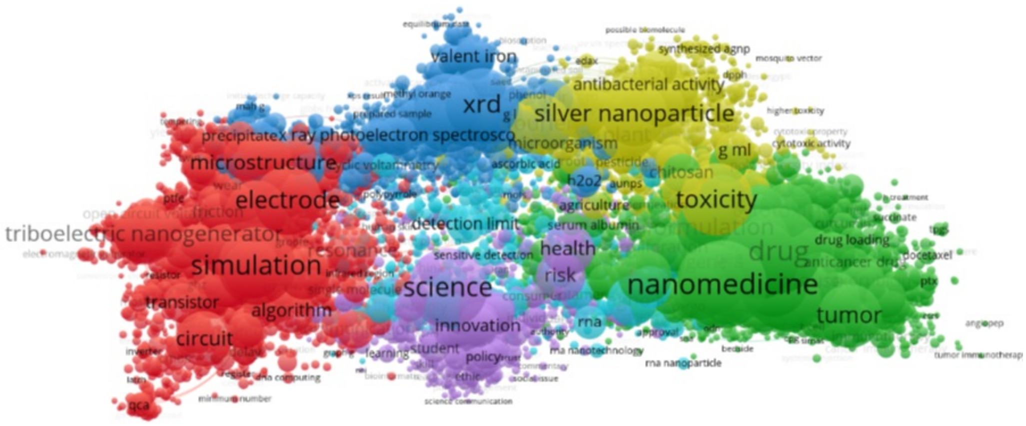

Main countries contributing on Nanotechnology

JONAS SANTOS, Leydi del Rocío Silva Calpa[1], Fernando Gomes de Souza Jr[1]

1 Universidade Federal do Rio de Janeiro

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Abstract

Nanotechnology is a cornerstone of the scientific advances witnessed over the past few years. Nanotechnology's impact on our world can be measured in several ways. So, this work gathered several scientific documents on nanotechnology and studied them using text mining tools. These contributions were subdivided by countries and re-evaluated, allowing us to understand the main contributions of these three nations and which themes are studied more modernly by them. Finally, a comparison is made with Brazil, which is in fifteenth place numerically. Thus, we hope that this document will guide future work in Brazil by understanding what the most prominent nations have developed on the subject.

1. Introduction

In the development of new technologies, several areas have passed through different transformations or created new areas of science (1–8). Nanotechnology, defined as "atomically precise engineering", brings innovation and changes in different areas and applications ranging from environmental recovery through sensors and medicine (9–37). As necessities towards a new and greener process of production of materials and improvements on life quality technologies, nanotechnology has shown intriguing and challenging routes in its development to improve human life. For that, understanding nanotechnology research and development tendencies favor one to be in the vanguard of technological development, assuring contributions to diverse areas as medicine, biotechnology, catalyzes, agriculture, energy, and others (38–44). One of its recent contributions was in the development of masks, biosensors, and tests, as well as vaccines to SARS-COV-2 pandemics, which facilitate the development of efficient responses to this crisis (45, 46). Applied in the energy area, it can develop nanogenerators with uses in solid oxide fuel cells and self-powered sensors/systems using piezoelectric and triboelectric nanogenerators (47–49).

New challenges are imposed due to climate changes, and new ones may be presented in a few years in economics, science, and life quality, requiring thoughtful strategic planning for developing countries, such as Brazil. Notably, worldwide efforts in generating science and products based on nanotechnology can be observed worldwide, although it is necessary to comprehend its trends in the past years to put strategic assets towards the most favored areas in nanotechnology.

Different methodologies can be applied to evaluate its trends, such as data mining of bases by bibliometrics and scientometrics approaches, as developed by COCCIA *et al.* (50). In this context, this work aims to evaluate trends and perspectives in nanotechnology worldwide, from 2010 to 2020, by mining bibliometric data of platform Scopus comparing Brazil nanotechnology tendency with worldwide and the three most productive countries: USA, China, and India, using the VOSviewer and Voyant Tools software in this intent.

2. Methodology

Worldwide tendencies on research about "nanotechnology" were determined by mining data. Information from the three most productive countries in the past decade and Brazil was obtained and analyzed according to the following steps.

First, the articles related to nanotechnology subscribed to the Scopus database were searched. Data from papers containing the term “nanotechnology” in the title, abstract, or keywords, using the key TITLE-ABS-KEY (nanotechnology) AND (LIMIT-TO (DOCTYPE , "ar")) were selected.

Then, the gathered information was classified by country/territory using the Scopus Database tools.

A data survey refinement from 2010 to 2020 was made for these four countries. The data files exported in RIS format are available at GitHub (https://github.com/jfsantosntec/Main-countries-contributing-on-Nanotechnology-A-systematic-study).

Finally, each country's RIS files were processed separately using the VOSviewer software, v. 1.6.17(51). The bibliometric classification was made in the "overlay" and "network" modes. The overlay and network graphs for each country were generated and analyzed. Additionally, the files were exported as NET and MAP files for the overlay and cluster classification, respectively. Data from MAP files were organized by clusters size and by the total link strength. The top-five nodes for each cluster were selected and plotted.

3. Results

The countries with the highest number of publications were the United States (first place), the People’s Republic of China (second place), and the Republic of India (third place). Brazil is in the fifteenth position and was presented to show the magnitude of the efforts needed to improve our scientific data. The keys per country used in the survey were:

United States: *TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "United States"))*

People's Republic of China: *TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "China"))*

Republic of India: *TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "India"))*

Brazil: *TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "Brazil")).*

This section presents the data results into two broad categories. The first one includes all data obtained in the period. The second category deals with data on nanotechnology according to the three most significant countries acting on the subject, which are the United States of America, the People's Republic of China, and India. Besides them, Brazil, which occupies the fifteenth position, was also included as a form of comparison and understanding the challenges that Brazilian people will face to reach the leading players in this field.

Scopus database possesses interesting native tools for the initial analysis of data. One of the simplest is the frequency of documents over time evaluated, as shown in Figure 1.

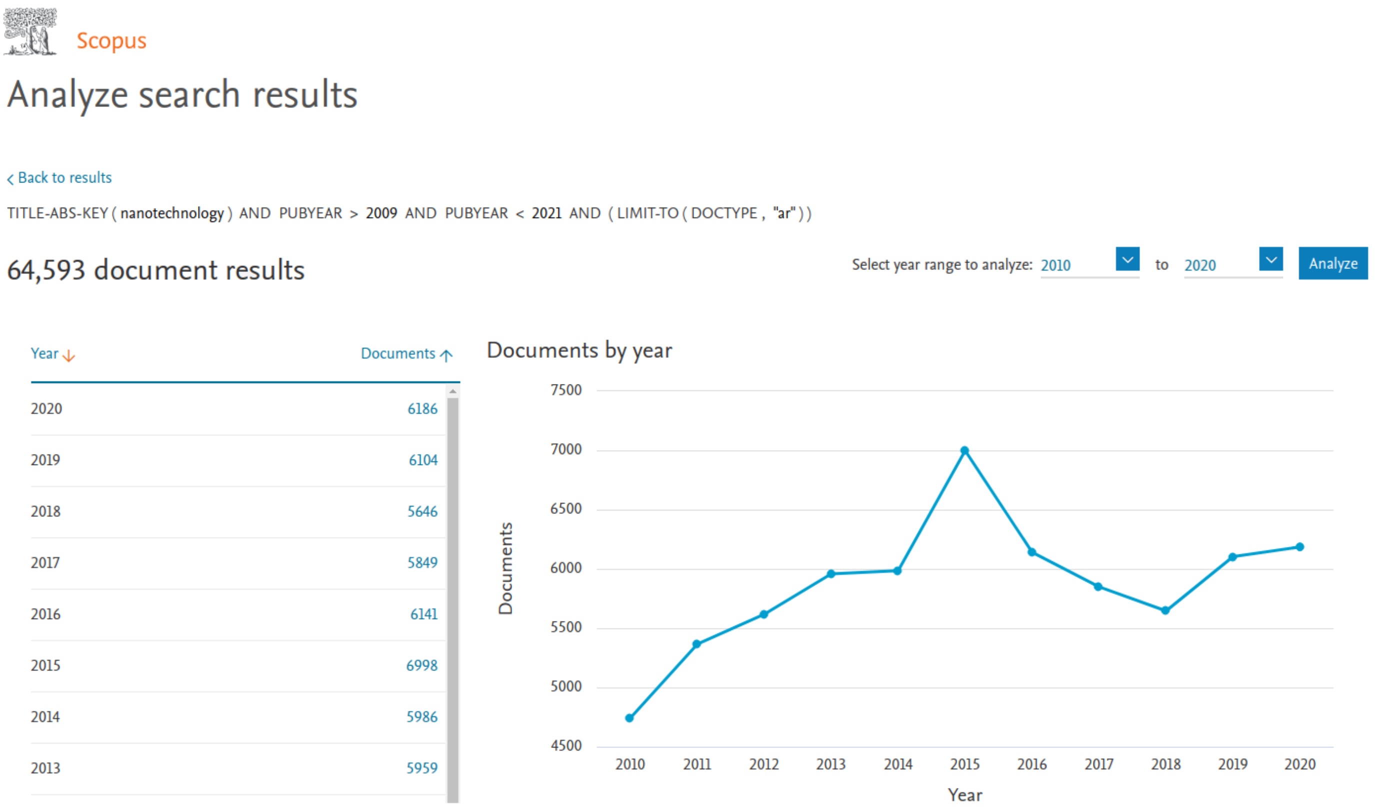

Figure 1. Frequency of documents retrieved from Scopus using the key TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar"))

Figure 1 shows an evident anomaly in the number of publications in 2015, characterized by a peak in the number of documents. This peak has some atypical induction mechanism, which deserves to be investigated in more detail. Thus, a new search was made using the critical TITLE-ABS-KEY (nanotechnology) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBYEAR , 2015)). This search returned 6998 results, from which all the respective titles were saved and processed using Voyant Tools (see Figure 2).

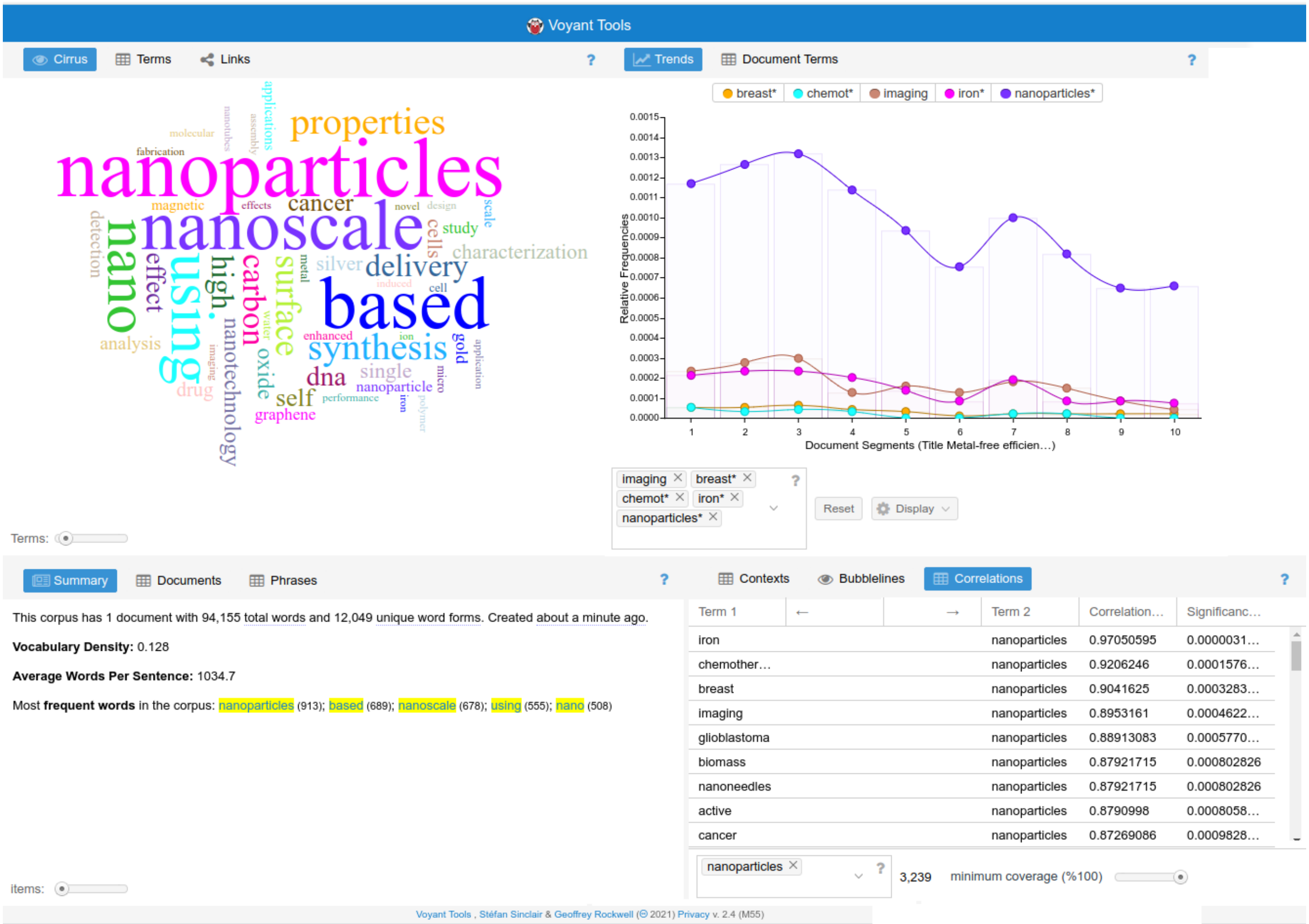

Figure 2. Main data from Voyant Tool available at https://voyant-tools.org/?corpus=cb02ea94762c9ed14c7d78f0441568e4

Data from Corpus in Figure 2 shows that the most frequent term is nanoparticles. Thus, this term was correlated with the others, which allowed us to determine that the highest correlations occurred with the terms "iron" (r = 0.97), "chemotherapy" (r = 0.92), "breast" (r = 0.90), and "imaging" (r = 0.89). These values show that the search for nanotechnological treatments against cancer during 2015 correlates strongly with nanoparticles. Thus, there must be a driver for this scenario.

A new search was performed using the keywords "2015", "nano", and "cancer" and the results are at shorturl.at/avJX3. This search returned as the first result the "Cancer Nanotechnology Plan 2015" by the U.S. Department Of Health & Human Services. We believe that this was the main driver responsible for the number of studies in 2015.

Figure 3 shows the main map extracted from the data mining of the term nanotechnology.

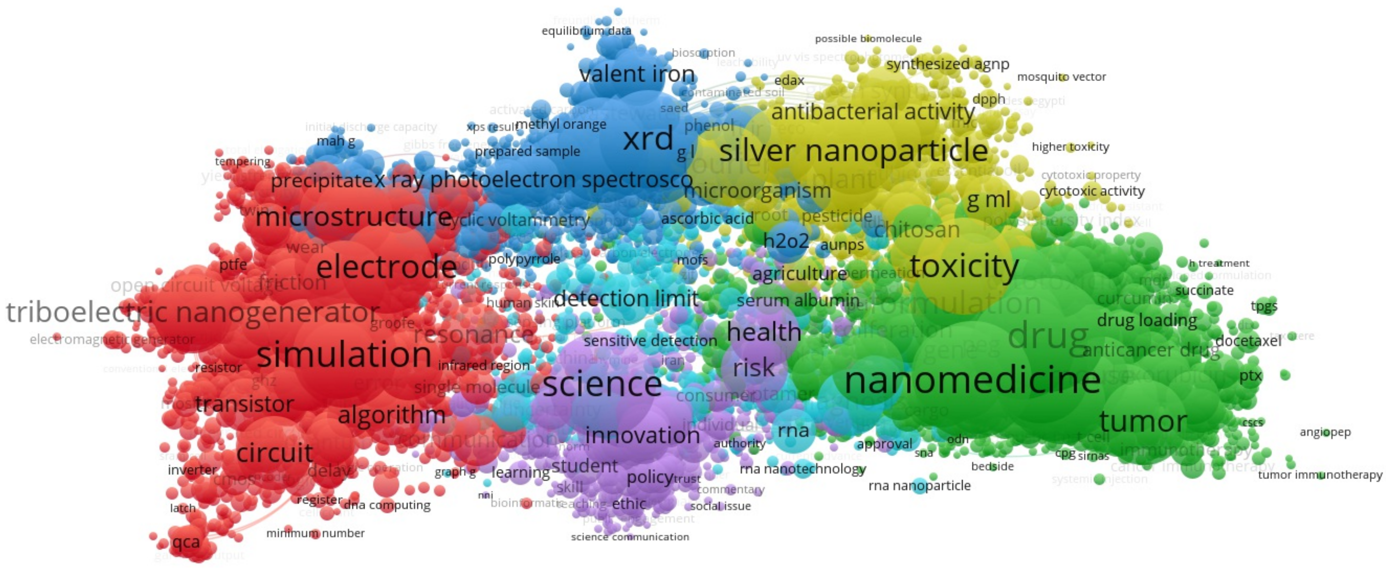

Figure 3. VOSviewer network from the key TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar"))

Figure 3 proves the existence of six clusters, each with several nodes, and each of the clusters had its top-five nodes listed in Figure 4.

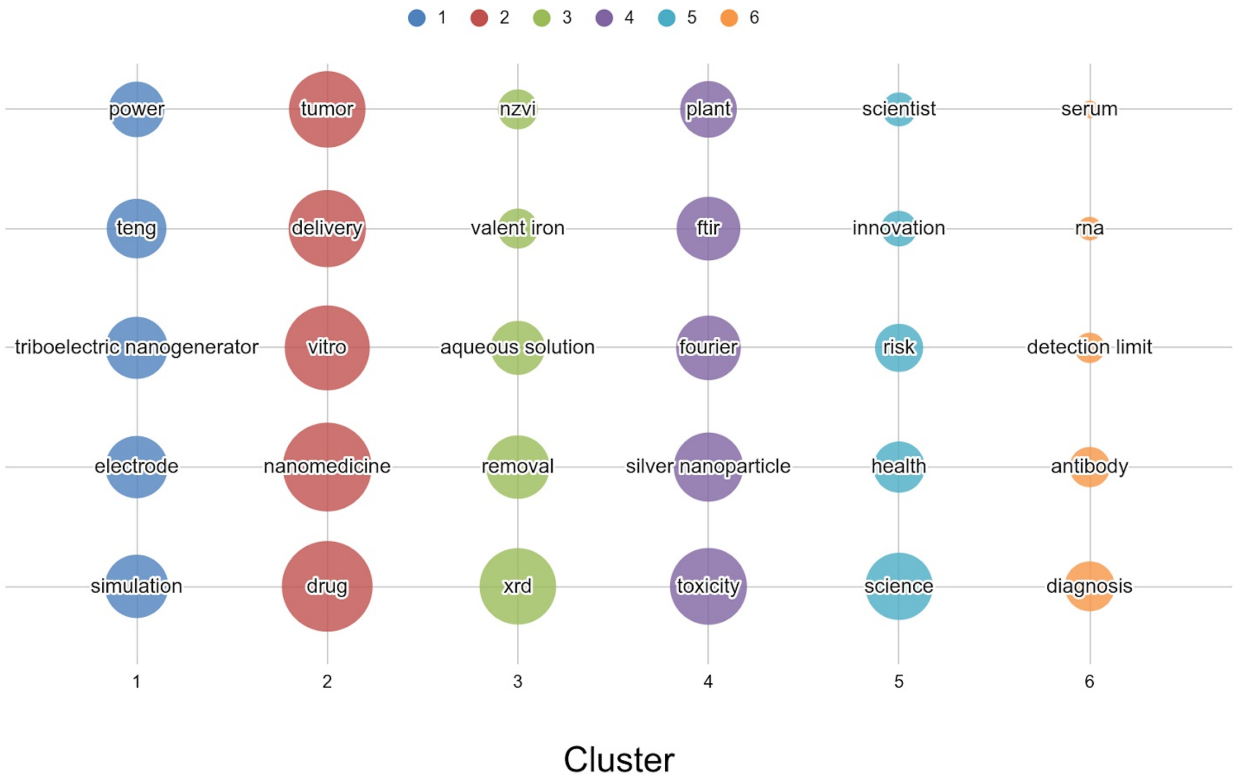

Figure 4. Clusters and top-five nodes from nanotechnology network, where the nodes are organized according Total link strength values.

The sequence of clusters was determined by VOSViewer and kept as received. Thus, Cluster 1 comprises "simulation", "electrode", "triboelectric nanogenerator", "TENG", and "power" nodes. Here, the presence of terms spelled in different ways, a genuine issue during data mining, is evident, as TENG is the abbreviation for triboelectric nanogenerator. Thus, the primary node of this cluster is the triboelectric nanogenerator.

Then, Cluster 2 presents as top-five nodes "drug", "nanomedicine", "vitro", "delivery", and "tumor". This second cluster highlights the importance of nanotechnology for improving people's quality of life by treating diseases, especially cancer.

In turn, Cluster 3 top-five nodes are "XRD", "removal", "aqueous", "solution", "valent iron" (probably from zero-valent iron), and "nZVI" (a highly reactive reducing agent). This cluster is closely related to the environmental recovery field.

Cluster 4 top-five nodes are "toxicity", "silver nanoparticle", "Fourier", "FTIR", and "plant". As in the case of the first cluster, FTIR and Fourier are terms derived from the same characterization technique, InfraRed Spectroscopy with Fourier Transform. Thus, the sum of the Total Link Strength values of these two items raises it to the category of the primary node of this cluster. The presence of a second characterization as a primary node proves that consolidated techniques are of great importance and need to be further explored by our research groups.

Cluster 5 top-five nodes are "science", "health", "risk", "innovation", and "scientist". This cluster is associated with concerns about safety during the use of nanomaterials. It must always be thought of with caution, avoiding damage to the environment and organisms that may contact these new materials.

Finally, the top five nodes of cluster 6 are "diagnosis", "antibody", "detection limit", "RNA", and "serum". Thus, this cluster proves the use of nanotechnology to produce systems capable of biological detection on a molecular scale, being probably one of the most exciting edges for Science regarding improving the quality of life of people affected by various diseases.

Figure 5 shows the Overlay Map produced by VOSViewer. This map has the same arrangement as the previous map. However, cold (blue) or warm (red) nodes are highlighted. These colors are associated with the temporal average of the citations of the term contained in the node. Thus, the more intense the red, the greater the average temporal value. Therefore, the node is more recent.

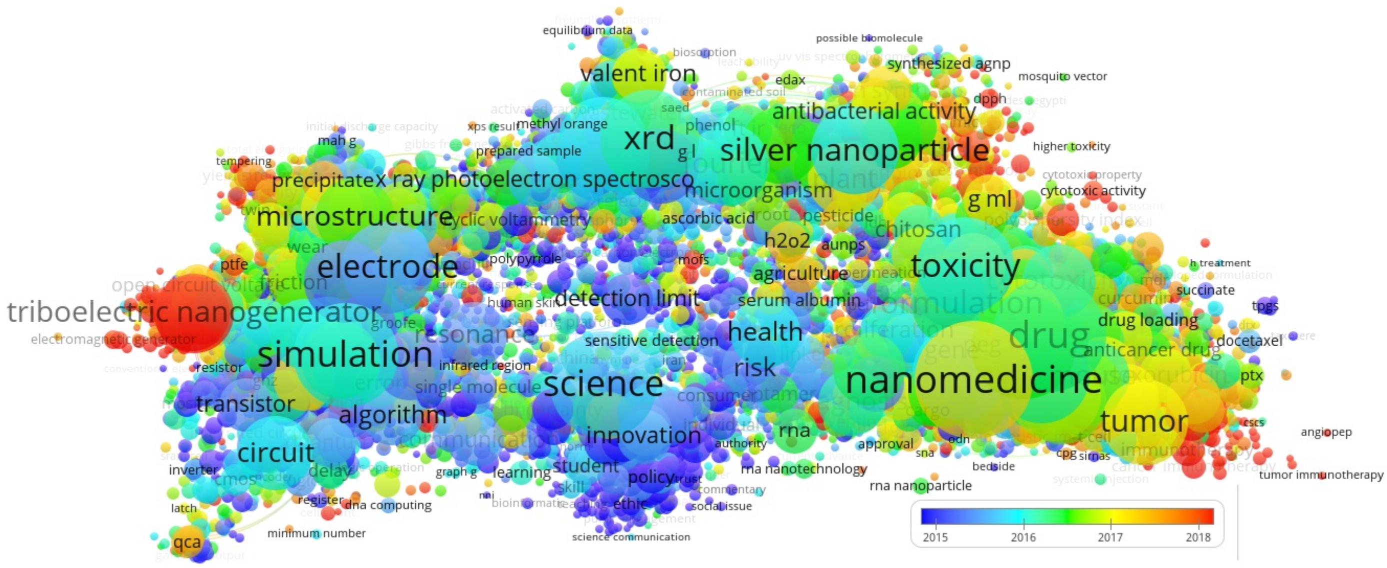

Figure 5. VOSviewer overlay network from the key TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar"))

The most recent nodes in each cluster are: “triboelectric nanogenerator” (Cluster 1 - 2018.5); “nanomedicine” (Cluster 2 - 2017.2); “plant” (Cluster 4 - 2017.1); “valent iron” (Cluster 3 - 2017.0); “RNA” (Cluster 6 - 2016.4); and “health” (Cluster 5 - 2015.9). Therefore, from the most recent issues point of view, the themes that should be a focal point to speed up the nanotechnology relevance of Brazil should be the issues associated with “triboelectric nanogenerator” and with “nanomedicine”.

3.1. UNITED STATES

Figure 6 shows the frequency of publications in the United States over the evaluated period. Even though the publications increased from 2010 to 2013, they dropped after 2013, going from 1850 in 2013 to about 1250 publications in 2020. The recovery peak shown in 2015 is probably related to the global peak observed in Figure 6, mainly related to research on cancer nanomedicine. To confirm this hypothesis, we searched for publications for the United States in 2015 using the key TITLE-ABS-KEY (nanotechnology) AND (LIMIT-TO (AFFILCOUNTRY , "United States")) AND (LIMIT-TO (PUBYEAR , 2015)) AND (LIMIT-TO (DOCTYPE , "ar")). The result showed 1825 documents. All the titles of these documents were exported and processed using Voyant Tools (See Figure 7).

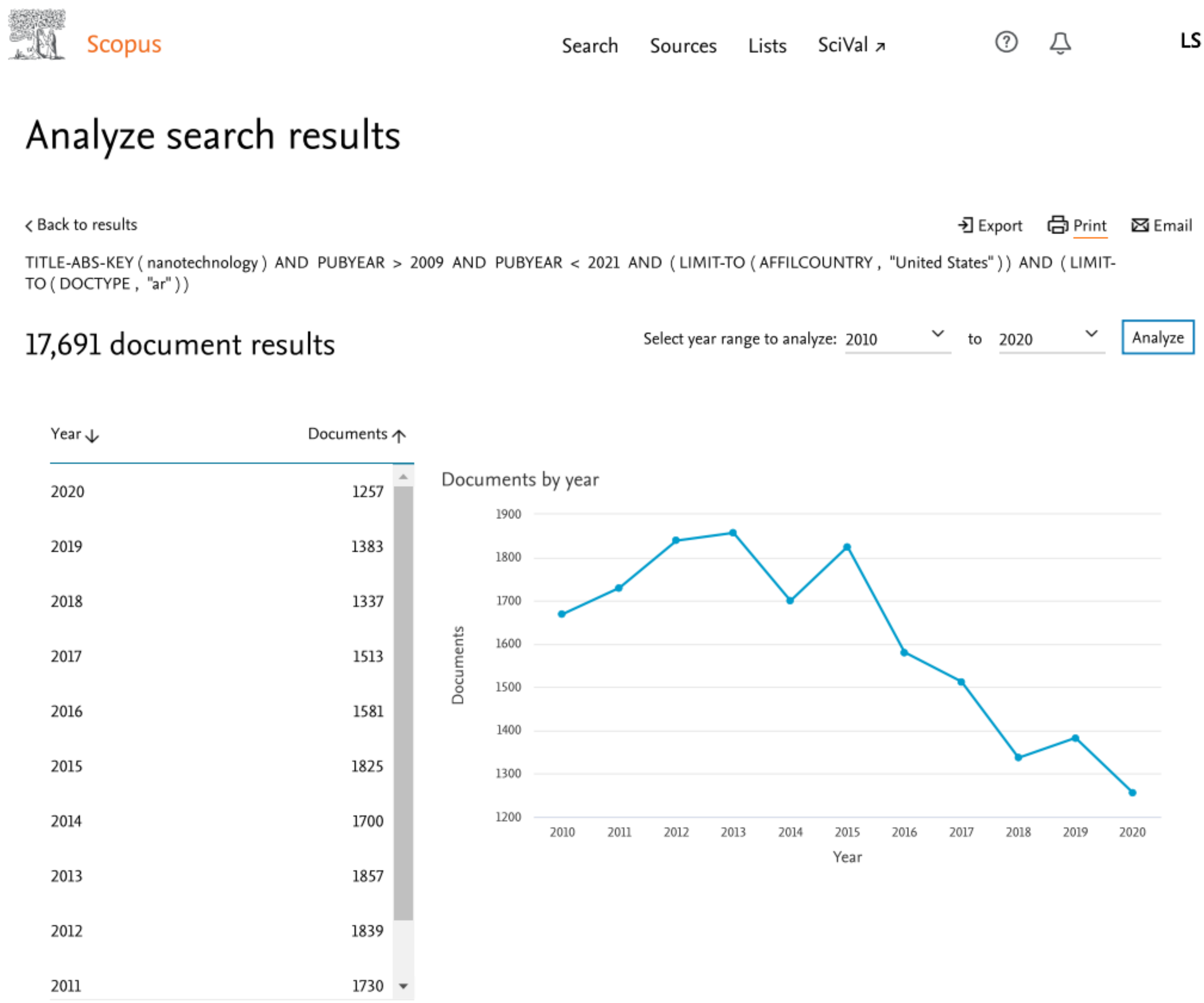

Figure 6. Frequency of documents retrieved from Scopus using the key TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (AFFILCOUNTRY , "United States")) AND (LIMIT-TO (DOCTYPE , "ar"))

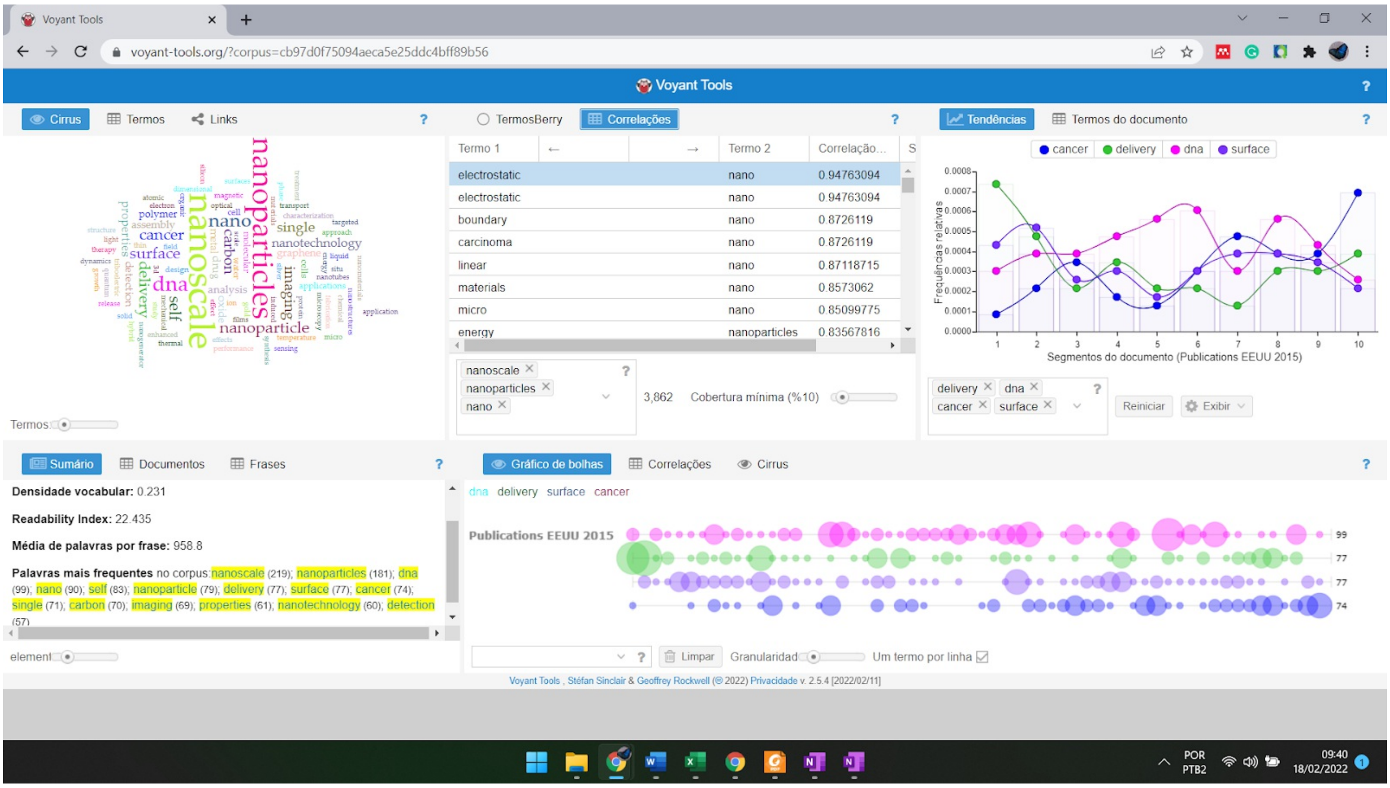

Figure 7. Article titles published by the United States in 2015 processed in Voyant Tools, available at https://voyant-tools.org/?corpus=cb97d0f75094aeca5e25ddc4bff89b56

Figure 7 shows the frequency of the terms appearing in the titles of publications by the United States in 2015. The three most frequent terms are general words related to nanotechnology: "nanoparticles," "nanoscale," and "nano," with 219, 181, and 90 occurrences, respectively. The correlation of these terms with the other words is shown in Fig. 7 (upper-middle graph). The three main correlations are "electrostatic," "boundary," and "carcinoma." Even though the two main correlations are referred to the properties of nanoparticles, the third term suggests that the peak in 2015 is also related to studies on cancer. The term "cancer" is the ninth most frequent word of this survey, with 77 occurrences (See the lower-left graph of Fig. 7). Furthermore, the Strategic Plan for the National Nanotechnology Initiative (NNI) report in the United States indicates that targeted drug delivery for cancer treatment was one of the significant goal applications, and now they have achieved robust developments in this area (52).

The network graph for the United States is shown in Figure 8. It classifies the data into six colored clusters. The size of the nodes represents the strength in which each node is related to the others. The top-five nodes of each set, organized by the total link strength, are depicted in Figure 9. The sequences of clusters for all the countries in this study were kept as determined by VOSViewer. It is worth noting that the colors of clusters in Fig. 8 and 9 are not correlated.

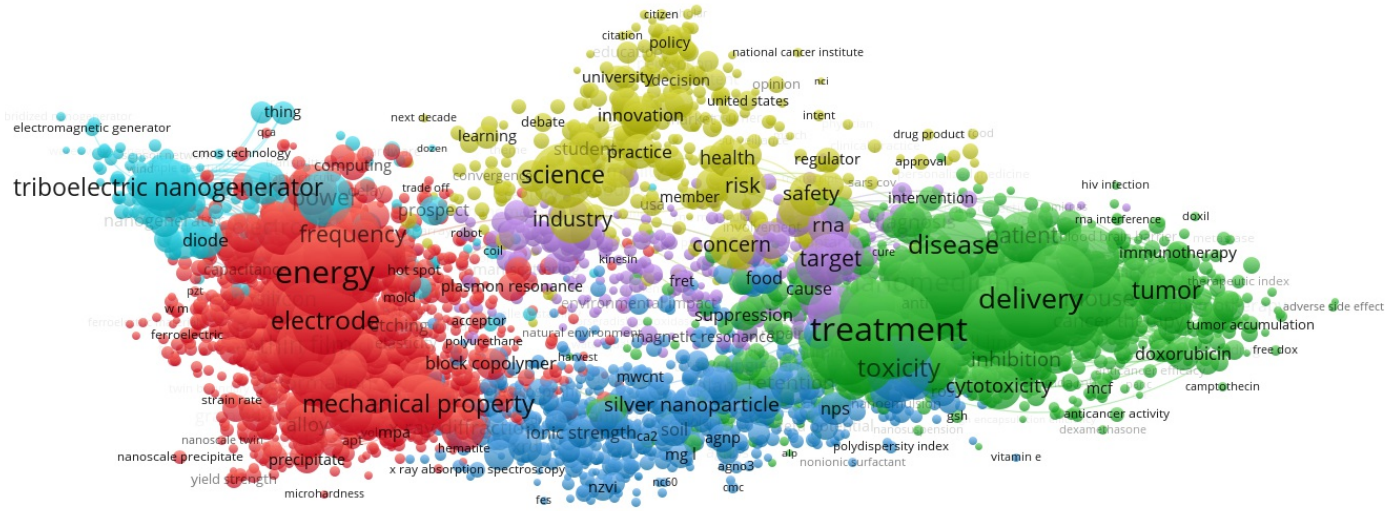

Figure 8. VOSviewer network from the key TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "United States")).

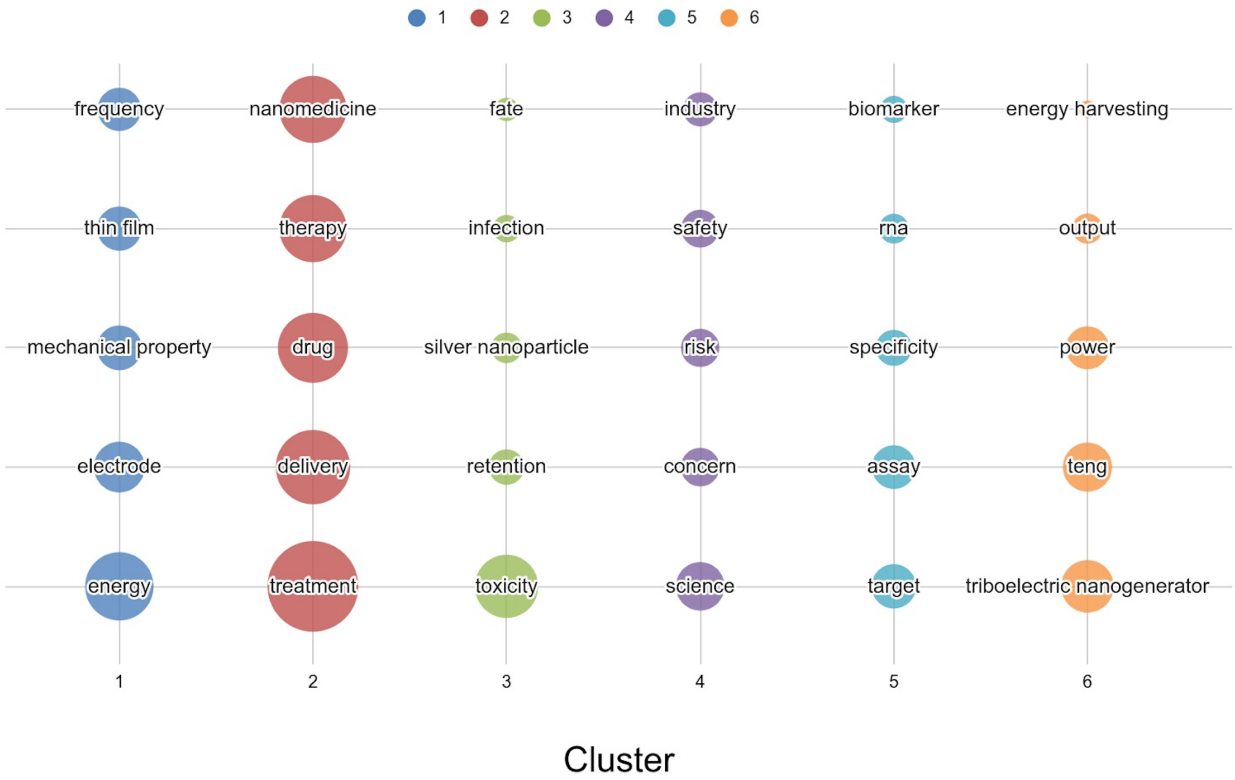

Figure 9. Top-five nodes of each cluster network depicted in Figure 8.

In Figure 9, Clusters 1 and 2 have the most prominent nodes and represent the most relevant research topics in the United States in the evaluated period. The terms of Cluster 1 are “energy,” “electrode,” “mechanical property,” “thin film,” and “frequency.” These are related to components for nanoelectronics. As described in the Strategic Plan for the NNI (52), the development of nanoelectronics was one of the main goals when it started in 2001. The current electronic demand has driven the development of architectures and devices that are only possible by using innovative nanomaterials, for example, bendable batteries, wearables, implantable mechanisms, flexible electronics, and nanoelectromechanical systems (NEMS). The performance of their thin and pliable components highly depends on their structural stability and mechanical behavior. The NEMS integrate electrical and mechanical functions to convert one form of energy into another and hence are also part of this significant area. Nowadays, the report of the NNI has stated that nanoelectronics research is a powerful example of how nanotechnology is contributing to the progress to daily lives, health, and national and economic security, as vital areas to the country.

Cluster 2 has the most prominent nodes in Figure 9. The top-five nodes of this cluster are related to health: “treatment,” “delivery,” “drug,” “therapy,” and “nanomedicine.” According to this, research on nanotechnology in the United States is intensely devoted to health development. The NNI report also indicates that nanomedicine is a mature and greatly expanded area nowadays, especially cancer nanomedicine. Nanomedicine and nanoelectronics are the most developed areas of nanotechnology in the United States (52). The interest of the United States in research on these areas is in line with the modern demands on health and technology and drives the research tendencies worldwide (see Figure 4).

Cluster 3 contains the terms: “toxicity,” “retention,” “silver nanoparticle,” “infection,” and “fate.” Silver nanoparticles have extended use due to their bactericide properties and infection prevention, and they are already present in many commercial products. In general, the unique properties of nanoparticles are due to their small particle size, high surface area, and enhanced chemical reactivity, but this does not ensure that they only catalyze desirable reactions. Many debates have arisen around their safe use and fate since they can become toxic in specific concentrations or exposure times. Therefore, many researchers are devoted to studying nanoparticles’ transport, retention, and destiny, especially those already commercially available, like silver nanoparticles. Even though the node’s prominence of cluster 3 is not as remarkable, the term “toxicity” stands out, showing a particular concern in this area, probably because it is related to health, a significant matter of whatever country.

Cluster 4 comprises the terms: “science,” “concern,” “risk,” “safety,” and “industry.” This cluster is similar to cluster 3 in terms of the concern about the risk and safety from nanomaterials exposition. Nonetheless, it can be more associated with the role of science in facing and proposing solutions to the unsafe wastes problem at the industrial level. The inherent risks of nanomaterials increase with their production scale. Therefore, as production increases, more significant efforts have to be made to ensure population safety. This area of research reveals that the United States is worried not just about developments in technology but also about the maintenance of environmental and health security.

In Cluster 5, we found the expressions: “target,” “assay,” “specificity,” “RNA,” and “biomarker.” RNA is considered a potential platform for a biomarker for a wide range of diseases, including Alzheimer's, cardiovascular diseases, infections, and tumors diagnostic. RNA sequencing technologies have allowed the detection of gene expression of known disease-causing species. The diversity of RNA species is a promise for multi-gene clinical tests. According to the literature, the current efforts of the United States are focused on the establishment of reference standards, assay optimizations, and tests reproducibility to facilitate the multi-gene assessment at the clinical laboratory setting (53).

Finally, Cluster 6 contains the terms: “triboelectric nanogenerator,” “TENG,” “power,” “output,” and “energy harvesting.” As mentioned above, the nodes “TENG” and “triboelectric nanogenerator” are equivalent and refer to systems that convert daily mechanical energy into useful electric power (54). This area of research is also one of the leading research fields worldwide (See Fig 4). For the United States, this area does not look outstanding (See Figure 9). Nonetheless, it can be due to a recent development in this field, and it can be verified from the temporal map (See Figure 10).

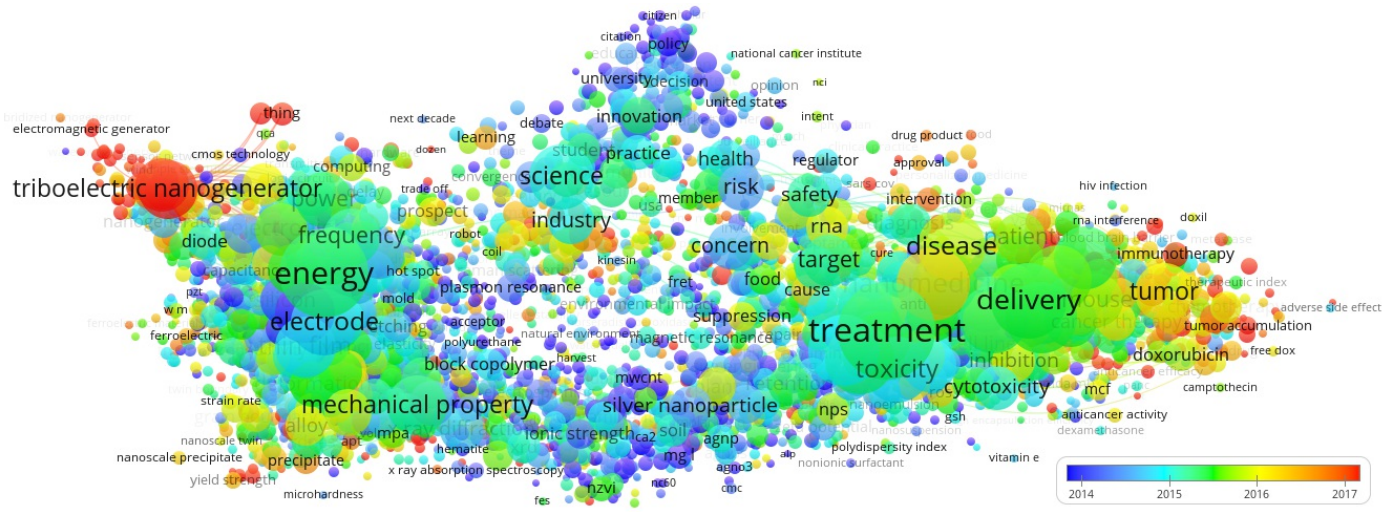

Figure 10. VOSviewer overlay map from data obtained by the key TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "United States"))

Figure 10 depicts the overlay temporal map of research in the United States. The scale goes from blue (oldest topic research) to red (most recent research). The most recent nodes per cluster are: “energy” (Cluster 1 – 2015.4); “nanomedicine” (Cluster 2 – 2016.4); “infection” (Cluster 3 - 2015.5); “safety” (Cluster 4 – 2015.2); “biomarker” (Cluster 5 – 2015.7); and “triboelectric nanogenerator” (Cluster 6 – 2017.0). From them, the most recent topic of research is “triboelectric nanogenerator''. Studies on TENGs are in development worldwide. Materials design and other technological issues are under investigation to improve electrical outputs and performance (54). Therefore, this graph suggests that from the most outstanding areas, research on TENGs has been a potential area and undergrowth in the United States since 2017.

3.2. CHINA

The cluster map for the Republic of China is depicted in Figure 11. Five colored Clusters represent the map. The top-five nodes of each Cluster were selected and displayed in Figure 12. In Figure 12, clusters 1 to 4 are more salient, while cluster 5 is smaller than others. They are analyzed below.

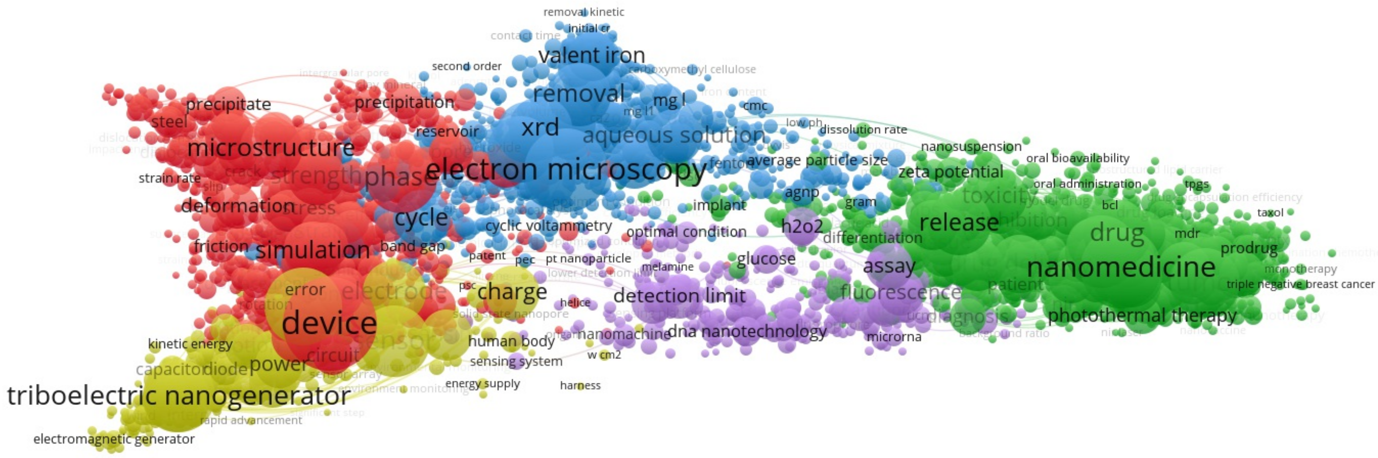

Figure 11. VOSviewer network from the key TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "China"))

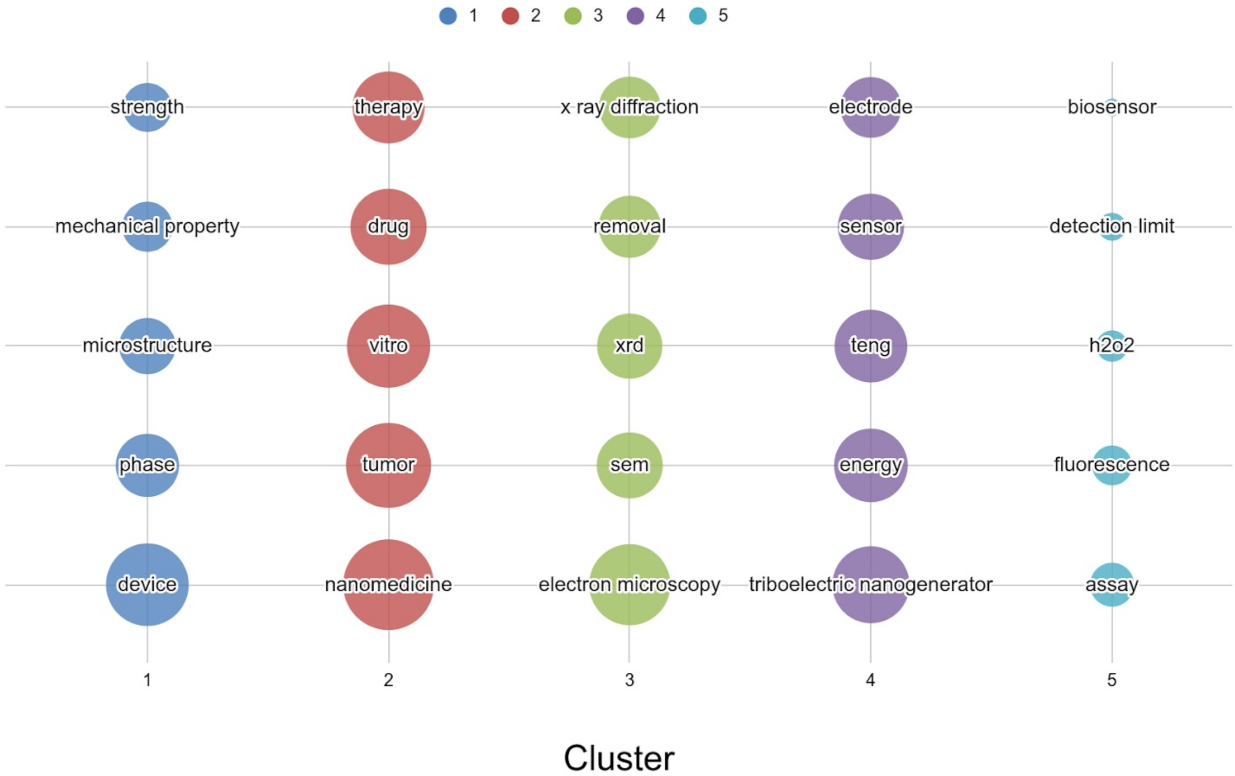

Figure 12. Clusters and top-five nodes from the network of Figure 9, where the nodes are organized according to the total link strength values.

Cluster 1 in Figure 12 contains the terms: “device,” “phase,” “microstructure,” “mechanical properties,” and “strength.” These terms are mostly related to the relationship structure-properties of materials. For solid materials with a fixed composition, their properties are directly affected by the microstructure and crystalline phase. The desired strength and other mechanical properties can be obtained by tuning such parameters. A slightly different term is “device,” represented by the primary node of this cluster. Since China is a significant producer of technological devices, we can conclude that this country has an important research area on materials with specific properties oriented to device production.

Cluster 2 contains the nodes for: “nanomedicine,” “tumor,” “vitro,” “drug,” and “therapy.” This is the most distinguished Cluster of Figure 12, where “nanomedicine” is the most notable node. This fact highlights the relevance of nanotechnology on health research in China, calling attention to the importance of tumor research. So far, two world powers, China and the United States have nanomedicine as the main field of nanotechnology research, and both of them have as one of the primary focus studies on cancer treatment. Indeed, this fact impacts worldwide tendencies.

The words that compose cluster 3 are: “electron microscopy,” “SEM,” “XRD,” “removal,” and “X-ray diffraction.” The terms “XRD” and “x-ray diffraction” are equivalent, and “SEM” is a kind of “electron microscopy.” The term “removal” is generally used to refer to the treatment of polluted effluents. Industrialization generates water contamination by several toxic substances like drug wastes, heavy metals, and organic pollutants. China is one of the most industrialized countries and probably has research to solve this problem ongoing. In developing active materials to remove specific contaminants, the employment of microscopy and XRD is a must for their characterization. Consequently, this cluster reflects the broad use of microscopy and XRD as characterization techniques, in part due to the studies of nanomaterials for environmental purposes.

Cluster 4 is the second biggest one of Figure 12. It contains the words: “triboelectric nanogenerator,” “energy,” “TENG,” “sensor,” and “electrode.” Where “Triboelectric nanogenerator” and “TENG” are equivalent terms. This cluster, related to nanosystems for energy harvesting, is similar to Cluster 6 for the United States (Figure 9). The difference is that Cluster 4 deals with the second most extensive application of TENGs, their use as sensors for detecting mechanical and chemical stimuli (54). This cluster shows that TENG is one of the most exciting research topics in China and, therefore, also impacts the tendencies around the world.

The terms contained in Cluster 5 are: “assay,” “fluorescence,” “H2O2”, “detection limit,” and “biosensor.” Many biological reactions rely on H2O2 concentration, but its assessment is challenging at the intracellular level due to the fast changes produced in the cell (55). Fluorescent biosensors are suitable for these measurements because of their optimal temporal and spatial resolution, non-invasiveness, and biocompatibility. One of the challenging goals is to determine the specificity of H2O2 probes since many reactive oxygen species often interfere in the measurements. The properties of fluorescent probes also make them suitable as sensors in detecting peroxide explosives (56). Research in this application is devoted to designing strategic materials to enhance the sensitivity and selectivity of the nanomaterials employed. Even though this area of research is the fifth most important in China, the nodes of this cluster are the smallest in Figure 12, suggesting that the leading research in China is mainly related to the first four Clusters.

So far, the research on nanotechnology from 2010 to 2020 in the two world power countries, China and the United States focuses mainly on health. Nevertheless, research in China is more diversified. It is distributed in four main fields: nanomedicine, triboelectricity, materials for electronic devices, and characterization of materials for environmental recovery. Temporal analysis shows that the United States is recently focusing on triboelectricity research. Below, we examine the most recent research tendencies in China.

Figure 13 shows the Overlay Map of research topics in China, distributed by temporal predominance. The most recent nodes of research per Cluster are: “microstructure” and “strength” (Cluster 1 – 2016.9); “nanomedicine” (Cluster 2 - 2018.2); “removal” (Cluster 3 – 2016.5); “triboelectric nanogenerator” (Cluster 4 – 2018.0); and “H2O2” (Cluster 5 – 2017.4). The most recent terms are “nanomedicine” and “triboelectric nanogenerator”. Therefore, the research tendencies in China are following the tendencies in the United States, and both strongly determine the worldwide tendencies.

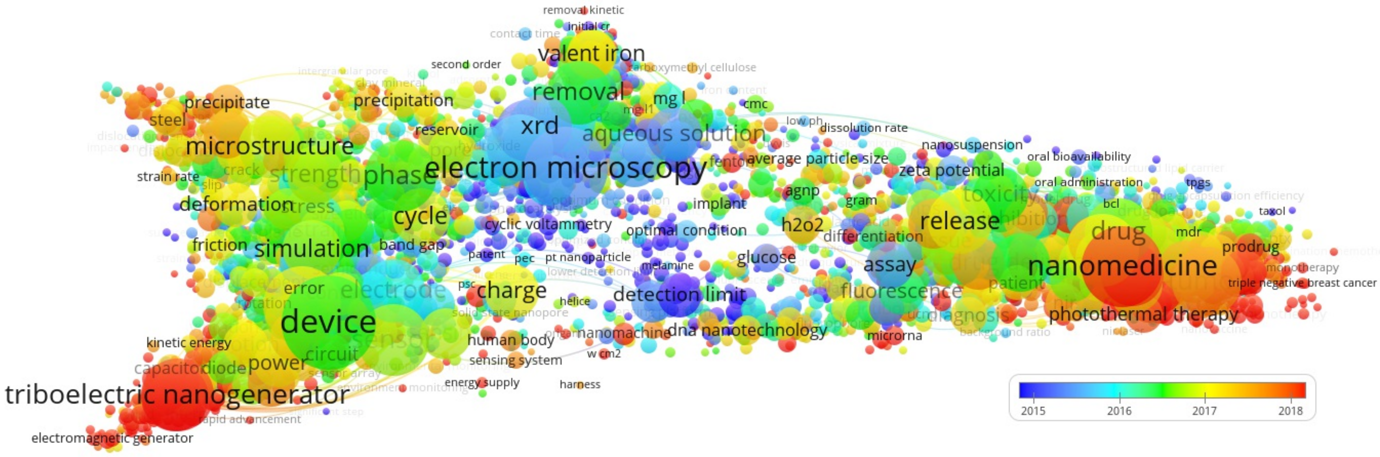

Figure 13. VOSviewer overlay network from the key TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "China"))

3.3. INDIA

Figure 14 describes the frequency of publications in India over the evaluated period. There is a growing tendency from 2010 to 2015. After this period, there was a drop of 554 to 412 publications between 2016 and 2017, followed by stagnation in 2018, with a similar result of 418 publications. From 2019 to 2020, a second growth tendency is seen, having a rise of 418 to 589 publications. The first growth tendency can be addressed by the global peak tendency in nanotechnology and the funding towards India’s national nanotechnology development plan. This plan created a road map to direct investments applied in critical areas to ensure competitiveness towards significant players in technology as the United States and China, although it works in a 5-years cycle. In the 12th cycle (2012-2017), the focus was directed to develop materials for industrial and commercial purposes (57–59), leading to a decrease in publications from 2016 to 2017, but a renovation for a new cycle (2017-2022) was done causing a rise in publications in 2019-2020.

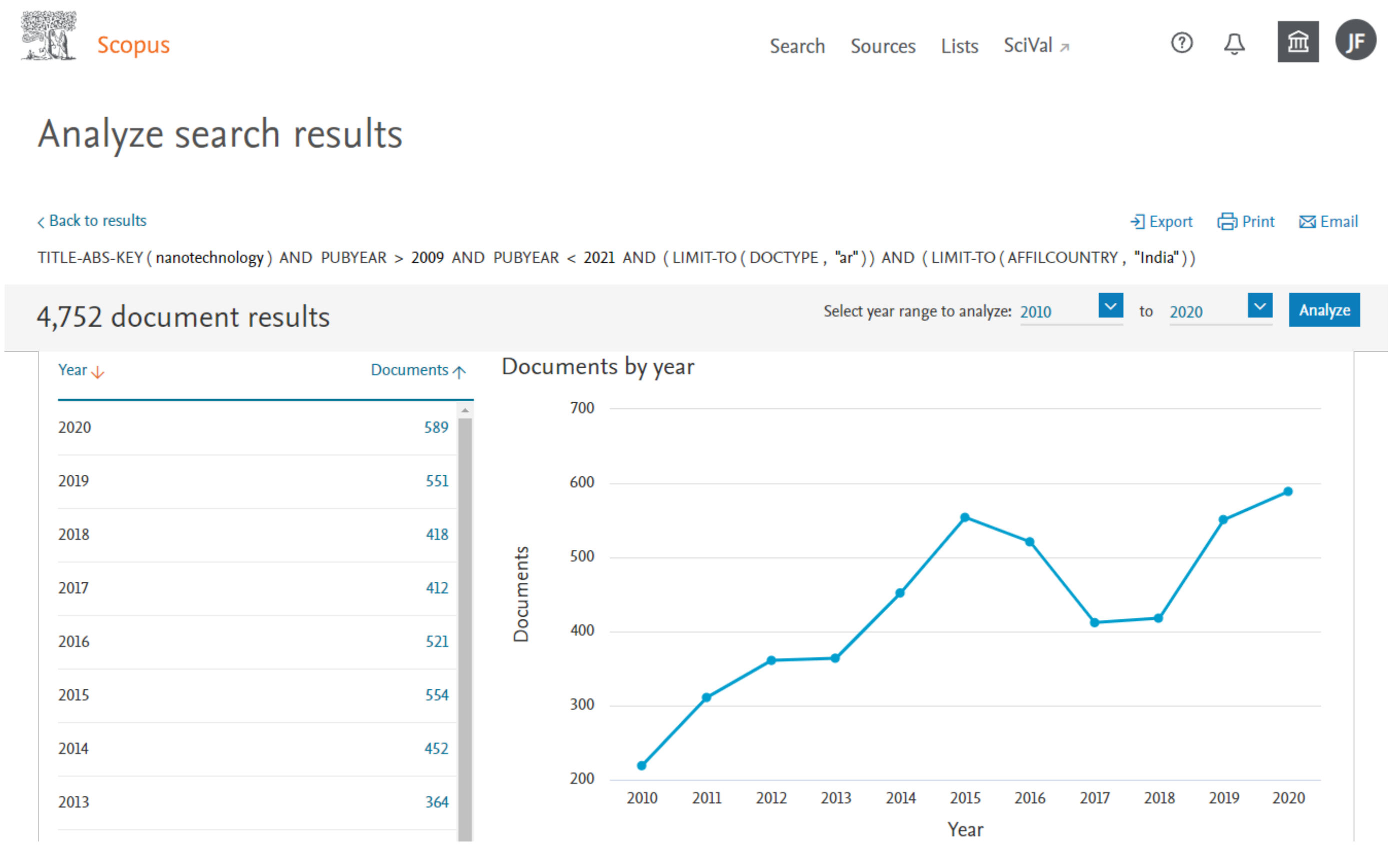

Figure 14. Frequency of documents retrieved from Scopus using the key TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "India")).

Evaluating the data in the Corpus in Figure 15, the most frequent term is "nanoparticles" as observed in Figure 2, having 154 occurrences, followed by "using" (83); "silver" (78); "synthesis" (78); and "based" (61). The correlations of these terms with other words were observed in the upper-center of Figure 15, having the three highest correlations attributed to the 7th, second, and fourth-ranked terms in occurrence, respectively: "drug" (r=0.93), "using" (r=0.90), and "synthesis" (r=0.88), despite "nanoparticles" correlation was of r=0.83. The three main correlations are "chemotherapeutic", "pathogenic", and "characterization" as for "nanoparticles", "formulation" was the main correlated word. In a closer look at the Corpus, not only nanomedicine and cancer-related terms, but also green synthesis-related, indicating this country also followed the global trend in 2015 (Fig. 1 and Fig. 2). As for the green synthesis related terms ("synthesis" and "characterization"), these correlate with cancer treatment and also in heavy metal and wastewater treatment.

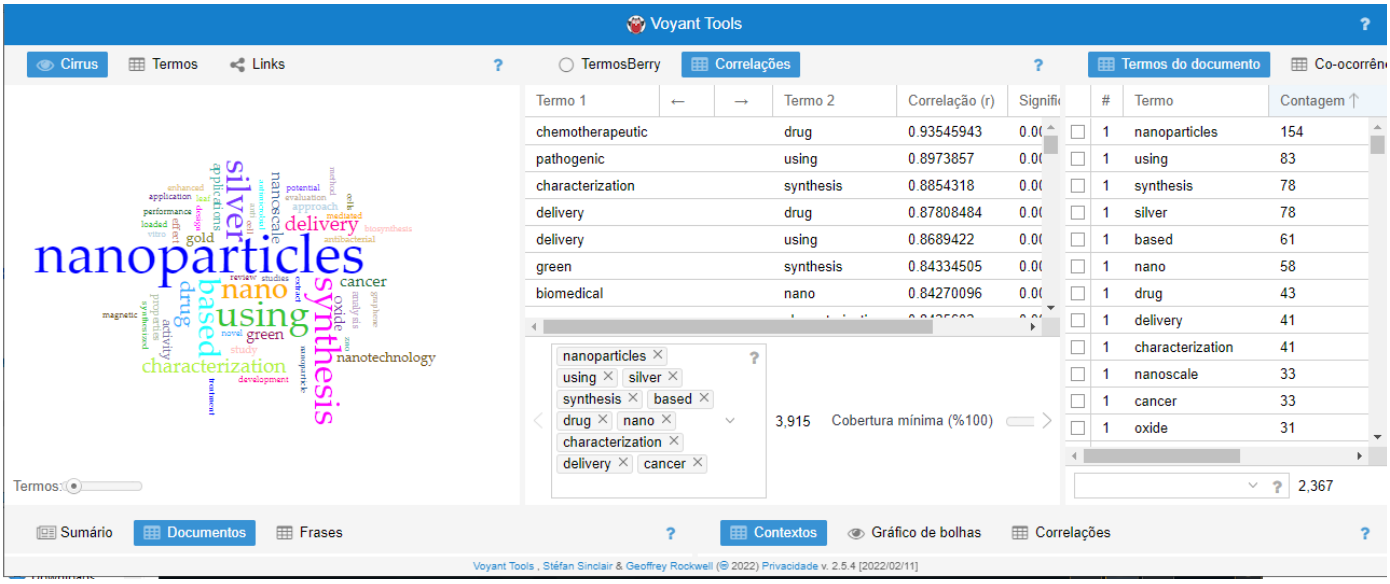

Figure 15. Article titles published by India in 2015 processed in Voyant Tools, available at https://voyant-tools.org/?corpus=30975291a68bbad824914e224a592331

Data from Corpus in Figure 16, as seen in Fig. 15, shows the same five most frequent terms repeated as being: "nanoparticles"; "using"; "synthesis"; "based"; and "nano" with frequencies of 264, 168, 149, 135, and 115, respectively. Curiously, regarding their correlation and correlated terms, none of the five were top-ranked, being the eighth term "oxide" with 93 occurrences to have the highest correlation. The top three words correlated to "oxide" were "anisotropy" (r=0,89), "az91" (r=0,87) and "blend" (r=0,87). These words were related to material science and engineering goods (metal products, industrial equipment and machinery, automobiles and their parts, and transport equipment), indicating that, as described by Rajput (57) and Samal and Manohara (58), India's economy have a large output of engineering goods and materials like steel and alloys, being a strategic matter to have goods capable of assuring its economic growth in the next years.

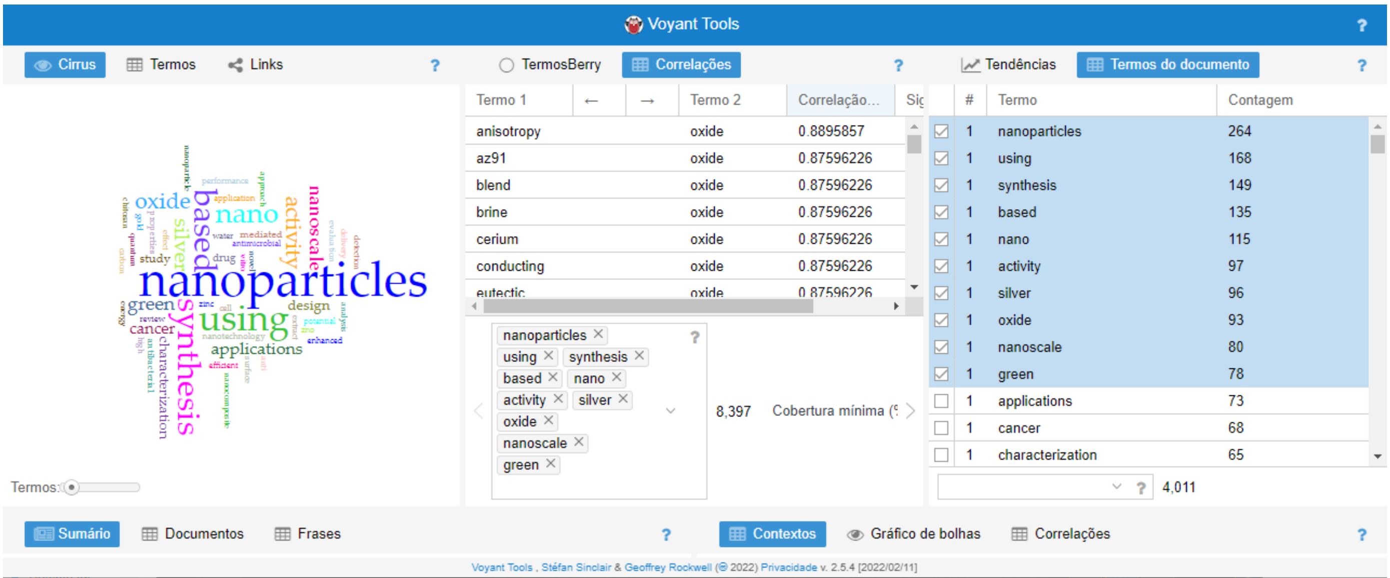

Figure 16. Article titles published by India in 2019-2020 processed in Voyant Tools, available at https://voyant-tools.org/?corpus=60041ba969f1292b2273d77e4732af9d

India’s cluster map was depicted in Figure 17, showing 4 clusters. In figure 18, the top-five nodes for each cluster are presented. The first cluster contains the nodes: “number”; “performance”; “device”; “technology”; and “paper”. These can be addressed to developing the techno-scientific basis and consolidation of efforts applied to the production of new devices, which were observed as minor nodes in the first cluster as energy and electronics-related materials and technologies. Still, some non-related nodes appear in this cluster, such as “paradigm”; “constraint”; “major issue”; and “difficulty”, which can be associated with the discussion of regulation, safety, and standards applied to nanodevices concerning the National Regulatory Framework Road-Map for Nanotechnology (NRFR-Nanotech) in India as described by Rajput (57).

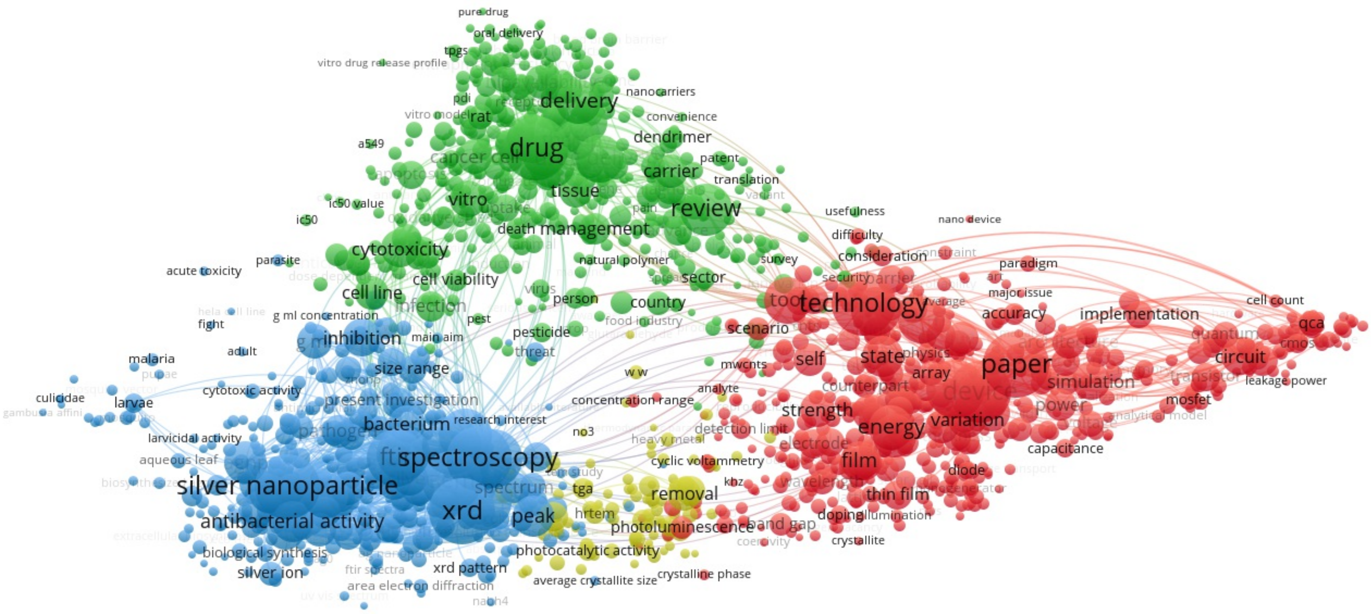

Figure 17. VOSviewer network from the key TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "INDIA"))

The second cluster's top-five nodes contain “review”, “cancer”, “drug delivery”, “formulation”, and “drug”, which indicates that India, as the USA and China, follows the same tendency in nanomedicine. The presence of the node “review” indicates numerous review papers directed to study cancer diseases and nanocarriers applied to the development of drugs with low rejection and cytotoxicity *in vitro* and *in vivo* assays.

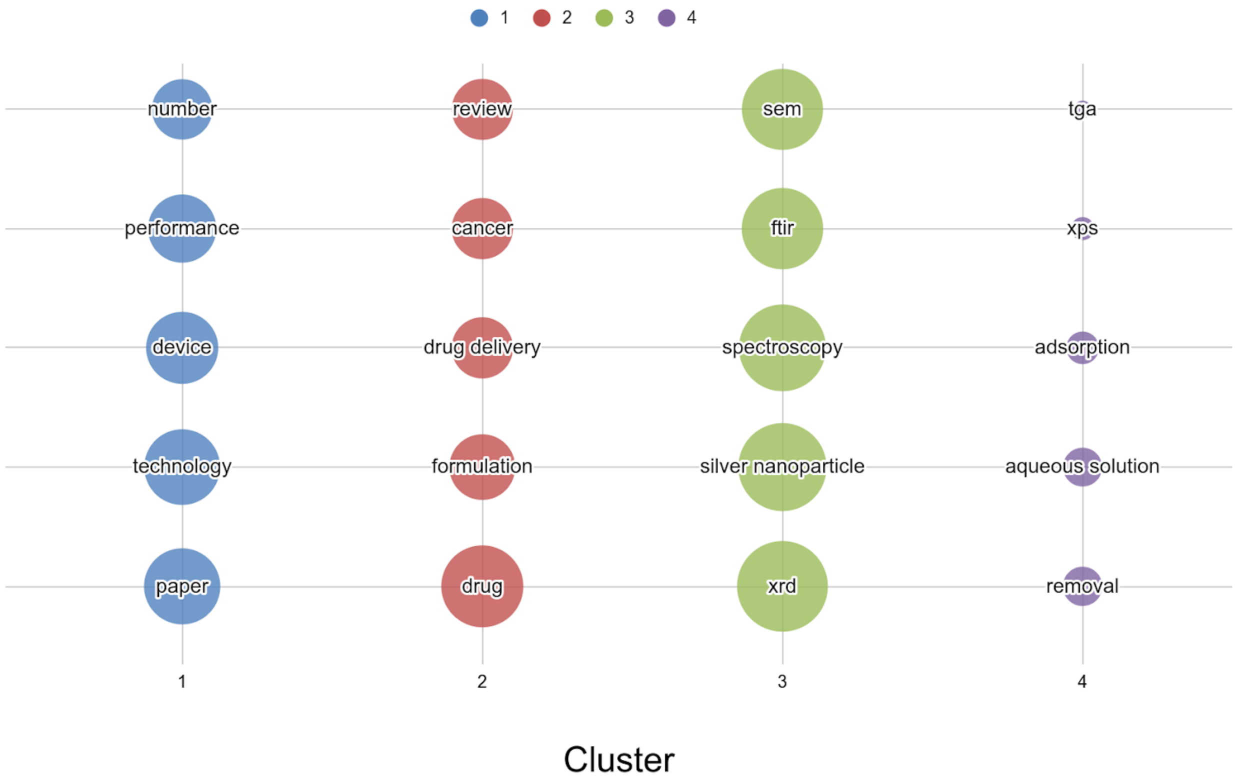

Figure 18. Clusters and top-five nodes from the network of Figure 15, where the nodes are organized according to Total link strength values.

The top-five nodes observed in the third cluster were: “sem”, “ftir”, “spectroscopy”, “silver nanoparticles,” and “xrd”. This cluster denotes a focus on the characterization of different materials in special silver nanoparticles. Silver as a nanomaterial shows significant antibacterial activity and can be applied in different strategies for green synthesis, using bacteria and eco-friendly chemicals, and in the treatment of different diseases, specifically cancer, due to its surface plasmon resonance property (41, 60, 61). Several techniques must be applied to characterize this nanometal, such as X-ray diffraction, Raman and Fourier transform infrared spectroscopies, and electron microscopy giving rise to the dissemination of these methods in literature applied in the characterization of this nanometal.

The fourth and last cluster contains the top-five nodes: “tga”; “xps”; “adsorption”; “aqueous solution”; and “removal”. With smaller nodes in comparison to the 3rd, this cluster focuses on nanomaterials and nanodevices with photocatalytic properties and high adsorption capabilities applied in removing toxic substances like pesticides and heavy metals in water principal analysis. This emphasis is due to recent industrialization efforts by India as a developing country, requiring intensive use of materials for efficient waste removal of water veils.

Figure 19 shows the Overlay map of each cluster. The most recent nodes per cluster were: “sars cov” and “covid” (Cluster

2 - 2020.6); “triboelectric nanogenerator”(Cluster 1 - 2019.8); and “cuo nps” (Cluster 3 - 2019.3). The most recent nodes are “sars cov” and “covid”, followed by “triboelectric nanogenerator” and “cuo nps”. The first two nodes were the most recent because of the COVID-19 pandemics, which caused a run to produce practical efforts capable of overcoming this emergency. The node “triboelectric nanogenerator” follows the tendency of the USA and China in the production of electronics and energy-related nanomaterials. Nevertheless, despite “cuo nps” it is related to green synthesis methods of nanomaterial using, as an example, leaf extracts, being a recent focus in the production of nanomaterials.

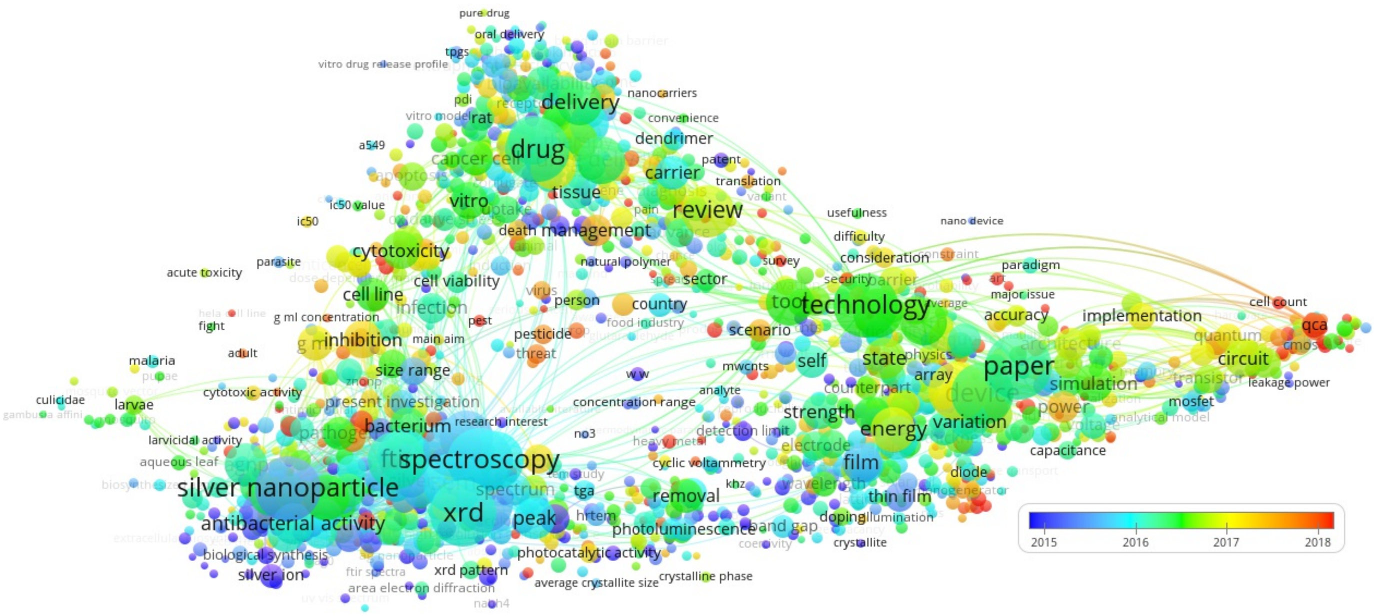

Figure 19. VOSviewer overlay network from the key TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "India"))

In light of these findings, and comparing with significant technological potencies like the USA and China, India follows the same tendency in the development of nanomedicine and electronic devices, although focusing on new transistors as the quantum-dot cellular automata, a promising successor of CMOS (Complementary metal-oxide-semiconductor) (62, 63). India has a growing necessity in water resources due to crescent industrialization and low scores in water and wastewater treatment compared to other BRICS countries (64). However, having a minor focus on water treatment-related research is a possible area of interest in future research.

3.4. BRAZIL

Figure 20 shows Brazil's result of occurrence of articles in the period analyzed. It can be seen that differently from India and USA, Brazil presents a smooth growth behavior, almost without significant variation in its tendency. The absence of a peak in 2015 may be attributed to internal affairs, regarded to economic apport and policy constraints towards research and development of nanomaterials and nanotechnology in general.

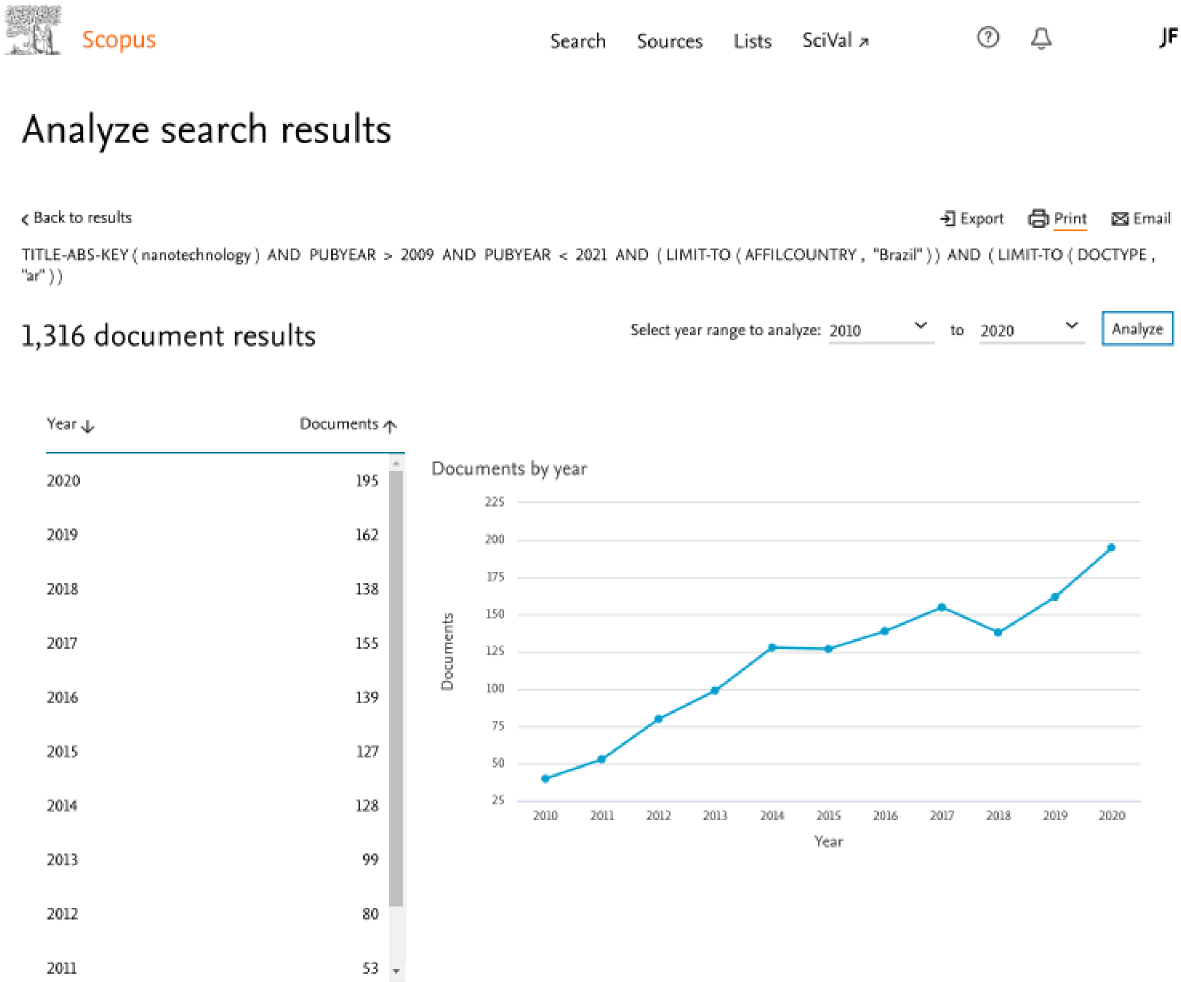

Figure 20. Frequency of documents retrieved from Scopus using the key TITLE-ABS-KEY (nanotechnology) AND

PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "Brazil")).

Brazil cluster map was depicted in Figure 21, where 4 clusters were shown. For a better view of the data, the five top nodes of each cluster were demonstrated in Figure 22. In the first cluster, the nodes "year"; "paper"; "environment"; "research" and "field" are the top-ranked in occurrences. It can be seen that the node's size is similar to each other by their correlation, meaning that these researches focused on the production of reviews and articles on environment-related areas, with correlation with the energy area.

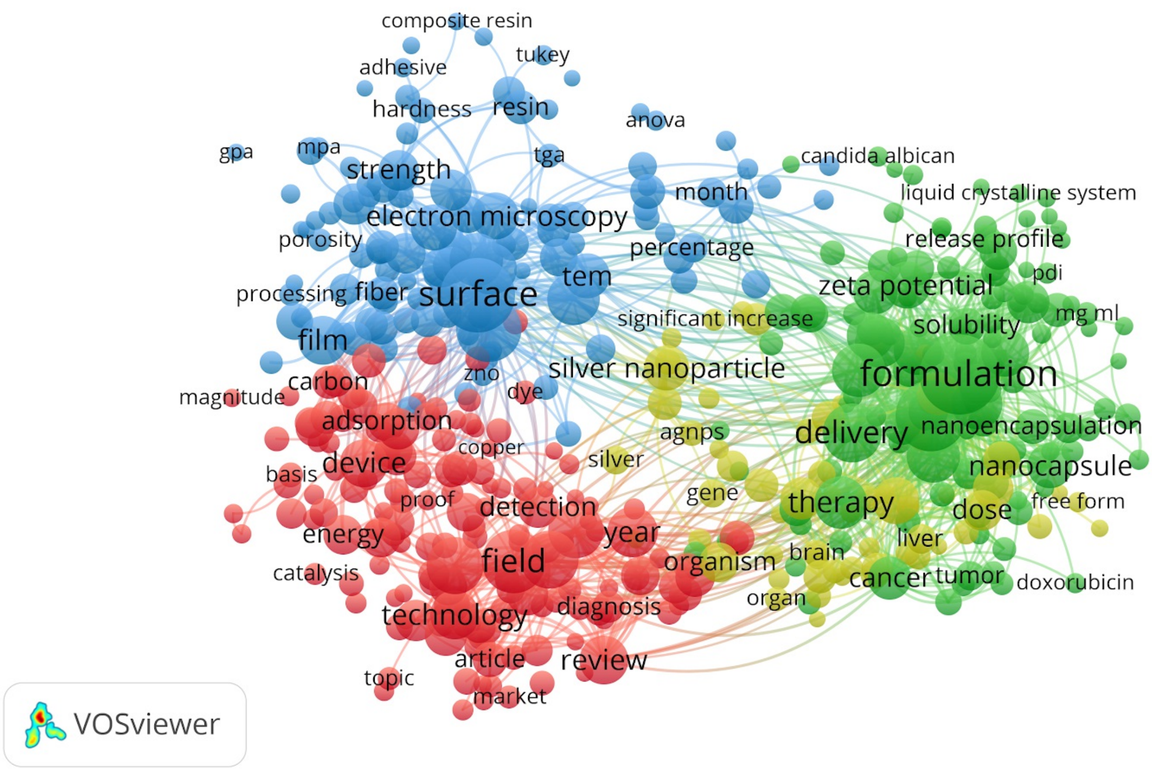

Figure 21. VOSviewer network from the key TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "Brazil"))

The second cluster presents as the five top-ranked words, in crescent order: “poly”; “efficacy”; “delivery”; “drug”; and “formulation”. As the nodes' size differs from itself, they correlate directly to nanoencapsulation and drug delivery strategies by using polymers as nanocarriers. In this cluster, nodes such as “cancer tumor”, “doxorubicin”, “release profile,” and “therapy” indicate a focus on the development of drug delivery systems directed to cancer treatment being possibly the principal application of nanoencapsulation and nanocarriers by this country.

The words “layer”; “tem”; “transmission electron microscopy”; “spectroscopy”; “surface” are the five-top ranked in the third cluster. These words correlate with characterization techniques and their aim, denoting this cluster focus. The nodes differ their size in a crescent order, from the word “layer” to the word “surface”, and the nodes “tem” and “transmission electron microscopy” are the same, indicating that this technique is well disseminated in literature in this country.

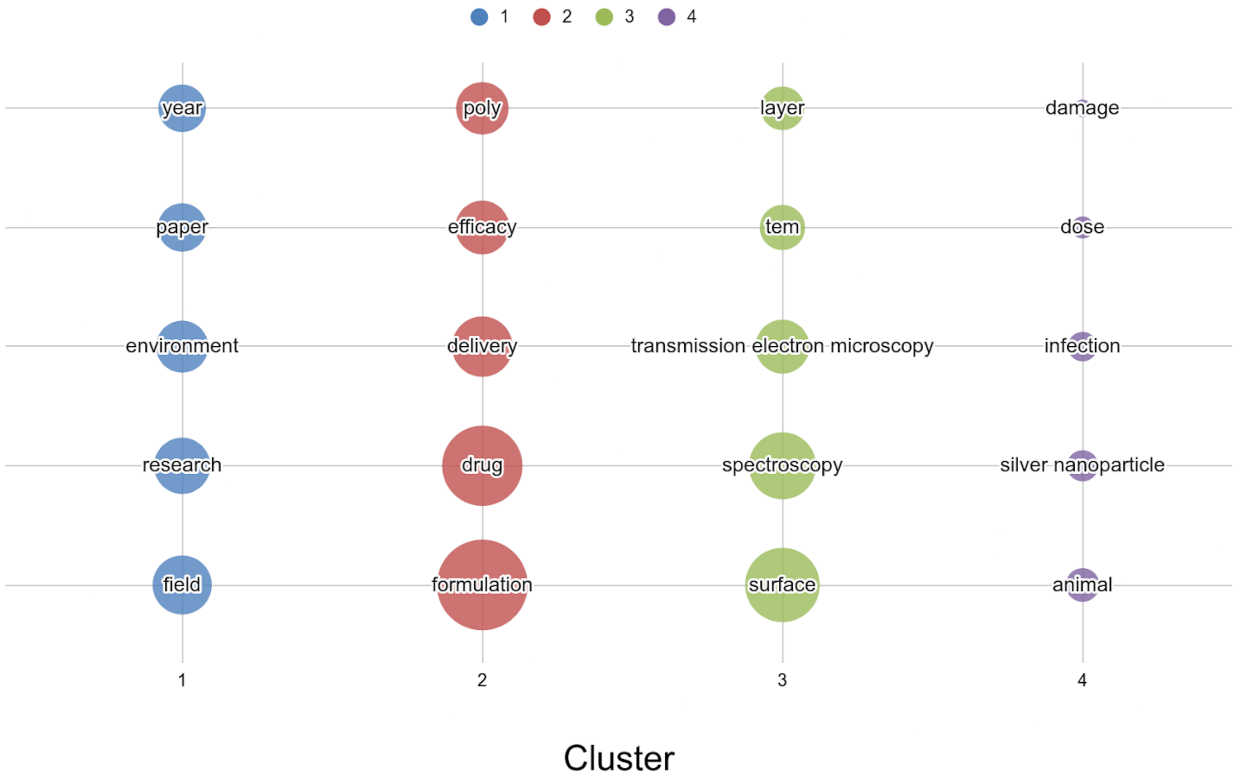

Figure 22. Clusters and top-five nodes from network of Figure 12, where the nodes are organized according to Total link strength values.

In the fourth cluster, the five top-ranked words were: “damage”; “dose”; “infection”; “silver nanoparticle”; and “animal”. The nodes are more petite than presented in other clusters, and their area of focus correlates with the second cluster, although with an emphasis on the use of silver nanoparticles and its nanomedicine application.

Comparing the global tendency in nanotechnology and the previous countries, Brazil shows a tendency towards nanomedicine focusing on nanocarriers, evaluation of nanosilver materials, and reviewing papers. These results do not contrast with other countries but show that Brazil does not focus on the electronics and energy area, as for nanogenerators, displaying that this has yet to develop in those areas. Nevertheless, Brazil must follow its internal interests in research and development, although being in alignment with significant players in nanotechnology research contributes to its development.

Figure 23 shows that the most recent nodes were concentrated in the second and fourth clusters, which focused on nanomedicine, principally in nanocarriers and silver nanoparticles. Differently from what was observed in the previous countries, which showed most recent nodes focused on energy and electronics areas despite nanomedicine related nodes that were less recent, in comparison. The most recent node shown was “promising strategy” (2019.5), associated with cancer treatment strategies towards nanocarriers and drug delivery-related nodes, indicating the continuous efforts of Brazil into nanomedicine and strategies for the treatment of diseases especially cancer.

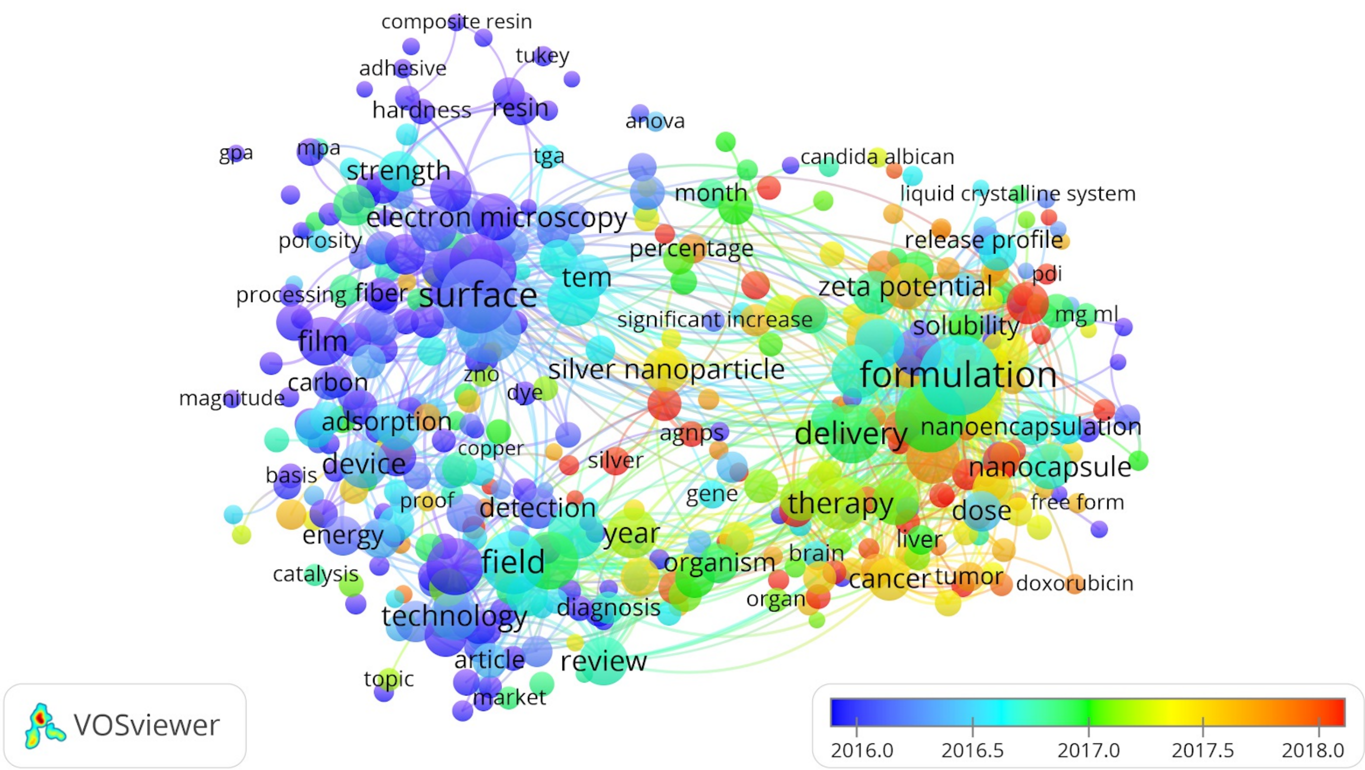

Figure 23. VOSviewer overlay network from the key TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "India"))

Compared to other countries analyzed and the worldwide trend, it is observed that Brazil focuses more on health science-related research using nanotechnology. In turn, India, EUA, and China, also have a relevant number of researches directed to energy, wastewater treatment, and electronics-related papers indicating that Brazil is yet to develop in those nanotechnology-related areas to follow the world and significant players trends in technology production. Although nanomedicine was one of the most developed worldwide, it also indicates that this country had followed this tendency observed in EUA, China, and India, which maintained the focus in the time-lapse, as shown in Figures 10, 13, and 19.

4. Conclusions and perspectives

This work makes evident the relevant scientific contributions of the United States, the People's Republic of China, and the Republic of India to the field of nanotechnology. Despite some convergence, different subjects are researched by each of these countries, which demonstrates different stages of maturity in the theme and different interests of each of these nations. This information is an essential piece on the geopolitical board, as it demonstrates, between the lines, the interests of each nation in this frontier field. Of course, each of them is looking to potentialize their impact on several new technologies and business opportunities, which can significantly improve the quality of life of their populations. Thus, continuous efforts must be expended for the evolution of this area of knowledge, especially when it is proven that Brazil occupies the fifteenth place in this ranking, which demonstrates the need for more inventions in research and better policies for targeting these resources.

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