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Magnetized water: impacts on global scientific and technological development

Água magnetizada: impactos no desenvolvimento científico e tecnológico global

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ABSTRACT: Research on magnetized water increases every year, several areas of science seek to apply this technology, since the properties of water are modified after the magnetization process. The objective of this study was to carry out an unprecedented bibliometric analysis to evaluate the evolution of research on magnetized water. The documents were retrieved from the Web of Science collection and a descriptive bibliometric analysis was carried out by year, research area, source, citation, and region. Bibliometric mapping techniques, cluster analysis through the occurrence of keywords, co-authorship and bibliographic coupling were also applied. The results indicated that research on magnetized water has grown exponentially, with emphasis on the countries, China, Iran and Egypt, and in areas such as engineering, chemistry, materials science, agriculture and physics. Most documents were categorized into five areas: concrete, agriculture, magnetic resonance image (MRI), scale and dust removal. Dust removal has been identified as a hidden prominent research area. Furthermore, it was revealed that concrete with magnetized water for sustainability is a research trend. The topic still has gaps that must be filled, showing the need to develop more effective and reliable methods to better understand water magnetization.

Keywords: Clean technologies; Magnet; Magnetic field; Scientometrics.

RESUMO: As pesquisas sobre água magnetizada aumentam a cada ano, diversas áreas da ciência buscam aplicar essa tecnologia, uma vez que as propriedades da água são modificadas após o processo de magnetização. O objetivo deste estudo foi realizar uma análise bibliométrica inédita para avaliar a evolução das pesquisas sobre água magnetizada. Os documentos foram recuperados do acervo da Web of Science e foi realizada uma análise bibliométrica descritiva por ano, área de pesquisa, fonte, citação e região. Também foram aplicadas técnicas de mapeamento bibliométrico, análise de cluster por meio da ocorrência de palavras-chave, coautoria e acoplamento bibliográfico. Os resultados indicaram que as pesquisas sobre água magnetizada têm crescido exponencialmente, com destaque para os países, China, Irã e Egito, e em áreas como engenharia, química, ciência dos materiais, agricultura e física. A maioria dos documentos foi categorizada em cinco áreas: concreto, agricultura, imagem por ressonância magnética (IRM), escala e remoção de poeira. A remoção de poeira foi identificada como uma área de pesquisa proeminente oculta. Além disso, foi revelado que concreto com água magnetizada é uma tendência de pesquisa para sustentabilidade. O tema ainda apresenta lacunas que precisam ser preenchidas, mostrando a necessidade de desenvolver métodos mais eficazes e confiáveis para melhor compreender a magnetização da água.

Palavras-chave: Tecnologias limpas; Ímã; Campo magnético; Cienciometria.

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1 INTRODUCTION

Magnetized water is produced when water molecules passes through a magnetic field, this process generates a decrease in surface tension, which can be measured using a tensiometer (Bharath *et al.,* 2016). Once in the presence of an electric dipole, the water molecules follow in the direction of the electric field, as water is a material with diamagnetic characteristics, this means that this material loses its magnetization as soon as the external magnetic field is suppressed.

Water molecules are oriented in the same direction as the magnetic field, this is explained by the fact that their molecules are polar (Mghaiouini *et al*., 2020). During the water magnetization process, the magnetic field induces the bond to decrease its angle to less than 105 degrees, leading to a decrease in the degree of consolidation between the water molecules and an increase in the size of these molecules, as well resulting in changes in the physicochemical properties of water, such as pH, surface tension, conductivity and viscosity (Ueno, 2012).

Water magnetization techniques are simple and the two main methods are: i) passing water through a magnetic field, and the other way is ii) using a static magnet near a certain volume of water. However, the magnetization process must have controlled conditions, since the strength of the magnetic field and the magnetization time have a direct impact on the properties of the magnetized water. In addition, the water magnetization process can also be considered a clean process, as it does not require energy consumption (Esmaeilnezhad *et al*., 2017).

Water has a structure aligned in a certain direction, but after the magnetization process, its structures change direction, the molecules change size and there are changes in the angles of hydrogen bonds, this causes the viscosity, surface tension, and hydration rate to increase after the magnetization process, so the rates of hydrogen bonding become stronger. Water molecules have a tendency to form clusters with hydrogen bonds, but with the presence of the magnetic field these clusters are broken, after the magnetization process (Abdel-Magid *et al*., 2017; Zhou *et al*., 2000).

The first solvent to be studied on the magnetization process was water. Some studies state that one of the advantages of the water magnetization is precisely the fact that this material retains these new properties for a long period, and this phenomenon makes scientists gain time to work with this material (Absalan *et al*., 2021).

As for the pH of magnetized water, some authors have already performed experiments that showed pH changes in magnetized water when the intensity of the magnetic field increases (Hasaani *et al*., 2015) or when contact time of the water with the magnetic field increases (Kotb, 2013). With increasing exposure time to the magnetic field, there is a decrease in the concentration of hydrogen ions, thus increasing pH, while with an increase in the strength of the magnetic field, the result may be related to the polarization of water molecules, since they will order in one direction with the decrease in the concentration of hydrogen ions (Gaafar *et al*., 2015).

Studies revealed that water in contact with a magnetic field has its viscosity increased, this phenomenon was observed through a capillary viscometer (Ghauri; Ansari, 2006), when the strength of the magnetic field is higher (2.3 T), there is a relative increase in the viscosity of the water, this for distilled water, demineralized water and dilute NaCl solutions. This fact can be explained because with magnetization there is an increase in the dispute between different hydrogen bond networks (intra and intermolecular), weakening the hydrogen bonds called intra-cluster, resulting in smaller clusters with stronger inter-cluster hydrogen bonds, that is, an increase in the number of clusters (Usanov *et al*., 2016; Toledo *et al*., 2008).

Water that has been exposed to a magnetic field suffers a decrease in its surface tension and an increase in electrical conductivity, in addition to changes in the biological activity of its molecules. The electrical conductivity was found to be 1.50 + 0.18 μS cm^{-1} for untreated water and 2.60 + 0.30 μS cm^{-1} for magnetized water (Porto, 2022). The increase in conductivity after the experiment is associated with the weakening of the hydration envelope around the H and OH ions, the increase in the thickness of the hydration layer around the ions and the thermodynamic functions of hydration (Holysz *et al*., 2007).

Currently, numerous studies in different areas of knowledge apply magnetized water for different purposes, such as agriculture, in studies with saffron production (Zuñiga Escobar *et al*., 2016), lettuce (Putti *et al*., 2013; Matulovic *et al*., 2021), carrots (Putti *et al*., 2018), among other uses in agriculture. In veterinary medicine and biology, evaluating productivity and blood parameters in geese (Animal Production Research Institute *et al*., 2017), in medicine as a therapeutic technique, for groups of patients with vascular diseases (Espinosa Álvarez *et al*., 1997). Another application is the insertion of magnetized water into concrete, where its workability, strength and other parameters are tested (Bharath *et al*., 2016; Abdel-Magid *et al*., 2017; Ali *et al*., 2021).

In this context, bibliometric analysis, as a statistical technique applied, can be used to study the evolution of knowledge on magnetized water based on data publication (Zupic; Čater, 2015; Belmonte-Ureña *et al*., 2021). Performance analysis uses indicators such as citation analysis, counting publications, word frequency analysis by a unit of analysis to provide data about the amount and impact of the research (Romanelli *et al*., 2021). Science mapping allows finding insights into patterns of a knowledge area that would be difficult to identify using traditional research review methods (Prieto-Jiménez *et al*., 2021), by assessing the impact, structural and dynamic organization of a knowledge topic, field of research, group of researchers, or a document, based on relation indicators (Marzi *et al*., 2017; Pizzi *et al*., 2020).

Water magnetization is not a new area of research. However, there are few review studies and no bibliometric studies yet. Thus, this study aimed to conduct a bibliometric analysis, addressing the perspective of the status and evolution of scientific research on magnetized water, its interrelations, thematic currents, and gaps.

2 MATERIAL AND METHODS

The bibliometric analysis was conducted in three phases according with previous studies (Yamaguchi *et al*., 2023).

2.1 SEARCH AND DATA COLLECTION

Analyzed metadata used in this investigation were obtained from the Clarivate Analytics WoS core collection database of the Institute for Scientific Information (ISI, Philadelphia, PA). Documents were retrieved by searching "magnetized water" or "magnetic water" or "magnetic treated water" or "water magnetization" in TITLE and ABSTRACT fields, on SCI-expanded collection. The search was conducted on August, 2023 and was narrowed to articles-type and English-only documents, resulting in 463 documents. The documents were individually screened to verify if they met the inclusion criteria and 368 were included.

All available metadata (abstract, keywords, funding, author, authors' affiliation information, year of publication, thematic area, journal) were downloaded as a CSV-file. The data were checked for debugging using Microsoft Excel software, and a thesaurus file was created. In the thesaurus file, the keywords were normalized, eliminating duplicities, unifying synonyms, and developing acronyms. For this purpose, the all keywords were included. The VOSviewer 1.6.18 software was selected for this phase, due to its remarkable visualization feature for bibliometric data and also because it is a freely available tool van Eck; Waltman, 2010).

2.2 PERFORMANCE ANALYSIS

In this step, the basic characteristics of retrieved documents was performed using a descriptive bibliometric analysis exploring: (1) publication output; (2) research area (3) most productive sources; (4) most cited documents; (5) most productive countries. For the analysis of the most relevant sources, the impact factors were obtained from the Journal Citation Reports (JCR) published in 2021 that assesses the journals performance via the SCIMago Journal Rank (SJR) indicator based on an average number of citations. Furthermore, the total citations (TC), the average number of citations per paper (AC), the normalized citations (NC), the average normalized citations (ANC), and Hirsch index (h-index) were also used to assess the citation impact and productivity of a document, authors and/or sources.

2.3 CLUSTER ANALYSIS AND VISUALIZATION

The third step included the cluster analysis and visualization by mapping technique. The co-authorship, bibliographic coupling and keyword co-occurrence were selected to be used as indicators. The maps were interpreted according to the generated weights and score attributes assigned to each cluster Prieto-Jiménez *et al*., 2021). An interpretive analysis was used to explore the evolution of the field and to identify thematic currents. Unique and significant keywords were identified in the co-occurrence mapping analysis. The search keywords ("magnetized water", "magnetic water", "magnetic treated water" and "water magnetization") and transversal terms (e.g., “magnetization”, “magnetic treatment” or “magnetic field”) were excluded, as they can be associated with various documents (Yakovleva; Vazquez-Brust, 2012; Pizzi *et al*., 2020; Belmonte-Ureña *et al*., 2021).

3 RESULTS AND DISCUSSION

3.1 PUBLICATION OUTPUT

The cumulative distribution of scientific production of documents output from its first issue in 1969 to august 2023, shows that the publication output increased over the years. Until 2000, only 43 documents were published. The number of published documents doubled after 10 years and has been constantly increasing since then. From 2017 the number of published documents increased dramatically and continues to grow, achieving a total of 368 publications in August 2023.

3.2 RESEARCH AREAS

The publications of the main fields classified by areas of research were i) Engineering, ii) Chemistry, iii) Materials science, iv) Agriculture and v) Physics. The first category represents 29 % of the total documents analyzed and it is of particular relevance. Also, the publications could be included in multiple categories.

3.3 SOURCES

The documents were published in 233 journals and the most relevant journals regarding the largest number of documents published are presented in Table 1.

Among the top ten journals, 3 of them are related to magnetic resonance, being two of them from biology and medicine. Two journals are related to agriculture, two with water, two related to materials, being one of civil engineering materials.

Regarding the number of documents by journal, Construction and Building Materials presented the largest number of documents (14), followed by the Journal of Biomolecular NMR (12), Magnetic Resonance in Medicine (8) and Journal of Magnetic Resonance (6). Journal of Biomolecular NMR was the most cited journal with 599 total citations (TC). Most journals presented high impact factor and h-index.

Table 1. The top 10 most prolific journals

Nº	Journal	D	TC	AC	NC	ANC	IF	h-index	Publisher
1	Construction and Building Materials	14	357	25.5	25.6	1.8	7.4	230	Elsevier
2	Journal of Biomolecular NMR	12	599	49.9	9.9	0.8	2.7	111	Springer
3	Magnetic Resonance in Medicine	8	317	39.6	8.4	1.0	3.3	243	John Wiley & Sons
4	Journal of Magnetic Resonance	6	351	58.5	7.9	1.3	2.2	131	Elsevier
5	Materials	5	56	11.2	5.5	1.1	3.4	148	MDPI
6	Powder Technology	4	146	36.5	9.6	2.4	5.2	162	Springer Nature
7	Water Research	4	436	109.0	4.7	1.2	12.8	354	Elsevier
8	Frontiers In Plant Science	4	5	1.3	1.7	0.4	5.6	187	Frontiers
9	Desalination And Water Treatment	4	26	6.5	1.3	0.3	1.3	75	Desalination Publications
10	International Journal of Agricultural and Statistical Sciences	4	3	0.8	0.7	0.2	0.2	18	DAV College

D = Number of documents, TC = Total citations, AC = Average number of citations per document, NC = Normalized citations, ANC = Average normalized citations, h-index = Hirsch index, IF = Impact factor.

The average number of citations per document (AC) show that Water Research stand out with 109 citations. However, when observing the normalized citation (NC), that is the number of citations of a document equals the number of citations of the document divided by the average number of citations of all documents published in the same year included in the data (van Eck and Waltman 2010), showed that Construction and Building Materials (NC = 25.6) is the most prominent source. This normalization corrects the fact that older documents have more time to receive citations than recent documents (van Eck; Waltman, 2010). Nonetheless, the average normalized citation (ANC), which indicates the NC divided by the number of documents, demonstrated that Powder Technology (ANC = 2.4) is the most noticeable journals.

Thus, it is noted that even though the total number of documents and TC indicate that magnetic resonance is among the most relevant sources, the normalized citation data indicate that journals related to applied research are among the most noticeable sources. This indicates that the number of citations alone is not adequate to assess the relevance of a document or journal (Simko, 2015).

3.4 DOCUMENTS

The most relevant documents based on the NC of the documents are presented in Table 2. It is observed that magnetized water is included in many different areas of research. When analyzing the NC, the most relevant document is related to water treatment, magnetic resonance, chemistry and civil engineering.

Table 2. The top 10 most-cited documents

No.	Title	Source title	TC	NC	Reference
1	Magnetic Field Application and its Potential in Water and Wastewater Treatment Systems	Separation & Purification Reviews	166	6.3	Zaidi *et al*. (2014)
2	Detection of Proton Chemical Exchange between Metabolites and Water in Biological Tissues	Journal of Magnetic Resonance	183	5.0	Guivel-Scharen *et al*. (1998)
3	The effect of a static magnetic field on the hydrogen bonding in water using frictional experiments	Journal of Molecular Structure	87	5.0	Wang *et al*. (2013)
4	Characteristics and applications of magnetized water as a green technology	Journal of Cleaner Production	108	4.8	Esmaeilnezhad *et al*. (2017)
5	An Optimized 3D NOESY–HSQC	Journal of Magnetic Resonance	167	4.3	Talluri and Wagner (1996)
6	An experimental comparison of the spray performance of typical water-based dust reduction media	Powder Technology	59	4.0	Wang *et al*. (2019)
7	Effect of magnetic field on the physical properties of water	Results in Physics	102	3.7	Wang *et al*. (2018)
8	Effect of magnetized water on foam stability and compressive strength of foam concrete	Construction and Building Materials	53	3.6	Ghorbani *et al*. (2019a)
9	WaterLOGSY as a method for primary NMR screening: practical aspects and range of applicability	Journal of biomolecular NMR	408	3.4	Dalvit *et al*. (2001)
10	Effect of magnetic water treatment on calcium carbonate precipitation: Influence of the pipe material	Chemical Engineering and Processing: Process Intensification	76	3.2	Alimi *et al*. (2009)

(conclusão)

TC = Total citations, NC = Normalized citations.

Magnetized water has been used for the most diverse purposes, among the most research it was observed that the application of the magnetic field has promising potential in terms of the effectiveness of solid-liquid separation processes, mainly through the aggregation of colloidal particles. The application also has a considerable influence on biological properties by improving bacterial activity. Thus, the material was used efficiently in the treatment of water and wastewater (Zaidi *et al*., 2014).

Guivel-Scharen (1998) used magnetized water in his studies on MRI. The study by Dalvit (2001) also applied magnetized water for use in MRI. Wang (2013) analyzed the effect of a static magnetic field on water, using friction experiments, and was able to verify that the friction coefficient was lower in magnetized water than in water, and even smaller with increasing magnet intensity. Furthermore, when the water temperature decreases, the coefficient of friction in the water increases. According to the author, the difference in friction is due to the low effect of the magnetic field on the hydrogen bonds in the water.

Some articles study the effects of magnetization, as well as measurement tools, treatment conditions, and properties of magnetized water (Ghorbani *et al*., 2019ab). Furthermore, the effects of the magnetic field on the characteristics of the water are analyzed. Within the article of Esmaeilnezhad (2017), magnetization mechanisms are mentioned, how they are used, and what they cause in the characteristics of the water such as pH, viscosity, electrical conductivity, as well as how the surface tension of the water decreased with the application of a magnetic field, while the pH increases, along with viscosity and electrical conductivity. However, there are no precise results. The review with petroleum and magnetized water stands out with the increase in microscopic and macroscopic scanning efficiency, the decrease in surface tension and increase in water viscosity, removal and inhibition of scale to avoid damage to reservoirs. Magnetized water has proven to be a clean technology option for producing more oil from underground reservoirs (Esmaeilnezhad *et al*., 2017).

In the article by Wang *et al*., (2019) the heat properties of magnetized water were analyzed, such as specific heat, amount of evaporation, and boiling point, concluding that after treatment with the magnetic field, there was an increase in the amount of evaporation, a shorter time for evaporation, and a decrease in the specific heat and boiling point of the magnetized material. Indicating an extremely revealing result, since this type of technology can be applied in industries aiming to save energy.

The research by Wang *et al*., (2019) the effects of water and other magnetized solvents in sprayers used to reduce dust, used in various industrial processes, were analyzed. The results of the study showed that the spray velocities for magnetized water, surfactant solution and magnetized surfactant solution were higher than that for tap water. This study demonstrated that it is capable of providing guidance aimed at reducing sprayed dust.

Civil engineering is one of the production sectors that most pollute the environment, therefore, the search for technologies that optimize the use of resources is becoming increasingly important and magnetized water plays a fundamental role in this search. Studies that incorporate magnetizes water into construction materials are increasing. In the study by Ghorbani (2019), they tested the effects of magnetized water on the stability of the foam and the compressive strength of foam concrete, and for this type of use, a significant improvement was noted with the use of magnetized water, highlighting the potential of the material in civil construction, in addition to other studies that prove the efficiency of magnetized water.

Alimi (2009) studies the calcium carbonate precipitation process, in which the encrusting water was exposed to a magnetic field, and it was observed that the crystallization of calcium carbonate, through the effects of magnetization, increased the total amount of precipitate and contributing to its formation in the bulk solution instead of its encrustation on the pipe walls.

3.5 COUNTRIES

The most productive countries are represented in Figure 1, according to the number of documents published based on corresponding authors affiliations. A total of 48 countries were analyzed. China was the most prolific region, accounting for 17.7% of the documents, followed by Iran and Egypt, which represented 17.4% and 12.0%, respectively. Finally, the United States of America (USA) accounted for 8.7% of the scientific production, followed by Iraq and Saudi Arabia, both accounting with 5.7% each.

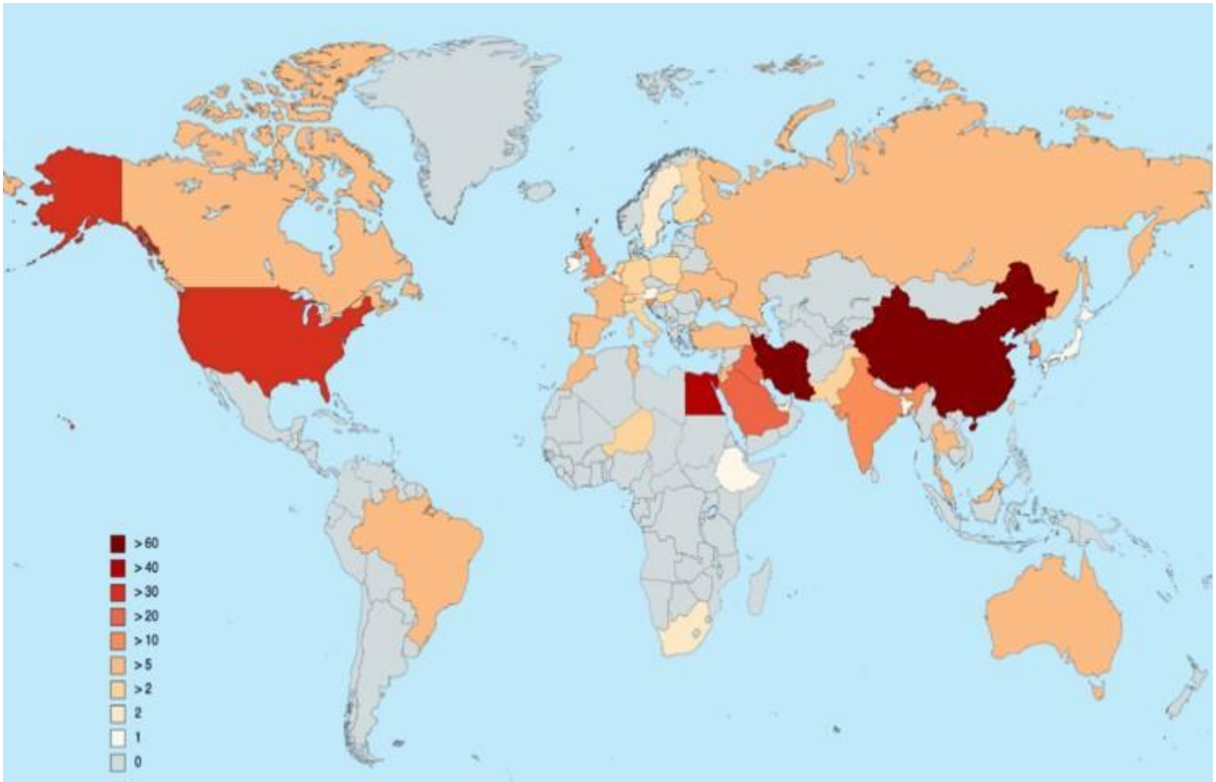

Figure 1. The geographical distribution of documents (www.mapchart.net)

To better understand international collaborations, the mapping of citations of countries according to the authors affiliations is presented in Figure 2.

Japan, Wales and Kwait did not present links, so they were excluded, resulting in 45 countries. Eight clusters were obtained with 371 links, and total link strength of 1898. The size of the circle reflected the number of citations (weights) in the dataset that were associated to the country. In addition, the citation characteristics of the clusters were provided in Table 3.

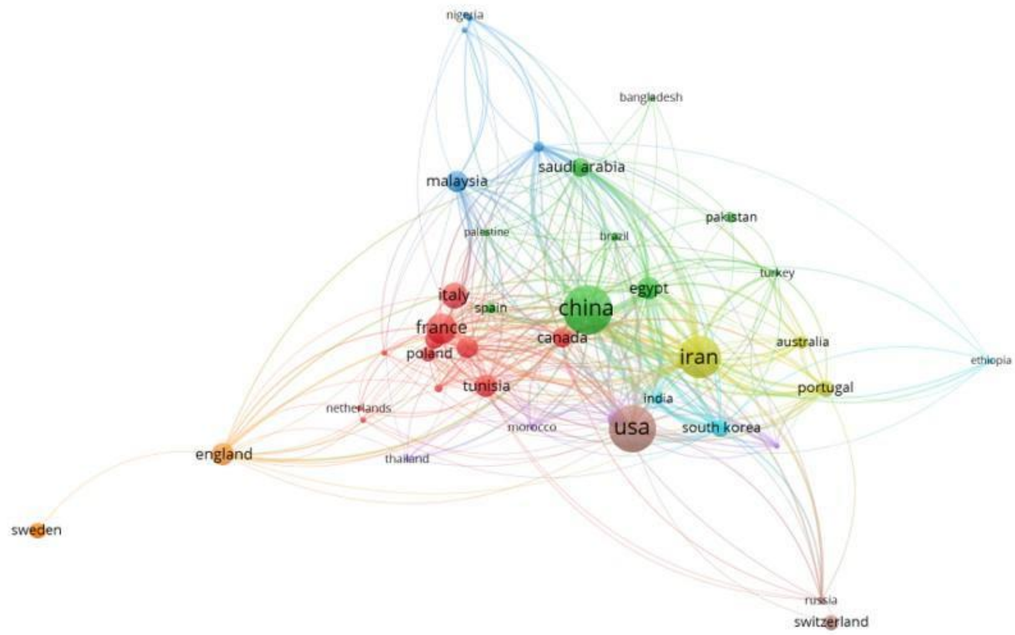

Figure 2. Clusters based on citations of countries according to the authors affiliations (Minimum number of documents of a country: 1; Items that meet the threshold from a total of 48 countries: 43; Clusters: 8; Links: 356; Total link strength: 1876; Weights: citations; VOSviewer 1.6.18.)

Table 3. Citation characteristics of most productive countries represented on clusters based on citations

Country	D	TC	AC	NC	ANC
China	65	1396	21	89	1.36
Iran	64	1023	16	65	1.01
Egypt	44	298	7	46	1.05
USA	32	1299	41	36	1.12
Saudi Arabia	21	209	10	20	0.96
Iraq	21	71	3	8	0.38
South Korea	12	182	15	15	1.28
India	12	54	5	14	1.13
Slovenia	12	280	23	6	0.48
Malaysia	10	271	27	15	1.55
England	10	313	31	12	1.16
Canada	10	234	23	10	1.04
Brazil	10	50	5	6	0.56

D = Number of documents, TC = Total citations, AC = Average number of citations per document, NC = Normalized citations, ANC = Average normalized citations.

It was observed that China presented the largest number of documents and the largest number of citations. Iran showed the same behavior, with high value for NC (> 1000). The USA, despite having a smaller number of documents compared to China, Iran and Egypt, presented a high number of citations. This result suggests that scientists tend to cite research that were conducted in a developed country. This might be related to the confidence and reliability of the data or even credibility in science produced.

The countries with higher ANC (ANC > 2) were Finland and Sweden. These findings further support the idea that developed countries are preferred to be cited in the literature compared to low-income countries or it may even be related to the quality of research carried out by these countries. Furthermore, the international collaborations are strongly recommended to improve the comprehend the diversity of scientific perspectives and applications despite not having been observed as much for this topic.

3.6 KEYWORDS

The analysis of keywords are essential in reflecting and defining the research contents and can be used to identify the framework of a main research in many areas (Wuni *et al*., 2019). The most relevant keywords co-occurrence were used to investigate the conceptual structure of the research on magnetized water to identify the prevailing thematic (Pizzi *et al*., 2020).

The results of the co-occurrence analysis of the diversity of 1,775 of all keywords from 368 documents analyzed with 5 as a minimum number of occurrences of a keyword, and no minimum number of citations and documents (Figure 3 and Table 4). The map resulted in 93 keywords that met the threshold in 5 clusters, 1250 links, and total link strength of 2036. The size of the circle reflected the number of occurrences (weights) of each keyword in the dataset.

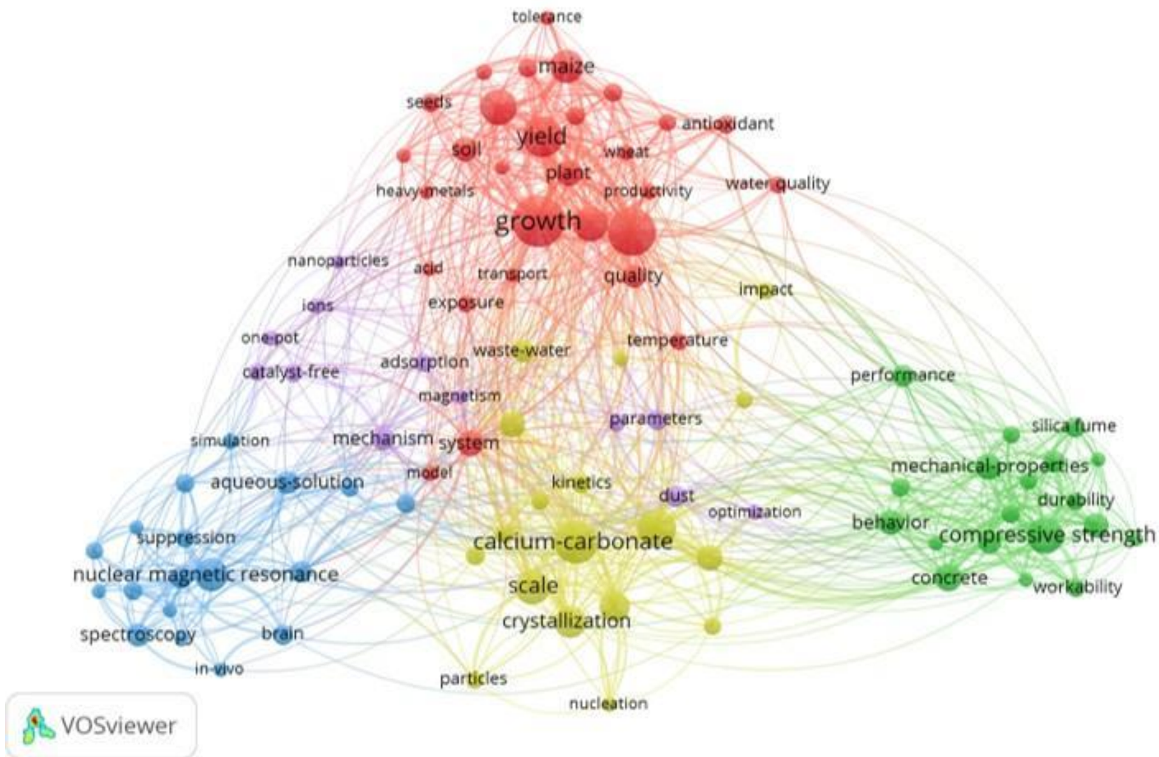

Figure 3. Clusters based on co-occurrence of all keywords (Minimum number of occurrences of a keyword: 5; Items that meet the threshold: 93; Clusters: 6; Links: 1250; Total link strength: 2036; Weights: occurrences; Maximum lines: 1000, VosViewer 1.6.18)

Table 4. General characteristics of clusters based on co-occurrence of all keywords

Cluster	Most used keywords*	Most influential keywords**	Items	ANC	Occurrences
1 (red)	Growth, irrigation, yield, germination, salinity, maize, plant, system, soil, quality.	Heavy metals, photosynthesis, exposure, tolerance, phytoremediation	29	0.8 ± 0.4	14.3 ± 14.3
2 (green)	Compressive strength, concrete, mechanical-properties, ash, behavior, strength, performance, self-compacting concrete, silica fume	Corrosion, durability, self-compacting concrete, statistical analysis, behavior, ash, silica fume, mechanical-properties, blast-furnace slag, stability, concrete, hardened properties, compressive strength, strength.	19	1.4 ± 0.5	10.7 ± 6.2
3 (blue)	Nuclear magnetic resonance, aqueous-solution, spectroscopy, protons, relaxation, brain	Aqueous-solution, in-vivo, suppression, spectra, saturation, protons, sensitivity, pulsed-field gradients, relaxation, conductivity, brain, nuclear magnetic resonance, simulation, enhancement.	17	1.0 ± 0.4	14.6 ± 11.4
4 (yellow)	Calcium-carbonate, surface, scale, crystallization, precipitation, reduction, water-treatment, waste-water	Electrolyte-solutions, surface, removal, pH, crystallization, calcium-carbonate, drinking-water, reduction, scale.	14	1.25 ± 0.54	10.43 ± 5. 83
5 (purple)	Mechanism, dust, parameters	Dust, adsorption, nanoparticle, wettability	12	1.0 ± 0.6	7.5 ± 2.43

ANC = Average normalized citation; * Included keywords with occurrences > 10; ** Included keywords with ANC > 1.00

Studies on agriculture are the most recurrent (Group 1), with the highest number of keyword occurrences. However, the analysis of citations showed that this topic is the one that is least cited, according to the ANC. Although many pieces of equipment are already commercialized, research on this topic is not yet very prominent. This may be related to the fact that studies contradict each other, some authors claim that the use of magnetized water increases plant productivity (Ali *et al*., 2019a, 2019b; Mostafa, 2020; Al-Mana *et al*., 2021) however, its effect may not only be favorable, but also harmful to the growth and development of some plants, since excessive absorption of some microelements ends up including harmful materials, such as heavy metals.

Therefore, the magnetization device must be adapted to the needs of the plant species and even varieties, in addition to considering the quality of the water that will be used. Analyzing this scenario, more studies are needed to make this technology more reliable (Dobránszki Judit,2023, Mohrazi *et al*., 2021; Hu *et al*., 2022).

Group 2 proved to be the most relevant topic according to the ANC score. The use of magnetic water in concrete to improve its properties is the main objective of this group. The corrosion and durability properties of concrete emerged as prominent themes. The use of waste such as ash, silica fume and blast furnace slag can also be highlighted in the sustainable aspect of concrete along with the use of magnetized water.

The earliest studies on magnetic water were related to medicine, mainly with MRI (Group 3). This topic is also not receiving much scientific attention according to citation analysis. MRI has been a known practice for many years, the studies related to magnetized water cited in this article are from 1996, 1998 and 2001(Talluri and Wagner, 1996; Guivel-Scharen *et al*., 1998; Dalvit *et al*., 2001), being articles with more than 20 years of publication, but still, being articles with a good number of citations in scientific circles, this makes the importance of the subject clear, but also shows the urgency for more current research on the topic.

Group 4 is related to calcium carbonate and the use of magnetized water to reduce scale formation and precipitation. Calcium carbonate precipitation has been in evidence, due to its wide use in industrial processes, but with it comes the deposition of calcium carbonate incrustations, which end up causing damage to domestic, agricultural and even industrial installations, being capable of cause clogging of pipes, membranes, etc., several methods and mechanisms have been tested aiming to reduce or eradicate these incrustations.

One of them is the decarbonization of water, in addition to several other treatments that involve the use of chemicals that are harmful to human health. And, in this context, some researchers aspire to use magnetized water to solve this issue, without harming the end consumer (Alimi *et al*., 2009). In addition to Alimi (2009), other authors have studied this topic, such as Aldeia (2019), Cao (2023), among other researchers who intend to seek sustainable alternatives to eliminate problems with calcium carbonate scale, therefore, it is worth highlighting that this group stood out for presenting a high ANC.

Group 5 identified a key hidden theme related to wettability and the ability to capture dust with surfactant-magnetized water. Studies have shown that the magnetization of water causes changes in its physical properties, such as an increase in the amount of evaporation, a decrease in its boiling point and specific heat, among other aspects, and these changes were incorporated into sprayers to seek to reduce pollution generated by dust in industrial processes. The keyword dust presented the highest ANC indicating a topic with scientific relevance (Holysz *et al*., 2007, Wang *et al*., 2019, Wang *et al*., 2018).

This article contributes to recent debates on magnetized water. It has been a long time and some still believe that there are no real effects. However, the literature shows that the effects of a magnetic field can contribute to changing the properties of water and lead to simple and sustainable solutions.

4 CONCLUSIONS

This bibliometric analysis provided a perspective of the state-of-art and evolution of the research trend in the field of magnetized water. The conclusions revealed: an increasing trend in magnetized water publications has been observed with increasing diversification in research areas; most documents were categorized into five main research areas: Engineering, Chemistry, Materials Science, Agriculture and Physics. The most cited documents and the most relevant sources indicated that the topics of great relevance were related to applied research according to standard citation analysis, such as Construction and Building Materials and Powder Technology. Additionally, China, Iran and Egypt were the most productive countries. However, developed countries were more relevant in citation analysis.

Also, keyword terms were classified into 5 groups: agriculture; construction; MRI; scale and finally, dust and magnetized water, and the terms with the highest occurrence were related to agriculture. The co-occurrence analysis of keywords identified concrete corrosion and durability and dust control as hidden key elements with greater relevance among the analyzed keywords. Applied research was found in greater numbers, mainly in the areas of engineering and agriculture. However, more in-depth studies about the changes that happen to water in the magnetization process are needed.

Finally, the analysis revealed that the proposed methodology using bibliometric analysis of documents and using magnetized water is of great relevance, as several research in this field are being carried out. Applications arise without a complete understanding of water magnetization mechanism. The mechanism of magnetized water is highly complex and still requires more detailed research. Therefore, future research should be directed towards filling this gap, through the development of more effective and reliable methods for understanding water magnetization.

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