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Original Research

Projected Futures: An In-Depth Analysis of Emerging Nuclear Fusion Technologies

Sahar Kousari
Associate Prof., Science Policy Department, National Research Institute for Science Policy (NRISP), Tehran, Iran.
Corresponding Author: kosari@nrisp.ac.ir
ORCID iD: https://orcid.org/0000-0003-3226-7175

Sajedeh Abdi
Ph.D. Candidate, Deputy of Research and Technology Department, National Research Institute for Science Policy (NRISP), Tehran, Iran.
abdi@nrisp.ac.ir
ORCID iD: https://orcid.org/0000-0001-5414-6070

Anna Eydan
Ph.D. Candidate, Department of Physics and Energy Engineering, Nuclear Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran.
anna.eydan@gmail.com
ORCID iD: https://orcid.org/0000-0001-8121-4307

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Abstract

This research aims to examine the nuclear fusion technology field using the intellectual structure drawing technique. It is worth mentioning that the reason for focusing on this area, atomic fusion, is its peaceful applications and unlimited fuel to generate power. The proposed strategy in this paper includes all the keywords related to the research topic. VOS viewer and R Studio software were employed for data analysis. In addition, the principal research topics were extracted and classified using scientific maps. This analysis indicates the intellectual structure of the topic, which is grouped into four fundamental clusters using citation networks. This study additionally identifies emerging issues and future research directions implementing strategic diagrams. Another aspect of this study that reveals the intellectual foundation of the research is that it provides insights into the importance of crucial topics, institutions, and publications in terms of the field's focus and the results obtained from the analysis of the period 1991-2023. It informs that the conceptual evolution of nuclear fusion and its growth is proceeding.

Keywords: Nuclear Fusion, Bibliometrics, Topic Analysis, Emerging Topics, Projected Futures.

Introduction

Nuclear energy is one of the significant achievements of nuclear science and technology, which will play a vital role in providing energy to advanced countries, in particular, that are determined to effectively develop and exploit fusion energy to achieve the aim of the country's development plans. Innovations are being accomplished to make nuclear energy a more affordable and notable option (Mathew, 2022). The environmental challenges of the 21st century are so concerning that people think of possible solutions; undoubtedly, one of these solutions would be nuclear fusion energy, which can be almost unlimited and one of the most environmentally safe energy sources on the earth. Therefore, the replacement of clean sources of energy, including nuclear fusion with other limited energy sources, has attracted the attention and awareness of mankind for several decades; extensive measures have been taken in this regard, an example of which would be the exploitation of hundreds of thousands of megawatts of renewable energy resources throughout the time of two recent decades.

It is inevitable to accept that achieving nuclear fusion is immensely difficult. However, in recent years, with the rise of international cooperation, accomplishing nuclear fusion energy appears to be more promising. A considerable number of scientists in several countries are working unyieldingly toward solving the enormous scientific and technical problems associated with nuclear fusion. Nuclear fusion is a sought-after technology in which two light elements fuse to create a heavier element and release great energy (A. Gabbar et al., 2018).

Apart from nuclear fusion, there is also the more familiar process of nuclear fission, which involves splitting the nuclei of heavy elements. The most well-known instance is uranium, by which the nucleus of this element is divided into two smaller and more stable nuclei. Nuclear fission was discovered in Berlin in 1938, about twenty years after atomic fusion, by two German physicists, Otto Johann (1879-1868) and Fritz Strassmann (1902-1980). Fusion is conceptually a relatively straightforward process; it is much easier than fission and much cleaner. A smaller amount of radioactivity is released in the fusion process, and the additional radioactive products will be manageable (Reinders, 2021). Early progress in fusion devices to produce energy was hampered; all fusion research, like fission research, not merely being for weapons development, but also power generation, was kept classified until the late 1950s. As a tangible example, the United States was concerned that fusion reactors could be used as a neutron source to produce bomb fuel, as a trigger for most fusion research in the early days was the production of bombs for thermonuclear weapons (Rampal & Chaisson, 2023). Fusion energy is expected to be a path to energy security for thousands of years. Nuclear fission and fusion reactors do not release greenhouse gases into the atmosphere and play a crucial role in fighting climate change (Mathew, 2022).

The expeditious developments of engineering sciences, which itself is caused by the breadth of vision and the use of the most recent scientific breakthroughs, as well as the vast industrial and economic development in the world, indicate the urgent need to recognize and develop advanced technology in the optimal use of energy resources, management and saving (Ghorashi & Sadigzadeh, 2015). Based on the significance of including different dimensions in identifying emerging fields related to fusion technology, a bibliometric study of global (international) scientific outputs can determine the structure, concepts, and components of a scientific field and the dynamics of science and technology. The outcomes will ultimately be effective in helping policy-making and research planning for the optimal use of financial and human resources at the local (national) level. In the present research, at first, the principal concepts related to fusion technology and a review of the literature will be conducted. Afterward, the presentation of the methodology and the main objectives of the research, such as "scientific production trends," "international country cooperation", "vocabulary co-occurrence network", "participation structure" and "thematic evolution" will be discussed. The current analysis specifically addresses these questions:

Research Questions

1. How has the volume of scientific production changed over time in the "Nuclear Fusion

Technologies" field?

2. What is the country’s international collaboration based on corresponding authors in the faculty members’ appraisal system?
3. What are the key patterns and trends observed in the connections between top journals, countries, and institutions?
4. What are the central or most influential terms within the co-occurrence network?
5. How have research themes or topics evolved in the field?

Literature Review

Nuclear fusion can be accomplished in various approaches, provided the fuel is compressed to a sufficient density and heated to an adequate temperature for enough time. However, two main experimental approaches, magnetic confinement fusion, and inertial confinement fusion, have received more recognition for developing fusion technology. Governments adopt these two technical methods and private companies and huge investments have been made in them. Meanwhile, the role of the public sector in private projects is vital, and cooperation between the private and public sectors is emphasized in advancing nuclear fusion technology (Meschini et al., 2023). In the following, these two approaches are examined as the most critical and common approaches to nuclear fusion. Additionally, a review of nuclear fusion technologies is provided, focusing on private sector developments in magneto-inertial confinement concepts for industrial applications.

Investigating the development of nuclear fusion technology applying the Magnetic Confinement Fusion (MCF) approach

The pioneering approach in nuclear fusion is magnetic confinement, presented at the "Atoms for Peace" conference in 1958 in Geneva. Nuclear fusion was a small part of this conference despite being at the center of attention. In previous years, only three countries, the United States, the United Kingdom, and the Soviet Union, conducted wartime research on the atomic bomb using nuclear fusion research programs in classified (Reinders, 2021). However, the progress was lagging, and it was argued that secrecy served no purpose; because nuclear fusion had no direct military application, the conference, primarily concerned with nuclear fission, served to lift this secrecy.

The conference turned into an immense exhibition where the United States and the Soviet Union tried to impress the public with their achievements, including the model Spitzer Stellarator. The Soviets also published all their research in four volumes swiftly translated into English to make it accessible to the rest of the world. This led to the first wave of activities in which, apart from the three foremost pioneers of nuclear fusion, an increasing number of other countries began to participate (ibid), and companies that put the design of fusion devices for commercial applications on the agenda grew significantly (Meschini et al., 2023).

After a decade of preliminary experiments with various devices, including various types of tokamaks, inverse field pinch devices, stellarators, and magnetic mirrors, the late 1960s witnessed the development of the tokamak. The Soviets, who invented the tokamak in the early 1950s, presented their results with the T-3 tokamak at the 1968 Novosibirsk conference. This was the second pivotal date and turning point in the story of nuclear fusion. Several countries, even relatively small ones, once conducted some nuclear fusion programs with tokamaks;.

However, fusion machines have become more extensive and consequently more costly, these programs have become longer. While some major countries, especially the United States and Russia, have significantly reduced their other programs to achieve nuclear fusion (Reinders, 2021).

Sadowski, Jakubowski, and Szydlowski (2004), in research entitled "Adaptation of selected diagnostic techniques to magnetic confinement fusion experiments," published in the Czech Physics Journal in 2004, emphasized the importance of these techniques in understanding the complex behavior of plasma in fusion and potential devices. They emphasize improving the efficiency and reliability of nuclear fusion technology. This study provides insights into the challenges and opportunities associated with implementing these diagnostic techniques in magnetic confinement fusion experiments and recommends areas for further research. Overall, this paper contributes to the emerging paradigms of nuclear fusion technology by emphasizing the critical role of diagnostic techniques in advancing our understanding of plasma behavior and improving the performance of fusion devices.

From another point of view, Huang and Li (2018) presented a brief overview of magnetic confinement fusion (MCF) technology. They proclaimed that there is a promising approach to producing clean and sustainable energy through nuclear fusion reactions. The authors discuss the principles of MCF, the current state of MCF research and development, and the challenges and opportunities encountered in this field. The method employed in this review is a literature search, which includes a comprehensive analysis of scientific articles, conference proceedings, and reports related to MCF technology. The authors reviewed more than 100 references published between 2010 and 2018, focusing on recent advances in MCF research. The population of this review includes the global community of researchers and professionals involved in the field of MCF technology. This research provides a brief and informative overview of MCF technology, covering its history, current status, and prospects. It is an applicable resource for researchers, policymakers, and stakeholders interested in understanding the potential of MCF as a sustainable energy source.

Kim, Hong, and Jung (2019) examine the ability of a country to participate in large scientific projects, mainly focusing on nuclear fusion research. The authors argue that multidisciplinary cooperation is necessary for the success of such projects and propose a framework for evaluating a country's capacity in this field. This investigation uses South Korea as a case study analyzes the country's progress in nuclear fusion research, and identifies areas that require improvement. The authors suggest that their framework can serve as a practical tool for policymakers and researchers to assess and enhance national capabilities in large multidisciplinary scientific projects.

Investigating the development of nuclear fusion technology applying the Inertial Confinement Fusion (ICF) method

Inertial Confinement Fusion (ICF) has always been the prominent method of achieving nuclear fusion and magnetic confinement. Of course, since it has always been a part of weapons research, the majority of the information related to it was classified, and some of this information is still confidential. However, in December 1993, a proposed legislation was passed to declassify much research related to inertial confinement (Hirschfeld, 2009). The original idea of inertial confinement fusion goes back to the hydrogen bomb, which reveals that fusion could be initiated by a sufficiently strong compressive force on a small amount of fuel. The first step in this field was taken in 1951 by the second atomic bomb test in Operation George, which was the world's first thermonuclear fuel (Reinders, 2021).

The idea behind ICF was first explored to build a hydrogen bomb. In this method, the fuel is compressed and heated quickly, providing fusing conditions before the fuel runs out. The inertia of the fuel (the tendency of a physical object to resist any change in its motion, either in the magnitude or direction of such motion) delays its escape. It causes the fuel to burn significantly before an explosion occurs. Explodes the target, burns, and releases energy. Therefore, the challenge of ICF as an energy source is to reduce the efficiency of the thermonuclear explosion to values that can absorb its energy and convert it into electricity. Like all energy-generating devices, nuclear fusion using the ICF method is also contingent on energy balance (ibid).

The paper entitled "Nuclear Detection for Inertial Plasma (ICF) by Frenje (2020) provides an overview of the development of nuclear diagnostic in ICF research from its beginnings in the 1970s to the present day. As ICF facilities have evolved and fusion efficiencies have increased, the complexity and requirements of nuclear diagnostics have increased. This paper discusses the rudimentary physics of the nuclear phase of an ICF explosion and the role of nuclear diagnostics in comprehending its performance. This includes the various types of nuclear diagnostics, such as neutron detection, gamma ray, charged particle, and radiochemistry, employed in ICF research over time, as well as current and next-generation nuclear diagnostics. This paper concludes that the progress of nuclear diagnostics and scientific understanding of ICF explosions has not been merely significant. Still, the next generation of nuclear diagnostics will also play a critical role in advancing ICF research in the future.

Furthermore, the research conducted by Gatu et al. (2017) debated the development of a platform to study nuclear reactions producing charged particles related to nuclear astrophysics by applying inertial confinement fusion explosions at the OMEGA Laser Facility and the National Ignition Facility. This platform focuses on optimizing explosions for high efficiency while maintaining a low surface density so that charged fusion products can escape easily. Advancements in inertial confinement fusion (ICF) have led to growing interest in Laser Inertial Fusion Energy (LIFE) as a potential solution for carbon-free, large-scale power generation. LIFE has the potential to provide clean energy with zero greenhouse gas emissions and an abundant, non-exhaustible thermonuclear fuel source. For LIFE to become a viable energy option, minimizing costs while optimizing target material efficiency or x-ray albedo is crucial. Current ICF targets at the National Ignition Facility (NIF) employ gold or depleted uranium cylindrical radiation cavities (hohlraums) with deuterium-tritium fuel encapsulated in a central plastic capsule. In this context, we compare the efficiency of gold and lead hohlraums in ablating deuterium-filled plastic capsules using soft X-rays. Our findings demonstrate that lead hohlraums perform as effectively as gold ones, yet at a significantly lower cost, which could substantially impact the feasibility and sustainability of LIFE-based power generation (Ross et al., 2013).

Investigating the development of nuclear fusion technology applying the Magnetic Inertial Confinement (MIF) method

Although MTF and MIF are frequently used interchangeably, the two concepts are not equivalent. The term MIF covers a broader range of equipment. MTF, however, is classified as a form of MIF. They are similar since both combine the features of the two main approaches: magnetic confinement fusion and inertial confinement fusion. The primary ideas behind MIF have been around for a long time. MIF involves creating a small-scale hot magnetic plasma target and rapidly detonating it, the same as inertial confinement fusion.

Lindström, Barsky, and Wetton (2015) examined magnetic target fusion (MTF), a type of nuclear fusion technology that uses high magnetic fields for compression. The magnetized plasma of the authors' model consists of a spherically symmetric domain with moving boundaries, which they solve numerically using a coordinate transformation and a flux-bounded finite volume method. This study aims to prove the feasibility of this technique and estimate the optimal conditions for successful fusion. The authors' work contributes to the development of research on MTF, which has illustrated significant progress due to improved technology and engineering methods.

Magnetized target fusion (MTF) is a pulsed approach to fusion that combines pressure heating in inertial confinement fusion with magnetic heat transfer and magnetically enhanced alpha heating from magnetic confinement fusion. Currently, a wide range of MTF systems are being investigated and typically utilize a magnetic field to confine the plasma and intensive heating generated by laser or mechanical liner implosion. As a result, in this hybrid approach, plasma confinement time is shorter than magnetic confinement time (Dahlin, 2001).

Corresponding to the problems with any fusion reactor design, there are problems with the commercialization of MTF. In this method, the requirement to form high-power magnetic fields in the center of the device conflicts with the need to extract heat from the inside and challenges the physical arrangement of the reactor. In addition, the melting process emits a large number of neutrons, at least in common reactions, which reduce the strength of the support structures and the conductivity of the metal wiring. Another problem is that the metal liners employed in the MTF are consumed during the reaction for the device to generate electricity. However, the value of that electricity is meager; In fact, the device must consume a lot of electricity (ibid). However, the research conducted by Howard, Laberge, McIlwraith, Richardson, and Gregson (2009) provided an analytical study on the emerging patterns of nuclear fusion technology, which is used as magnetic target fusion (MTF) plasma, with a strong focus on the development of integrated compact chips (CTs).

Abedi-Varki (2023), in an article titled "Laser-Plasma Interaction: A Bibliometric Study," conducts a comprehensive analysis of laser-plasma interaction literature operating bibliometric methods. The study covers 50 years, from 1973 to 2022, and includes over 10,000 articles from various scientific databases. The researcher examines trends in research topics, collaboration patterns, author productivity, and citation criteria. The results indicate that the field of laser-plasma interactions has experienced significant growth in recent years, with a considerable increase in publications and citations. The study also highlights the emergence of new subfields, such as high-intensity laser-plasma interactions and intense UV sources. In general, valuable insights about the evolution and current state of the field that can inform future research strategies and resource allocation decisions are raised.

MCF, ICF & MTF comparison

The conventional pathways to fusion-MCF and ICF-have proven to be very long and expensive. These two approaches are now embodied in two multi-billion-dollar facilities, ITER (International Toroidal Experimental Reactor) for MCF and NIF (National Ignition Facility) for

ICF (Lindemuth & Siemon, 2006). Magnetized target fusion (MTF) is an alternative approach to fusion in which plasma lifetime and density are those between inertial confinement fusion and magnetic confinement fusion (Li, Zhang & Yang, 2014). Additionally, this approach serves to achieve the objective of controlled fusion. It harmoniously integrates the benefits of magnetic and inertial confinement fusion, as its parameter range is situated between the two conventional techniques. (Li et al., 2016).

Nuclear fusion, the process that powers the Sun, has the potential to provide an almost unlimited and clean source of energy. However, achieving fusion conditions on Earth is challenging due to the extreme temperature and density required. Two main experimental approaches, magnetic confinement fusion (MCF) and inertial confinement fusion (ICF), have engrossed considerable attention recently, as private companies have invested remarkably in their development. The innovation of the present research deals with the bibliographic review of scientific outputs at the global (international) level to identify the structure, concepts, and components of the scientific field of nuclear fusion and the dynamics of science and technology in this field.

Materials and Methods

According to the selection of the bibliometric approach, the source of data collection was the Clarivate Analytics WoS database, whose primary information in the field of fusion technology systems in all fields of human knowledge is described in Figure 1. This study was conducted from 1991 through 2023, in which a total of 668 articles were extracted, with an average of 17.19 citations/article, the average age of the document was 10.08, and a total of 18708 references were extracted (Figure 1).

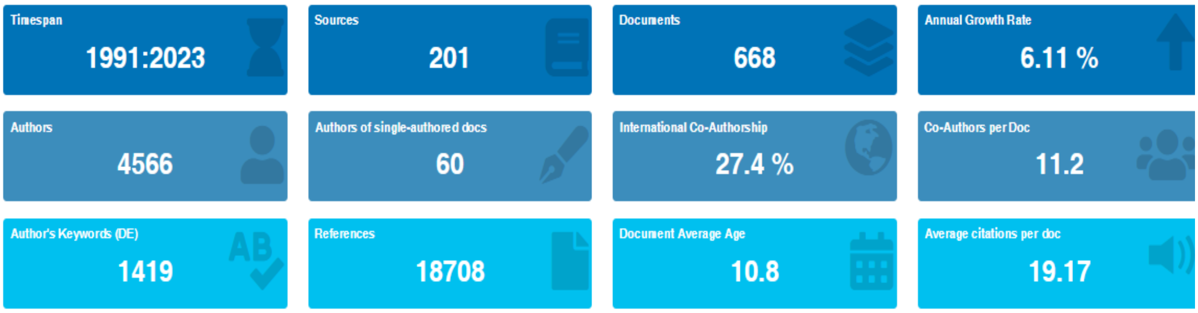

Figure 1: The Main Obtained Information Focused on Developing Nuclear Fusion Technology

The search strategy for obtaining research data was such that keywords related to the field of fusion technology were entered in the subject field and searched in all Clarivate Analytics Web of Science databases on August 2, 2022. The result of this search, after limiting the type, language, and period of the retrieved documents to articles and English language from the beginning to the end of 2021, was 668 articles that formed the statistical population of this study. Search fields included article title, abstract, and keywords. An integral component of the research process, the search strategy guarantees the thoroughness and reliability of the study. In the subsequent stages of the current study search strategy, it is displayed in a gray hue to facilitate recognition and promote transparency.

TS=(("inertial confinement fusion" or ICF or “Magnetic Confinement Fusion” or MCF or “magneto-inertial fusion” or MIF or "Magnetized Target Fusion” or MTF) and ("Fusion energy" or "plasma physics" or "Nuclear fusion" or “Nuclear Technology*" or " Nuclear Science " or “Nuclear energy" or “Nuclear physics" or “Nuclear Reactor" or “Nuclear Material" or “Nuclear Engineering" or "Fusion System" or “Nuclear Technology*" or “Nuclear Reactor" or "Fusion reaction" or "fusion plasma" or "Fusion physics " or "Fusion Engineering" or "quantum Engineering" or “Reactor physics” or “tokamak physics” or "Magnetic Fusion" or "Inertial Fusion" or “ignition temperature” or "magnetic field" or "Nuclear Fission Energy" or "fission reaction" or "fission Technology*") and (emerging or current or present or modern or running)).

The indicators studied in this research were "scientific production trends," "international country cooperation," "vocabulary co-occurrence network," "participation structure," and "thematic evolution," which in the following, from the databases of Clarivate Analytics Web of Science were extracted. The enumeration method was used in this research, and sampling was not conducted. Each document included bibliographic characteristics: author names, affiliations, title, keywords, journal, year, volume, issue, pages, editor(s), and number of citations. For data analysis, descriptive statistics and scientometric methods along with tables and graphs were used, and to draw social analysis networks, Rstudio and Bibliometrics software were employed.

To achieve research findings, various methods were used to analyze and quantify scientific research, including:

1. Bibliometrics: This method has been used to analyze the output of research and the trend of scientific publications in the field of study.

2. Time Series Analysis: Analyzing scientometric data over time can help identify trends, cycles, and patterns in research productivity, collaboration, and impact.

3. Analyzing the collaboration patterns among authors, countries, and Institutions can provide insights into research networks, topic dynamics, and the distribution of expertise within a field.

4. Keyword Analysis: Identifying and tracking the frequency and distribution of keywords in scientific publications can reveal emerging research themes, topics, and conceptual shifts.

5. Structure Analysis: This method represents relationships between journals, institutions, or countries as nodes and edges in a network, allowing for studying structural properties and patterns.

6. Visualization Techniques: Various visualization techniques, such as scatter plots, Sankey diagrams, and maps, are used to represent and explore complex scientometric data in a more accessible and interpretable manner.

7. Evolution of Scientific Fields: Investigating how research themes and topics have evolved within specific disciplines or across multiple fields.

Results

1. How has the volume of scientific production changed over time in the "Nuclear Fusion Technologies" field?

Figure 2 illustrates the volume of annual scientific productions in the field of fusion technology. Based on the findings related to the trend of scientific production, the average growth rate of research in two years was 11.6 percent.

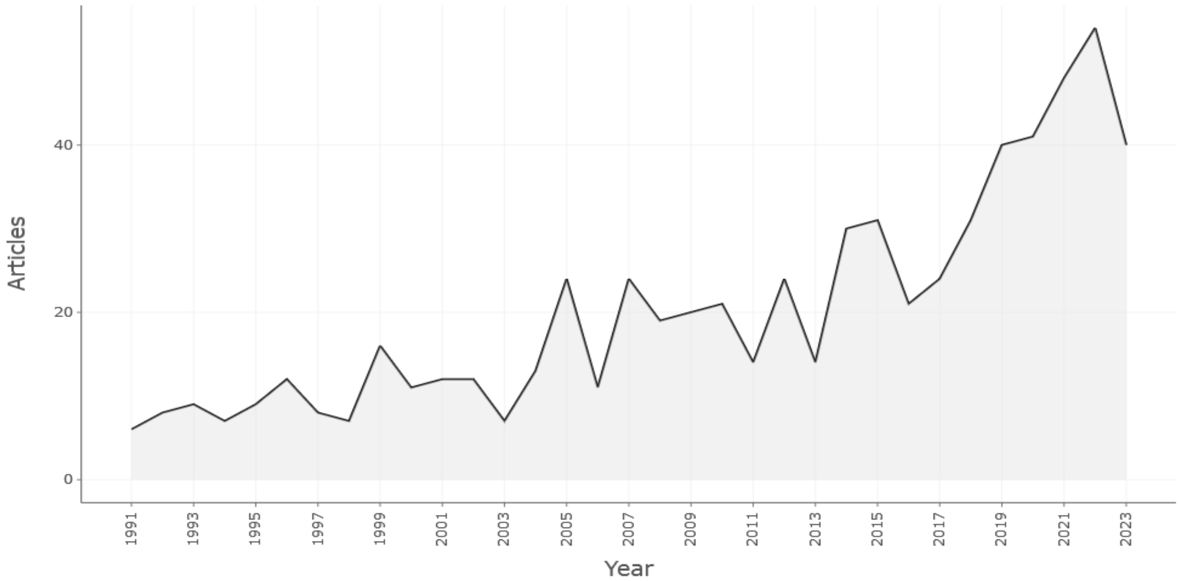

Figure 2: Annual Scientific Production Related to Nuclear Fusion Technology

This study shows that although the expansion of studies in the field of fusion technology has been prevalent in the past years, there have been drops in various periods such as 2002-2003, which is in contrast to its significant increase, especially from 2016 onwards is not very impressive (Figure 2). Besides, based on the rising rate, it was found that although the production of this field is increasing, this escalation happened gradually. Therefore, the growth rate graph indicates a sinusoidal growing trend in this area.

2. What is the country's international collaboration based on corresponding authors in the faculty members' appraisal system?

Figure 3 indicates the country of the authors corresponding to the studied field. The correspondent is the author who sends the article to the journal's editor and handles all correspondence with them. Likewise, their email address usually appears on the article's first page and serves as the author's communication with other interested researchers (Mattsson, Sundberg & Laget, 2011). In other words, the cooperation of different countries in a field of study is identified through the affiliation of the corresponding authors to the countries.

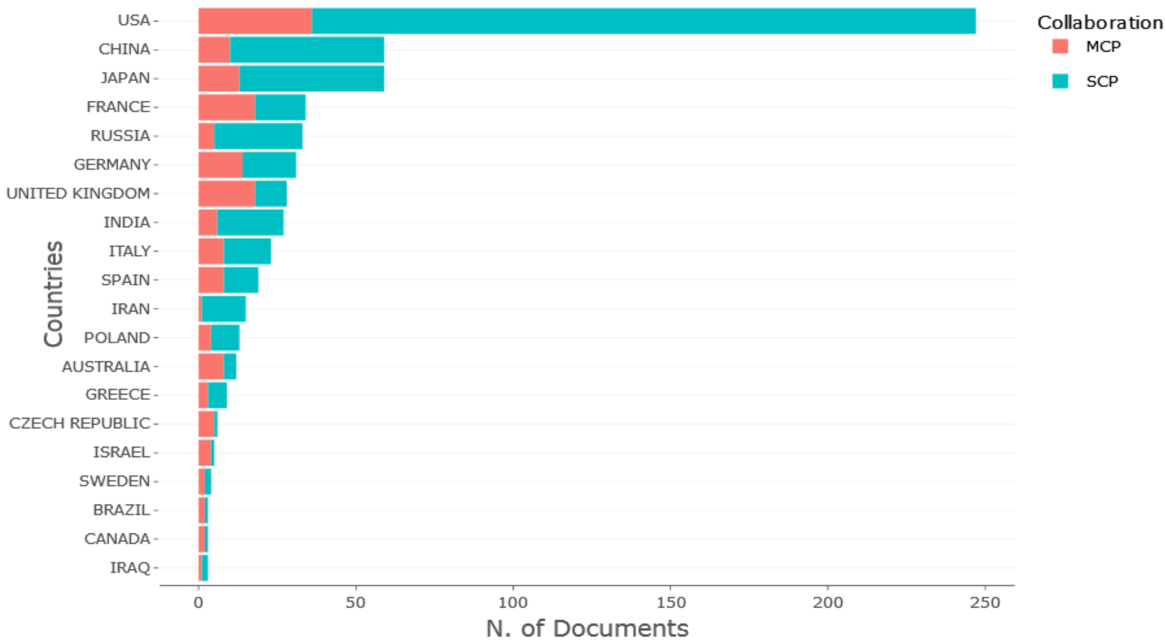

Figure 3: The Status of Corresponding Authors' Single Country Publication (SCP) and Multiple Country Publication (MCP)

National scientific production and cooperation networks are shown in Figure 4. The blue color on the map indicates the presence of publications for a particular country on the research topic, and the gray color designates the absence of journals in that country. States in darker blue represent more issuing countries, and red lines illustrate the collaborating networks of issuing countries. The country that has most actively cooperated is the United States. As the country with the most publications, the authors of this country have a high common scientific output.

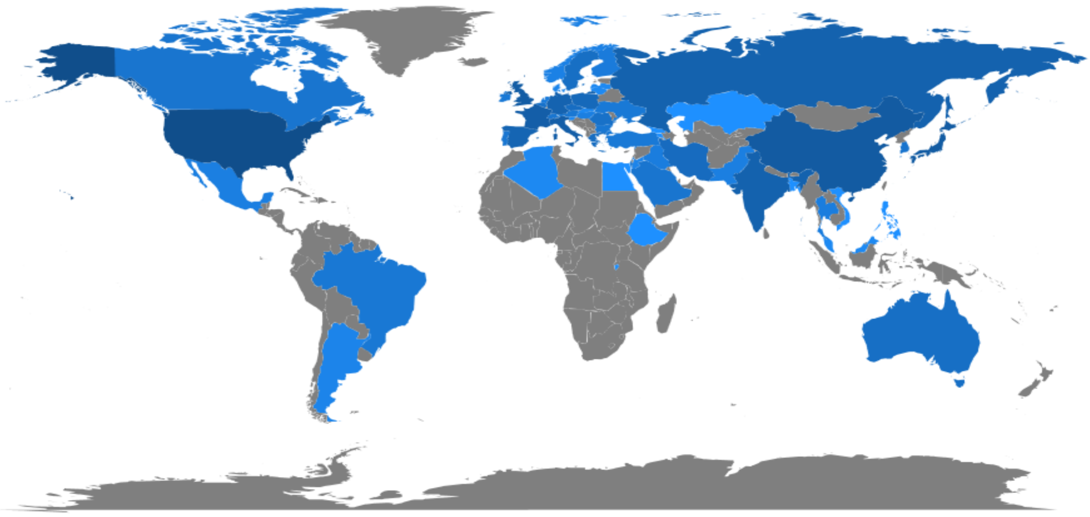

Figure 4: International Collaboration Map in the Field of Nuclear Fusion Technology

3. What are the key patterns and trends observed in the connections between top journals, countries, and institutions?

In Figure 5, the performance of the 10 most productive countries and universities with the top 10 publishing sources is summarized through a three-axis design. This figure presents the idea of the relative participation of institutions in a country's overall research output.

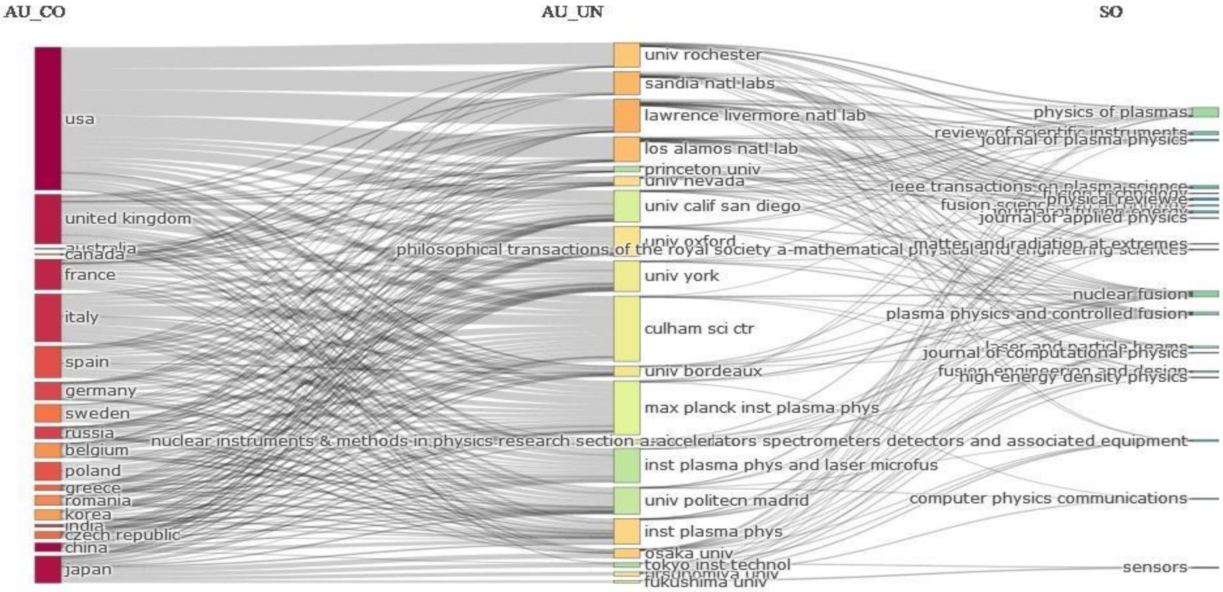

Figure 5: Triple Axis Map of Top Journals, Countries, and Institutions

For the United States, most of the research institutes and top universities presented significantly contribute to the country's total publications, while the scenario is different for other countries. Interestingly, Spain and South Africa have no dominance of any particular institution in scientific production. Interestingly, Canada and Australia have had the least cooperation in this field. At the same time, the distribution of publications among different institutions is evident and shows the diversity of institutional contributions in the total number of publications at the international level. From the point of view of publishing sources (publications), Plasma Physics is the highest-release publication, primarily by authors from all leading countries, and the publications in other publications are randomly distributed among different publishing countries.

4. What are the central or most influential terms within the co-occurrence network?

The co-occurrence of words in a document indicates its content; as a result, if the amount of this co-occurrence is measured, the concept network of a scientific field can be drawn. The red cluster with the keyword "Inertial Confinement Fusion" is in the center of the map and is instructed by creating close relationships with the words "Goals," "Design," and "Energy." The green cluster is led by the keyword "plasma," which is closely related to the words: "ignition," "laser," and "physics basis." In the yellow cluster, the dominant word is "physics," with links to the words: "fusion," "density," and "magnetic confinement." Finally, the blue color cluster consists of the words: "nanoparticles," "drug delivery," and "therapy." On the other hand, it can be explained that the mediation of nodes, such as plasma, energy, radiation, etc., are the essential components of the fusion process, which makes it possible to achieve the fusion process (Figure 6).

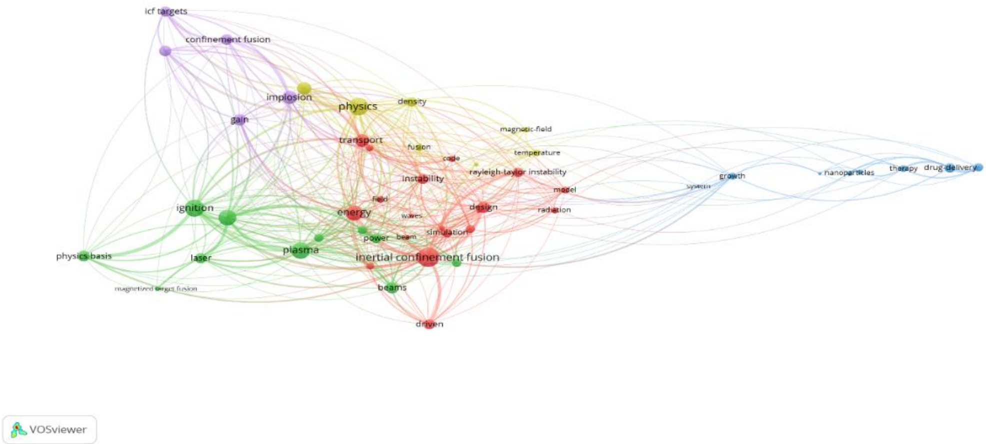

Figure 6: Keywords Co-occurrence Network

5. How have research themes or topics evolved in the field?

Furthermore, this research presents the evolution of topics in time to obtain deeper information about various topics. Based on the research process, the application of text mining is divided into two stages: 1991-2014 and 2023-2015 (Figure 7).

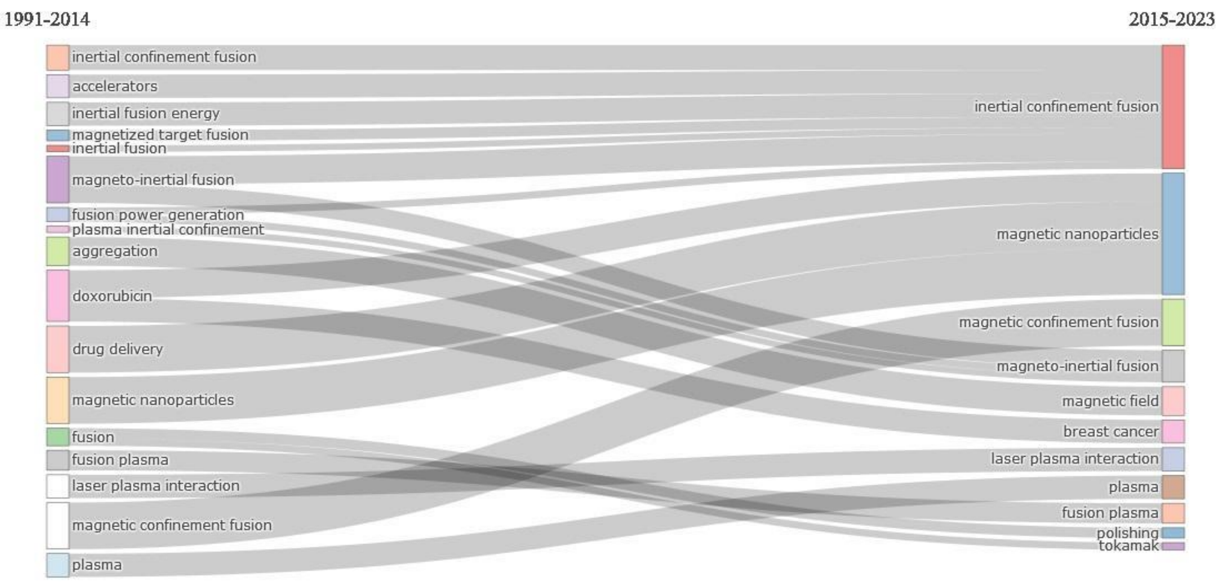

Figure 7: Thematic Evolution

Subsequently, the results are presented as a strategic diagram, as shown in Figures 8 and 9, to analyze the most prominent issues for each sub-period. Figures 8 and 9 show a set of topics organized in a two-dimensional space based on their centrality on the x-axis and density on the y-axis (Cobo, López-Herrera, Herrera-Viedma & Herrera, 2011). In these spatial representations, the volume of the spheres is also depicted in proportion to the number of documents related to each topic. Engine themes, which are highly interconnected and essential to the field structure, are located in the upper right quadrant of the map. These themes are well-developed and characterized by keywords that often occur together (Aria & Cuccurullo, 2017).

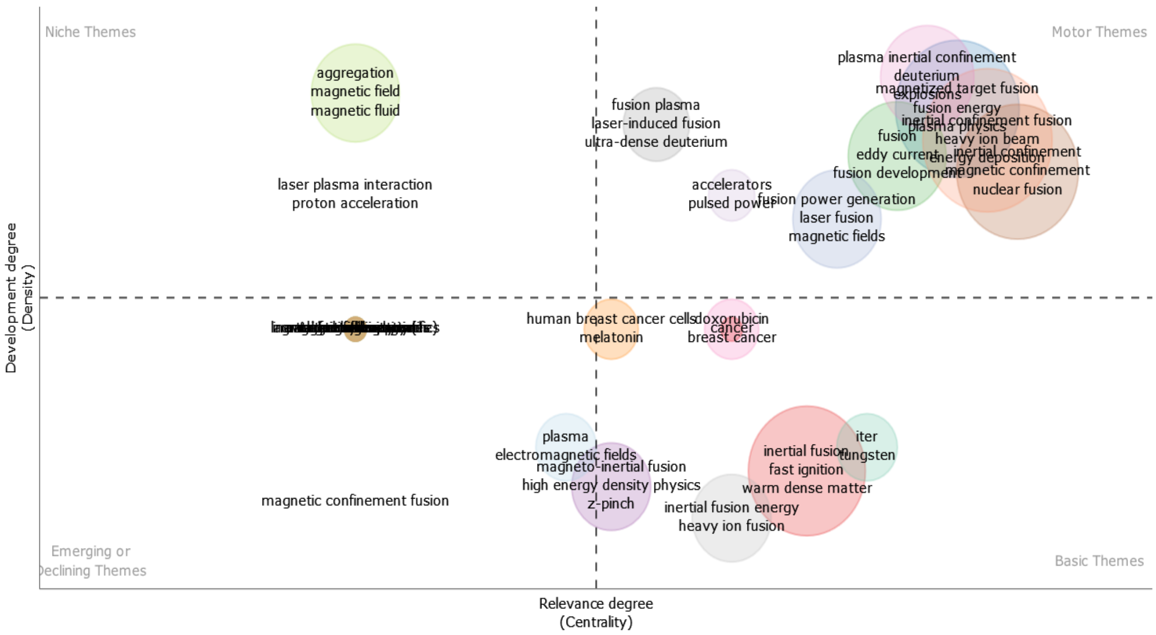

Figure 8: Strategic Diagram of the First Stage of Literature (1991-2014)

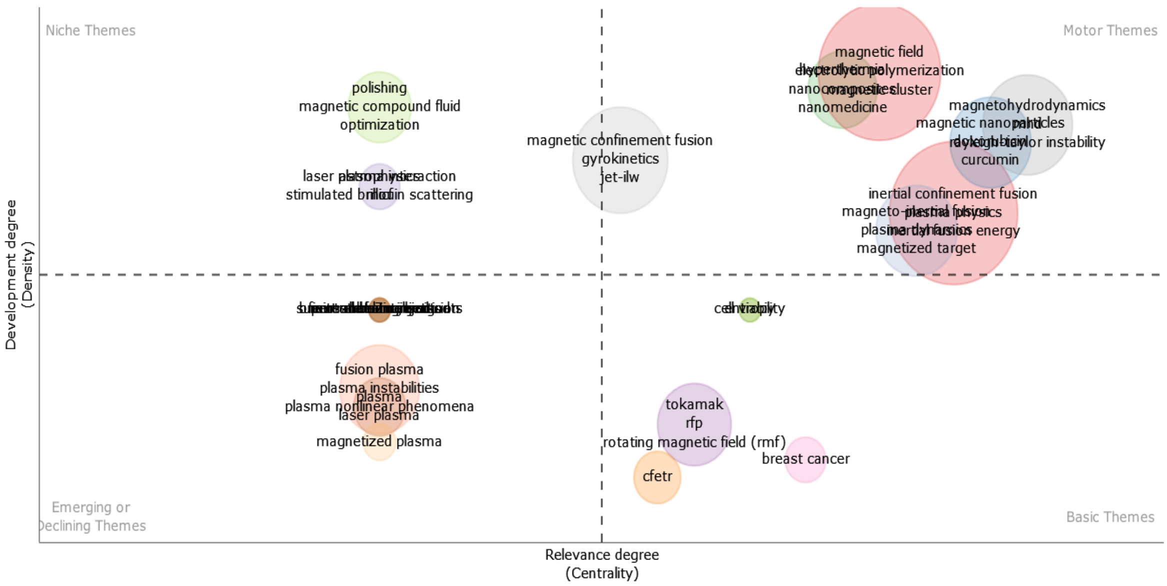

Figure 9: Strategic Diagram of the Development Stage (2015-2023)

Each research topic in the strategic diagram has two parameters. The former is the parameter represented by the horizontal axis, called "centrality," and is the strength of the external connection between the themes. We can acknowledge it as a parameter to measure the importance of the topic in the development of the entire field of research. The latter is a parameter shown by the vertical axis called "density," which is the strength of the connection between keywords in the subject. It can be understood as a parameter to measure the degree of the subject. In this sense, the upper right quadrant of the strategic diagram illustrates themes with high density and centrality, indicating that these themes are well-developed and paramount for building the research field.

The lower right quadrant of the strategic diagram contains themes with high centrality but low density, and these themes are essential to the development of the research field, though they need to be better developed and are generally fundamental topics in the research field. The upper left quadrant of the strategic diagram contains themes with high density but low centrality. It demonstrates that these themes are well-developed but have a limited impact on the research field. The majority of these themes are side themes or extremely specialized themes. The lower left quadrant of the strategic diagram highlights the low density and centrality of themes, indicating that both the importance and development of these themes are weak and that themes may be emerging or disappearing in this context.

On the other hand, Tables 1 and 2, with information about the performance values (CallonCentrality, CallonDensity, RankCentrality, RankDensity, and ClusterFrequency), have been mentioned to provide an overview of the impact of themes in each of the periods, which, in other words, provides additional details on each of the themes in Figures 5 and 6.

Table 1
Indicators of the Period 1991–2014

Cluster	Callon Centrality	CallonDensity	Rank Centrality	Rank Density	Cluster Frequency
inertial confinement	1.338095238	62.58571429	29	23	33
inertial confinement fusion	0.757916667	70.72916667	28	25	41
magnetized target fusion	0.694444444	85.31144781	27	27	35
plasma inertial confinement	0.666666667	109.5238095	26	29	15
fusion	0.494885362	64.44444444	25	24	17
ITER	0.458333333	43.75	24	5.5	6
fusion power generation	0.444444444	60	23	20	13
inertial fusion	0.286210317	41.89814815	22	4	29
doxorubicin	0.25	50	19.5	13	5
inertial fusion energy	0.25	25	19.5	1	10
cancer	0.25	50	19.5	13	2
accelerators	0.25	62.5	19.5	21.5	4
fusion plasma	0.166666667	72.22222222	17	26	7
magneto-inertial fusion	0.111111111	39.81481481	15.5	3	10
human breast cancer cells	0.111111111	50	15.5	13	5
plasma	0.0625	43.75	14	5.5	6
aggregation	0	94.44444444	7	28	13
IFE	0	50	7	13	2
imaging	0	50	7	13	2
lagrangian hydrodynamics	0	50	7	13	2
avalanche-like quench	0	50	7	13	2
drug delivery	0	50	7	13	2
magnetic nanoparticles	0	50	7	13	2
target fabrication	0	50	7	13	2

Cluster	Callon Centrality	CallonDensity	Rank Centrality	Rank Density	Cluster Frequency
inertial fusion energy (IFE)	0	50	7	13	2
tritium inventory	0	50	7	13	2
magnetic confinement fusion	0	33.33333333	7	2	3
laser-plasma interaction	0	62.5	7	21.5	4
magnetic levitation	0	50	7	13	2

Table 2
Indicators of the Period 2015–2023

Cluster	Callon Centrality	Callon Density	Rank Centrality	Rank Density	ClusterFr equency
inertial confinement fusion	0.659386973	60.24790184	22	16	91
magnetic field	0.480952381	146.7335004	20	24	74
magnetic confinement fusion	0.075	65.31746032	13	19	28
magnetohydrodynamics	1	78.61111111	24	21	23
magnetic nanoparticles	0.819444444	73.21428571	23	20	17
magneto-inertial fusion	0.483333333	57.8	21	15	17
fusion plasma	0	46.13095238	6.5	6	16
tokamak	0.216666667	36.80555556	15	4	13
hyperthermia	0.416666667	90	19	23	11
polishing	0	79.16666667	6.5	22	9
plasma	0	38.88888889	6.5	5	6
CFETR	0.166666667	20	14	1	5
breast cancer	0.395833333	25	18	2	4
laser-plasma interaction	0	62.5	6.5	17.5	4
astrophysics	0	62.5	6.5	17.5	4
magnetized plasma	0	33.33333333	6.5	3	3
finite element method	0	50	6.5	10.5	2
cell viability	0.25	50	16.5	10.5	2
superconducting magnets	0	50	6.5	10.5	2
mcf-7 cells	0	50	6.5	10.5	2
entropy	0.25	50	16.5	10.5	2
bremsstrahlung emission	0	50	6.5	10.5	2
neutral beam injector	0	50	6.5	10.5	2
neutral beam injection	0	50	6.5	10.5	2

In the period of 1991-2014, the significant issues that can be mentioned under the heading of movement themes are 1) Inertial Confinement Fusion (ICF) and 2) Magnetized Target Fusion (MTF) methods. However, from 2015 to 2023, Motion themes are assigned with the priority of functional value in the following order which reveals the activity of the two areas of ICF and MTF under the title of motor themes of communication with current global challenges for a long time.

1. Inertial Confinement Fusion (ICF),
2. Magnetic Confinement Fusion (MCF),
3. Magneto-Inertial Confinement Fusion (MIF),
4. Magnetized Target Fusion (MTF)

As shown in Figure 6 and Table 2, the concept of inertial confinement fusion (ICF) is the most frequent theme in the center of the map, which shows its importance over many periods.

Between 1991 and 2014, the concept of fusion by magnetic-inertial confinement (MIF) was one of the topics on the border between emerging and underdeveloped quadrants. In the next period, this topic was promoted to the field of development of the fusion field. Likewise, MCF has found a preferable performance value to MIF, which had almost the same status and was considered among the emerging themes.

Ultimately, from 2015 through 2023, all the desired themes are mentioned in the form of motor themes, and none of those as mentioned earlier, themes have become isolated and highly developed. Of course, according to Figure 8, the functional position of MCF, which is placed between the two quadrants of development and lateral and specialized, should not be neglected, because it shows that this theme is well developed, which has become a lateral or highly specialized theme.

Discussion

The main focus on environmental issues has been due to the growth of fossil energy consumption, which pollutes the environment. Accordingly, increasing energy consumption for economic growth has led to raising the earth's heat by releasing carbon dioxide gas into the atmosphere. Therefore, one of the pivotal priorities of the energy policy is to diversify energy sources and find a safe and economical energy source that does not emit greenhouse gases; as (Mathew, 2022) pointed out, their essential role in reducing climate change. The future world will have no alternative but to use nuclear energy to provide a significant part of its energy consumption.

The increasing development of exploitation of the advantages of peaceful nuclear technology, particularly in recent decades, and its wide-ranging effects in providing the welfare of human societies has led to the expansion of the activities of the Atomic Energy Organization of Iran to benefit the country from the advantages of this innovative technology, has been accompanied by rapid growth and the establishment of the undeniable rights of the current and future generations of Islamic Iran should be put on the agenda with strength and firmness. Long-term planning to produce nuclear electricity, complete the fuel supply chain required by power plant units, the increasing development of the employ of radiation in the fields of health and treatment, industry, and agriculture, besides create a suitable platform for the optimal use of the existing facilities and capacities in the field of science. Laser and quantum techniques are a part of the vision drawn to advance the global objectives of the nuclear industry. Ross et al. (2013) highlight Laser Inertial Fusion Energy (LIFE) as a potential solution for large-scale, carbon-free electricity generation.

Expanding knowledge, dealing with unanswered questions, innovation and problem-solving, interdisciplinary collaboration, and keeping pace with social changes can be called vital reasons for addressing new fields of study and exploring emerging fields of any kind. The field of nuclear energy is not an exception which expands the boundaries of knowledge and contribute to the collection of available information with many explorations. This expansion leads to a deeper understanding, new theories, and novel perspectives. Furthermore, emerging fields often arise from unanswered questions or gaps in existing knowledge, and by studying these fields, researchers can fill the gaps and provide insights that have not been explored before. This process helps to modify existing theories and paradigms. Based on the importance of including contradictory dimensions and levels in the process of identifying emerging fields related to fusion technology, the bibliometric study of the field of scientific outputs at the global (international) level can identify the structure, concepts, as well as components of a scientific field and the dynamics of science and technology. It portrays and finally identifies innovative approaches and technologies to meet social expectations that help practical applications and improve the well-being of individuals and societies. This analysis should provide researchers and science policymakers with a comprehensive picture of the thematic evolution of the subject. According to the results, the number of studies conducted in this field has increased yearly, and it is evident that the growth rate of WoS research between 2017 and 2022 has been growing. This finding is consistent with what Huang & Li (2018), Reinders (2021), and Abedi-Varaki (2023) have raised regarding the increasing trend of research as well as institutions and countries involved in this field. Therefore, we propose a research mapping based on network analysis in this study and descriptive and applied bibliometric studies of about 40 years. The explanatory and functional analysis results showed that, first, the United States of America, followed by China and Japan, have significant scientific capacity and an effective collaborative network that brings the most national and international cooperation.

According to the three-pronged plan, Canada has actively cooperated with all institutions. The journal Physics of Plasma is one of the primary sources in which the best countries and institutions have published materials. Co-occurrence analysis of keywords shows that the research literature is mainly related to the terms "Inertial Confinement Fusion", "Plasma", "Physics," "energy," and "ignition." Besides, based on Figure 5, the geographic distribution of companies (or public institutions) looking to design fusion devices for commercial applications provides an insight into where these projects are being developed globally, which can be used to understand regional trends in research. The fusion technology development efforts and potential opportunities or challenges related to the location of these projects are helpful, which is in line with the research results (Meschini et al., 2023). Accessibility, infrastructure, or regulatory frameworks that may affect their progress. However, thematic evolution analysis shows that given the increasing pace of energy demand in the world and the efficiency of nuclear energy compared to traditional sources, the desired research topics, including ICF, MCF, MTF, and MIF, have not remained on the theme of basic and undeveloped themes, conversely, have been developing rapidly.

Research limitations

1. **Data availability:** The study relies on scientific publications as its primary data source. This might exclude other relevant information sources, such as patents, industry reports, or government documents, which could provide a more comprehensive view of the field.
2. **Classified information:** The study might be constrained by the existence of classified or sensitive information related to nuclear fusion technology, which could be withheld from public-domain research. This may limit the comprehensiveness of the analysis and the

identification of trends and patterns in the field.

3. **Interdisciplinary perspective:** The research seems to focus on nuclear fusion's scientific and technological aspects. However, incorporating a multidisciplinary perspective, including social, economic, and environmental factors, could provide a more holistic understanding of the field and its implications.

4. **Influence of military applications:** The historical context of nuclear fusion research, driven partly by its potential military applications, might still influence the field's political landscape. This could create barriers to open collaboration and knowledge sharing, affecting the research's ability to capture the full scope of global efforts in nuclear fusion technology.

Conclusion

Over the past few decades, research into emerging nuclear fusion technologies has dramatically increased. This trend is evident from the increasing number of studies published since the 1990s, which aimed to provide a comprehensive and analytical perspective. Thematic mapping and conceptual evolution of this field is a basis for researchers to design their publication strategy based on motor, specialized, introductory, or emerging themes. This approach can guide future researchers in advancing the science of nuclear fusion technology. The conceptual evolution of this field illustrates that it has altered from basic research to applied research and technology development. This trend is expected to continue with the increase of nuclear fusion technologies in the coming years. Focusing on technology development makes it possible to commercialize nuclear fusion as a sustainable source of clean energy.

Research proposals

Based on the results of the intellectual structure mapping analysis, some suggestions for future research in the field of nuclear fusion technology are proposed:

1. **Development of more efficient and practical fusion reactors**: Fusion technology is still in the experimental stage, and more efficient and practical reactors that can produce a significant amount of power are needed. Future research should focus on improving the design and operation of fusion reactors, reducing costs, and addressing technical challenges such as materials science, plasma confinement, and heat management.

2. **Integration of fusion technology with renewable energy sources**: Fusion technology has the potential to provide a reliable and sustainable energy source, but it must be integrated with renewable energy sources to create a more sustainable and flexible energy system. Future research should explore integrating fusion technology with solar, wind, and hydropower sources to create a more efficient and reliable energy system.

3. **Environmental and social effects of fusion technology**: While fusion technology has the potential to provide a clean and sustainable energy source, it also has environmental and social effects that should be considered. Future research should focus on understanding these impacts, including radioactive waste disposal, the potential for nuclear accidents, and the social and economic implications of fusion technology.

4. **International cooperation and governance**: Fusion technology is a complex and expensive field, and international collaboration and management are needed to ensure its safe and responsible development. Future research should focus on understanding the governance and regulatory frameworks for fusion technology, including intellectual property, liability, and security issues.

5. Public Understanding and Acceptance: Fusion technology is a complex and often misunderstood field and requires public understanding and acceptance to ensure its successful development and deployment. Future research should focus on public awareness and acceptance of fusion technology, including risk perception, trust, and communication issues.

6. Training and development of the workforce: Fusion technology requires a highly skilled and specialized workforce, and it requires training and development of the workforce to ensure its successful development and deployment. Future research should focus on understanding the training and workforce development needs for hybrid technology, including issues related to training, certification, and career development.

7. Economic and financial aspects: Fusion technology is a complex and expensive field that needs monetary and financial aspects to ensure its successful development and establishment. Future research should focus on understanding fusion technology's economic and financial factors, including investment, financing, and economic analysis issues.

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Conflict of Interests

The authors claim to have no conflict of interest.

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