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Derleme / Review

Nanobilim ve Nanoteknoloji Eğitimi Araştırmaları Üzerine Bir Bibliyometrik Analiz

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Özet: Bu çalışmada, bibliyometrik haritalama analizi yoluyla nanobilim ve nanoteknoloji (NNT) eğitimi üzerine araştırmalardaki eğilimler ortaya konmuştur. Önemli sayıdaki makalenin analiz edildiği bu çalışma; yeni araştırmalar için bir rehber oluşturmayı, ilgili alandaki eğilimleri tanımlamayı ve mevcut araştırmaları kıyaslamayı hedeflemektedir. Bibliyomektik analiz için VOSviewer yazılımı kullanılmıştır. Web of Science veri tabanı kapsamındaki hakemli dergilerde 2001 ve 2021 yılları arasında yayımlanan toplam 196 makale bibliyometrik analize tabi tutulmuştur. Analiz sonuçları, incelenen makalelerde nanoteknoloji, aktif öğrenme, 3 ve 4. sınıf lisans öğrencileri, lisansüstü eğitim ve laboratuvar eğitimi kelimelerinin en sık tekrarlanan anahtar kelimeler olduğunu göstermiştir. Ayrıca Amerika Birleşik Devletleri, İsrail, Fransa ve Tayvan'ın NNT eğitimi üzerine en çok yayın yapan ülkeler olduğu anlaşılmıştır. Bununla birlikte çalışma, NNT eğitimi araştırmalarındaki son gelişmelerin ortaya konulması için kapsamlı bir inceleme de sağlamıştır.

Anahtar kelimeler: Nanobilim ve nanoteknoloji, bibliyometrik analiz, bibliyometrik haritalama

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GENİŞ ÖZET

Giriş

Richard Feynman, 1959'daki ünlü konuşmasında "küçük ölçekteki yapıları manipüle etme ve kontrol etme" üzerine odaklanan yeni bir araştırma alanını tanıtmıştır (Lin vd., 2015). Feynman'ın fikirleri nanobilim'in yeni bir araştırma alanı olarak gelişimini tetiklemiş,

sonraki yıllarda bu alan araştırmacılar tarafından büyük ilgi görmüştür. Bu ilginin bir sonucu olarak da nanobilim ve nanoteknoloji (NNT) son birkaç on yılda bir araştırma alanı olarak oldukça gelişmiştir. Bu alanın potansiyel ekonomik etkileri nedeniyle de birçok ülke NNT alanına yatırım yapmış ve günlük yaşamda yaygın olarak kullanılan nano ürünleri geliştirmiştir (Lin vd., 2015). NNT'nin geniş sosyal ve ekonomik sonuçları olduğu ve önümüzdeki yıllarda da devam edeceği yaygın olarak kabul görmektedir (Hingant & Albe, 2010).

NNT'nin hızlı gelişimine yanıt olarak birçok ülke, öğrencilerin NNT ile ilgili kavramları kavramalarını geliştirmek için bu alanları okul öncesinden üniversite seviyesine kadar fen müfredatına adapte etmiştir. NNT alanındaki gelişmeler üzerine farkındalığın artmasıyla NNT eğitimi alanı daha da önem kazanmıştır. Bu öneme binaen, bu çalışmada Web of Science üzerinden NNT eğitimi ile ilgili araştırmalara ulaşılarak bu araştırmalardaki eğilimlerin bibliyometrik haritalama yoluyla incelenmesi amaçlanmıştır. Mevcut literatür taraması araştırmalarından farklı olarak bu çalışmada, NNT eğitimi ile ilgili makalelerde kelimeler ve özet kısımlarında en sık tekrarlanan kelimeler, en çok alıntı yapılan araştırmacılar, dergiler ve ülkeler incelenmiştir. NNT eğitimine odaklanan ve çok sayıda çalışmanın analizine dayanan bu çalışmadan yeni çalışmalara yol göstermesi, alandaki eğilimleri belirlemesi ve konuyla ilgili mevcut araştırmaları karşılaştırması beklenmektedir. Ayrıca çalışma, aşağıdaki araştırma sorularını yanıtlayarak bu alandaki araştırmacılar için yararlı bir kaynak olmayı hedeflemektedir.

Makalelerde sıklıkla kullanılan anahtar kelimelerin dağılımı nasıldır?

Makalelerin özet bölümlerinde sıklıkla kullanılan kelimelerin dağılımı nasıldır?

Makalelerde en çok atıf alan yazarlar kimlerdir?

NNT eğitimi üzerine hangi dergiler daha sık yayın yapmaktadır?

NNT eğitimi alanında en üretken ülkeler hangileridir?

Yöntem

Pritchard (1969), bibliyometriyi "matematiksel ve istatistiksel yöntemlerin kitaplara ve diğer iletişim araçlarına uygulanması" olarak tanımlamaktadır. Bibliyometri, araştırmacılara araştırmanın tarihini ve mevcut durumunu ortaya çıkarma ve gelecekte hangi eğilimlerin ortaya çıkma olasılığının olduğunu gösterme fırsatı sunar (Vogel & Masal, 2015). Bibliyometrik analiz; yayınların, araştırmacıların veya araştırma kurumlarının bilimsel etkisi hakkında bilgi ortaya koymak için genellikle bilimsel çıktı (yayın sayısı), bilimsel etki (alıntı sayısı) veya bilimsel işbirliği gibi bibliyometrik göstergeleri kullanır (Waltman & Noyons, 2018). Bu bilgi genellikle belirli bir disiplinde veya çalışma konusunda yapılan çalışmaları keşfetmeye, organize etmeye ve anlamlandırmaya yardımcı olur (Ferreira vd., 2014).

Bibliyometrik analiz, farklı alanlardan araştırmacıların dikkatini çekmiş (Bhatt vd., 2020) ve sıklıkla bilimsel yayınları nicel olarak analiz etmek için kullanılmıştır (Chen vd., 2016). Ayrıca bibliyometrik analiz için Perish (Harzing & Van der Wal, 2009), HistCite (Garfield, 2009), BibExcel (Persson vd., 2009) ve CiteSpace (Chen, 2004) gibi farklı yazılım programları da bulunmaktadır. Bu çalışmada ise bibliyometrik haritaların oluşturulması ve bu haritaların detaylı bir şekilde incelenmesine olanak sağlayan VOSviewer yazılımı tercih edilmiştir. VOSviewer; bibliyometrik ağları oluşturmak, keşfetmek ve görselleştirmek için kullanılabilen bir yazılım aracıdır (Van Eck & Waltman, 2011). Yazılım, literatürden çıkarılan anahtar terimlerin birlikte meydana getirdiği ağları oluşturmak ve görselleştirmek için metin madenciliği imkânı sunmaktadır. VOSviewer, Van Eck ve Waltman (2010) tarafından geliştirilmiş ve birçok araştırmada kullanılmıştır (Arici vd., 2019; Krauskopf, 2018; Lulewicz-Sas, 2017; Olczyk, 2016). Bu çalışmada incelenen makaleler Web of Science (WoS) veri tabanından Science Citation Index Expanded (SCI-E), Social Sciences Citation Index (SSCI), Social Sciences Citation Index (SSCI) ve Arts & Humanities Citation Index (AHCI) kullanılarak derlenmiştir.

Sonuç ve Tartışma

Bu çalışma, WoS veri tabanında bulunan 196 makale içeriğine dayalı olarak NNT eğitimi üzerine araştırmaların tarihsel gelişimi ve mevcut durumu hakkında bir genel bakış sunmaktadır. Araştırma bulguları 2001-2007 döneminde makale sayısında göreli bir artış olduğunu, ilk kayda değer artışın 2007'de gerçekleştiğini, 2012 yılında 22 makale ile en yüksek sayıya ulaşıldığını göstermiştir. Ancak 2012'den sonra makale sayısında azalma eğilimi başlamıştır. Yıllara göre toplam atıf sayısında da benzer eğilimler gözlenmiştir. Bu bulgulara göre araştırmacıların 2012 yılına kadar NNT eğitimi alanına ilgi gösterdikleri ancak 2012 yılından sonra ilgilerini nispeten kaybettikleri anlaşılmıştır.

Bulgular, makalelerde en çok kullanılan anahtar kelimelerin nanoteknoloji, aktif öğrenme, 3 ve 4. sınıf lisans eğitimi, lisansüstü eğitim, deney ve laboratuvar eğitimi olduğunu göstermiştir. Ayrıca lisans birinci sınıf, uygulamalı öğrenme, sorgulamaya dayalı öğrenme ve materyal bilimi son yıllardaki çalışmalarda sıklıkla kullanılan anahtar kelimeler olmuştur. Bu bulgular, NNT eğitimi ile ilgili kavramların öğretiminde uygulamalı etkinliklerin sıklıkla uygulandığına işaret etmektedir. Bu etkinlikler, özellikle laboratuvar ortamlarında 3 ve 4. sınıf lisans ve lisansüstü eğitimde gerçekleştirilmiştir. Sorgulamaya dayalı öğrenme, araştırmacıların son yıllarda NNT eğitiminde kullanmaya başladıkları bir yaklaşımdır. Araştırmacılar bu yaklaşımı tercih etme nedenlerini hem öğrencilerin soyut fen kavramlarına ilişkin bilgilerini kendi başlarına yapılandırmalarına destek olmak hem de NNT'ye ilgilerini artırmak olarak ifade etmişlerdir (Cheng vd., 2016; Jones vd., 2006; Paluri vd., 2015).

Alandaki en üretken yazarlara gelince, M. G. Jones ve R. Blonder hem üretken hem de en çok alıntı yapılan yazarlar olmuştur. M. G. Jones hacim ve ölçek kavramlarının öğretimi, R. Blonder ise özellikle lise fen derslerinde öğretilecek NNT kavramların belirlenmesi ve bu kavramların müfredata uyarlanması üzerine çalışmıştır. NNT eğitimi alanındaki en aktif dergilere yönelik bulgular ise Journal of Chemical Education, International Journal of Engineering Education ve International Journal of Science Education isimli dergilerin en aktif dergiler olduğunu ortaya koymuştur. İlginçtir ki bu dergilerin hiçbiri spesifik olarak NNT eğitimi üzerine yayınlar çıkaran bir dergi değildir. Ne yazık ki WoS veri tabanında özellikle NNT eğitim araştırmaları üzerine yayınlar çıkaran bir dergi bulunmamaktadır.

Son olarak NNT eğitimi alanındaki en verimli ülkeler incelenmiştir. Bulgular, ABD'nin NNT eğitim alanının merkezi olduğunu göstermiştir. Çin, son yıllarda NNT ile ilgili makale sayısında en üretken ülke olmasına rağmen bu ülke kaynaklı NNT eğitimi alanındaki makale sayısı oldukça sınırlıdır. Öte yandan NNT eğitim araştırmaları konusunda ülkeler arasında sınırlı sayıda işbirliği olduğu da tespit edilmiştir. Sonuç olarak bu çalışmanın, NNT eğitimi alanındaki eğilimlerin, etkili araştırmacıların, dergilerin, ülkelerin belirlenmesi, son gelişmelerin anlaşılması için bir fikir sağlaması noktasında araştırmacılar ve eğitimciler için faydalı bir kaynak oluşturma potansiyeline sahip olduğu ifade edilebilir.

Öneriler

Araştırma bulgularına dayanarak aşağıdaki önerilerde bulunulmuştur.

- NNT kavramlarını öğretmek için öğrencilerin soyut konularda kendi bilgilerini yapılandırmalarına olanak sağladığı için aktif öğretim yöntemlerinin kullanılması önerilmektedir.

- NNT eğitimi alanında araştırmacılar ve ülkeler arasında daha fazla araştırma işbirliği önerilmektedir. İşbirliği, araştırmacıların NNT eğitim konularını farklı açılardan ele almalarına imkân tanıyabilir.

- NNT eğitimi alanında her yıl çok sayıda makale yayımlanmaktadır. NNT eğitimine özel olarak yayın yapan bir derginin kurulmasının, bu alanda yapılacak çalışmaların desteklenmesine katkı sağlayacağı düşünülmektedir.

A Bibliometric Analysis on Nanoscience and Nanotechnology Education Research

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Abstract: This study aimed to investigate the research trends in Nanoscience and Nanotechnology (NST) Education through a bibliometric mapping analysis. With its focus on NST education and an analysis of a comprehensive number of studies, this study is expected to provide a guide for new studies, identify the trends in the field and compare the existing research on this topic. VOSviewer software was used to examine and visualize bibliometric networks between the research units. The bibliometric analysis included a total of 196 articles published between 2001 and 2021 in peer-reviewed journals covered by the Web of Science database. The results indicated that the most used keywords were nanotechnology, hands-on learning, upper-division undergraduate, graduate education, and laboratory instruction. The most-productive countries in NST education research were the United States, Israel, France, and Taiwan. The results provided a comprehensive review to understand the recent developments in NST education research.

Keywords: Nanoscience and nanotechnology, bibliometric analysis, bibliometric mapping.

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INTRODUCTION

Richard Feynman introduced a new research field focusing on "manipulating and controlling things on a small scale" in his famous talk in 1959 (Lin et al., 2015). His ideas promoted the development of "nanoscience" as a new research field. This field attracted great attention from researchers. As a result of this attention, the nano-related science and technology field has been developed in the past few decades. The economic potential effect of nanotechnology taken into consideration, many countries invested in nanoscience and developed nano products widely used in everyday life, such as electronics and energy (Lin et al., 2015).

The manipulation of materials at their atomic, molecular, and macromolecular scales, where their characteristics change noticeably from those at a larger scale, is the focus of nanoscience (Royal Society, 2004). On the other hand, nanotechnology is concerned with the creation, use, and application of structures, devices, and systems by manipulating their size and shape at the nanoscale level (Royal Society, 2004). It can be deduced from the above definitions, nanoscience is concerned with the behavior and functions of matter at atomic and molecular levels, while nanotechnology aims to control and use matter at a nano scale to produce new devices. Both fields have developed recently and very rapidly (Gilberta & Lin, 2013). Each year, the number of new nano products appearing on the market has increased at an exponential rate. It is widely accepted that NST has broad social and economic consequences and will continue in the coming years (Hingant & Albe, 2010).

In response to the rapid development of NST, many countries have added these fields to their science curriculum from K-12 to university level to enhance students' understanding of NST related concepts. The field of NST education took on greater importance with the raising awareness of developments on NST fields. Stevens, Sutherland, and Krajcik (2009) have argued that students need to learn the essential NST concepts and skills to become part of the future nano workforce. As a result, science educators engaged in determining the most effective ways to teach people the essential concepts and processes involved in NST (Jones et al., 2013). Jones et al.'s (2013) review of the literature showed that there was a clear call from policy and government circles for new educational programs that could teach the next generation of scientists and the general public about NST. In Taiwan, great efforts were devoted to NST education to enhance all levels of students' interest in learning nanotechnology and teachers' professional development (Lin et al., 2015). A comprehensive National Program on Nanotechnology was implemented by the government. Another national program was also funded to train teachers to enrich their understanding of nanotechnology. In the US, an attempt was started to incorporate nanotechnology into high school science programs (Blonder & Sakhnini, 2012). As a result of extensive work, a group of nano scientists and science educators agreed upon nine "big ideas of nanotechnology" (Blonder & Sakhnini, 2012). These nine big ideas are size and scale, the structure of matter, size-dependent properties, forces and interactions, quantum effects, self-assembly, tools and instrumentation, models and simulations, and science, technology and society (Stevens et al., 2009). These are the fundamental concepts of nanotechnology in gaining a basic knowledge of the field.

In France, the Nano-INNOV program dedicated to innovation in nanotechnology was launched in 2008 (Hingant & Albe, 2010). Twelve training centers spread on the French territory were operated to provide access to equipment and tools to train the students in

this field (Bonnaud & Fesquet, 2013). China as a rapidly growing economy also paid attention to NST education (Wu et al., 2014). For example, many universities are offering academic majors in nanotechnology, nano-related scientific discoveries are being introduced to high school students in chemistry textbooks, and even nano-related questions were used in college entrance exams.

In Europe, the European Commission integrated nanotechnology education in its policies. The commission required the European Union member countries to encourage interdisciplinary training, student mobility and education for R&D in NST (Malsch, 2014). Accordingly, European universities composed nanotechnology courses, researchers published articles on NST education, digital education sources were developed such as nanoyou. In the meantime, nano education outreach programs (Moraes, 2012; Saidi & Sigauke, 2017), integrating nanotechnology in the science curriculum (Blonder & Sakhnini, 2017; Neves, 2018; Yu & Jen, 2020), developing hands-on activities (Bagaria et al., 2011; Furlan, 2009; Lati et al., 2019), determining public understanding, awareness or attitudes towards NST (Scheufele & Lewenstein, 2005; Senocak, 2014; Vandermoere et al., 2011), instrument development (Lin et al., 2013; Schönborn et al., 2015) research studies were implemented.

Considering a notable growth of interest in NST education by researchers, policy makers, and governmental authorities from different perspectives, attention has been directed to this growing field. Within this context, many studies have been published on NST education, and some efforts have been undertaken to review the published literature on NST education. These review efforts have a wide range of relevance. For example, some studies reviewed the NST studies published in certain fields, such as dentistry or the literature review studies only focused on the history of NST (Bhushan, 2016; Giakoumettis & Sgouros, 2021). Also, studies on some specific topics such as nanotechnology-based activities were reviewed (Ghattas & Carver 2012). Unlike current literature review research focusing on the results of previous research, this study examined the most-used keywords, the most commonly used words in abstracts, the most-cited researchers, journals, and countries in the articles on NST education. The co-authorship networks between most-cited authors and co-authorship networks between countries of the research on NST education were also visualized using co-authorship analysis. With its focus on NST education and on an analysis of a comprehensive number of studies, this study is expected to provide a guide for new studies, identify the trends in the field and compare the existing research on the topic. Further, the study can be a useful resource for researchers in this field by answering the following research questions:

What is the distribution of keywords frequently used in the articles on NST education?

What is the distribution of the words frequently used in the abstract of articles related to NST education?

Who are the most cited authors in the articles related to NST education?

Which journals are active in the field of NST education?

Which are the most productive countries in the field of NST education?

METHOD

Bibliometrics is a field of research examining bodies of knowledge (Holden, Rosenberg, & Barker, 2005). Pritchard (1969) describes bibliometrics as "the application of mathematical and statistical methods to books and other media of communication." Bibliometric methods are interested in encoded bibliographical information from scientific publications attained from scholarly data sources (Andres, 2009; Glänzel, 2003). Bibliometrics provide an opportunity for researchers to reveal the history and current status of research and indicate which trends are likely to emerge in the future (Vogel & Masal, 2015). Bibliographic data may be also used to get an overview of the connections of authors, institutions, countries, and collaborative networks among them. Bibliometric analysis often uses bibliometric indicators such as scientific output (the number of publications), scientific impact (the number of citations), or scientific collaboration to provide information about the scientific impact of publications, researchers, or research institutions (Waltman & Noyons, 2018). This information is often helpful in exploring, organizing, and making some sense of the work that has been done in a certain discipline or subject of study (Ferreira et al., 2014).

Bibliometric analysis has gained the attention of researchers from different fields (Bhatt et al., 2020) and is frequently used to quantitatively analyse scientific publications (Chen et al., 2016). It has some the superior aspects of the bibliometric analysis over classical literature reviews (e.g., meta-analysis, meta-synthesis or systematic literature reviews). For example, while meta-analysis focuses on summarizing empirical evidence by examining the direction and strength of effects and relationships among variables, bibliometric analysis concentrates on describing the bibliometric and intellectual structure of a field by analysing the social and structural relationships between various research constituents (such as authors, countries, institutions, and topics) (Donthu et al., 2021). When the dataset is small, a systematic review of the literature on the subject is performed; however, when the dataset is too big for a manual review, bibliometric analysis is applied (Donthu et al., 2021). Also, there are different software programs performed for bibliometric analysis, such as Perish (Harzing & van der Wal, 2009), HistCite (Garfield, 2009), BibExcel (Persson et al., 2009) and CiteSpace (Chen, 2004). We preferred VOSviewer to conduct the bibliometric analysis because of its usefulness for

displaying large bibliometric maps in an easy-to-interpret way and allowing bibliometric maps to be examined in detail.

The VOSviewer is a software tool that can be used for creating, exploring, and visualizing bibliometric networks such as journals, researchers, or individual publications (Van Eck & Waltman, 2011). It also offers text mining to construct and visualize co-occurrence networks of key terms extracted from a body of scientific literature. The software was developed by Van Eck and Waltman (2010) and applied in much research (Arici et al., 2019; Krauskopf, 2018; Lulewicz-Sas, 2017; Olczyk, 2016). The program is freely available software (www.vosviewer.com) and runs on many hardware and operating system platforms (Van Eck & Waltman, 2011). In the study, the articles published on NST education up to 2021 were gathered from the Web of Science (WoS) database using three indexes: The Science Citation Index Expanded (SCI-E), the Social Sciences Citation Index (SSCI), and the Arts & Humanities Citation Index (AHCI). The WoS database was chosen for the current study because it provides for the distinction of more effective studies in the field of investigation, and highly cited publications offer better awareness of the pertinent field and more innovative chances for further research (Shih et al., 2008; Tosun, 2022).

In this study, we conducted three sequential steps for data collection and evaluation of the field aiming to identify the trends in the field, identify influential studies/researchers and provide a guide for future research in the field. These steps are scanning, selecting and analysis of articles.

Scanning the Literature

As expressed before, the articles related to NST education were gathered from the WoS. Some keywords were used for searching the literature, in the search option "topic", as follows nanotechnology, nanoscience, nanoscale, nanoparticle, and education. Combinations of different strings of the keywords ("nanotechnology" and "education" or "nanoscience and education" or "nanoscale and education" or "nanoparticle and education") were used to search the relevant studies. The search was conducted in December 2021 and resulted in a total of 346 articles.

Selecting the Articles

After the scanning of the literature, the gathered data were checked for unrelated articles. We further read all articles to guarantee that the sample was a representative sample of NST studies. All articles were evaluated for their suitability for the aim of study, and any that didn't directly address NST education were excluded. As a result, a total of 196 articles was accessed based on the research parameters. After selecting related articles, the search records were saved in a Win format to include all the essential

paper information such as paper title, authors' names and affiliations, abstract, keywords, year published, times cited and references. The resulting Win file was used for further data analysis.

Analysis of the Articles

The Win file was uploaded to the VOSviewer program. Then, we performed a bibliometric analysis including two phases: A quantitative analysis and a network analysis. First, the quantitative analysis was performed to calculate the basic bibliometric indicators like number of the articles published by year. Second, the network analysis was performed to reveal the network visualization of the most used keywords, words in the abstracts, the highly cited authors, the most cited journals, and the active countries in the field. We especially focused on the network and "link strength" between the key research units. VOSviewer was used to examine and visualize the relationship between the research units in the file.

FINDINGS

As aforementioned, before presenting the network analysis findings, the basic bibliometric indicators (articles and citations) are analyzed. Trends in publications and citations are seen as performance indicators of a discipline within the research system (Aksnes et al., 2019; Hernández-Torrano & Ibrayeva, 2020). A total of 196 articles with 1700 citations in the field of NST education were accessed from the WoS database. Figure 1 presents the distribution of the number of the articles by years. According to Figure 1, the first article was published in 2001 and there was not a consistent increase in the number of articles during the period of 2001-2007. However, after 2007, there was a growth of interest in the field, with a significant increase in the number of articles. In 2012, 22 articles were published, and the articles were cited 190 times. In 2013, the number of articles decreased dramatically to 12 with a significant decrease in the number of citations (123 times). After 2013, there was an increasing trend involving the total number of articles and citations, however this trend was short-lived. Following 2015, the total number of articles and citations started to decrease again.

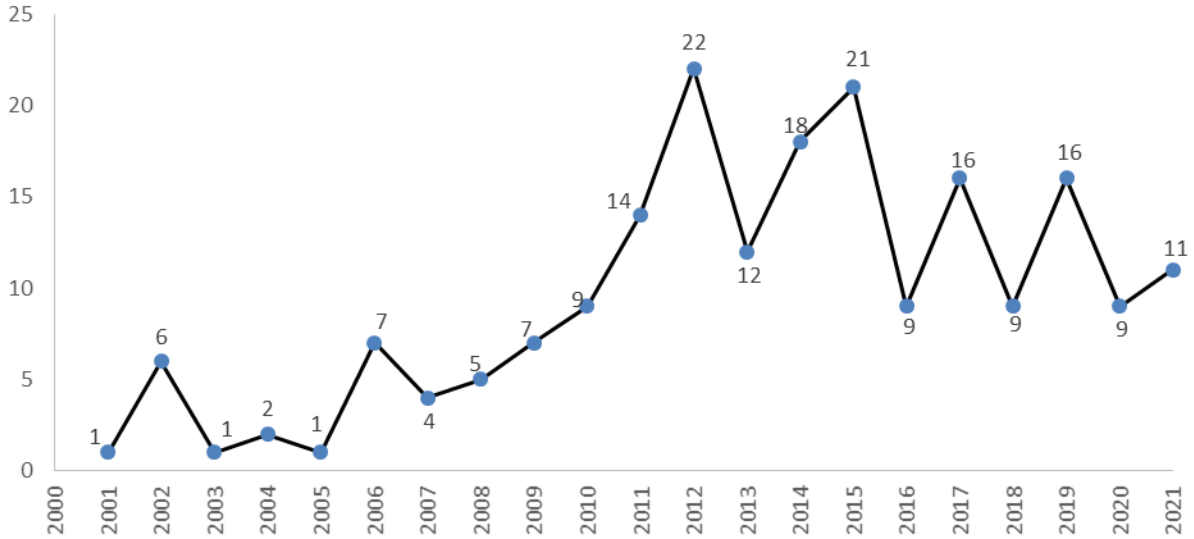

Figure 1

The Distribution of the Number of Articles by Years

The Most Used Keywords in the Articles

After the quantitative analysis, the network analysis was performed. Revealing the distribution of keywords frequently used in the articles was the target of the first research question. A map was created based on text data for the most-used keywords using the VOSviewer software. Minimum number of occurrences of a keyword was determined as five. The analysis resulted in a total of 29 keywords. Figure 2 presents the VOSviewer visualization of the co-occurrence of the author keywords network. Each circle represents a keyword. The size of a circle refers to the total number of the keyword frequency. Lines refer to co-occurrence links between keywords. Colors refer to clusters of keywords that are strongly connected to each other by co-occurrence links. The thickness of the line connecting circles refers to the strength of the relationship between them. Also, Table 1 represents information about the number of links and total link strengths of the most-occurred keywords.

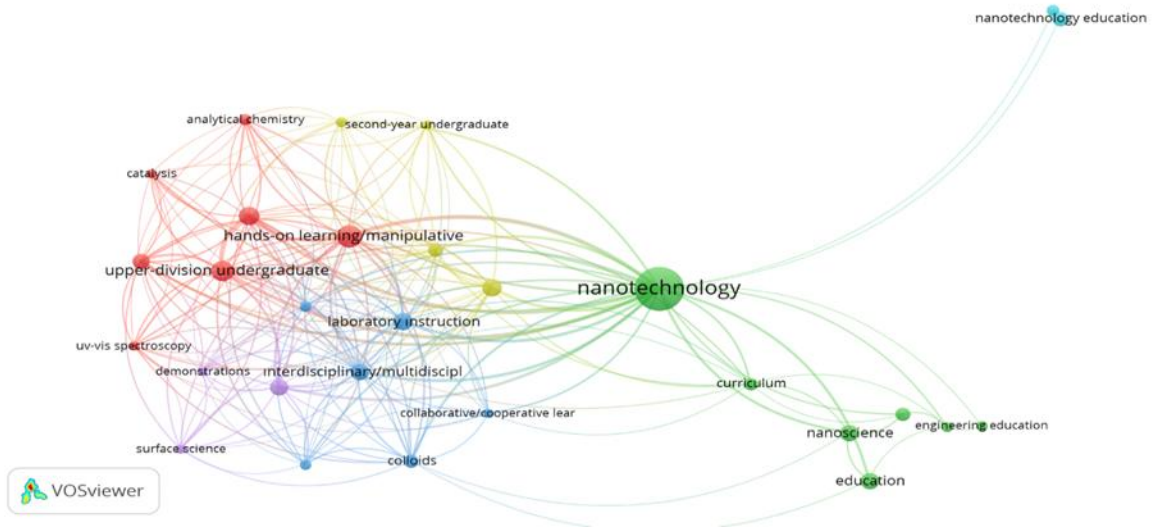

Figure 2

Co-occurrence Network of the Most Used Keywords in the Articles

Table 1

Most-occurred Keywords, Number of Link and Total Link Strengths

Most-occurred keywords	Number of links	Total link strength
Nanotechnology	97	227
Hands-on learning	25	127
Upper-division undergraduate	22	114
Graduate education	17	95
Laboratory instruction	15	84

Figure 2 shows that there are five clusters which have more than 2 items. These clusters are composed of three to seven keywords and frequently include a dominant keyword (i.e., largest circle). According to Figure 2, the top five most-used keywords are nanotechnology (f= 97), hands-on learning (f= 25), upper-division undergraduate (f= 22), graduate education (f= 17), and laboratory instruction (f= 15). These keywords can give hints of the research priorities and interests of researchers in the field of NST education. Figure 2 also shows the term of nanotechnology has the highest link strength among all keywords and is highly connected to the terms of hands-on learning, upper-division undergraduate, graduate education, first-grade undergraduate, and laboratory instruction, respectively. The strength of the network among these keywords indicates a

close relationship among them. According to these findings, it can be said that the articles mostly focused on NST education through hands-on activities for undergraduate or graduate students in laboratory environments.

The distribution of the keywords by years is presented in Figure 3. Figure 3 shows that the keywords of first-year undergraduate, hands-on learning, inquiry-based learning, green chemistry and material science have been becoming popular in recent years. These keywords can be indicators of the fresh research interests of researchers in the field. However, the keywords of nanoscience and science education are losing their popularity among researchers.

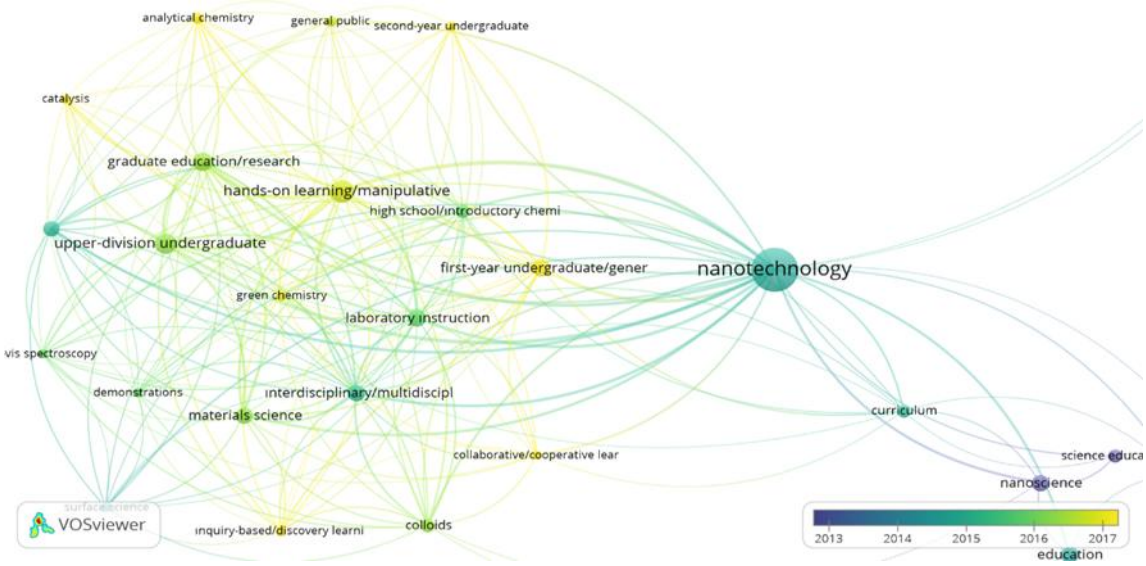

Figure 3

The Distribution of the Articles Using the Keywords by Years

The Most Used Words in the Abstracts

The second research question of the study was about the distribution of the words frequently used in the abstracts of articles. To determine the words frequently used in the abstract sections of articles, the database file was uploaded into the VOSviewer software. Minimum number of occurrences of a keyword was determined as 10. The analysis resulted in a total of 71 keywords. Then, a map was created based on text data for the most-used words in the abstract sections. The map is presented in Figure 4.

Figure 4 shows that there are five clusters (red, green, blue, purple and yellow networks) and there are the top five most-used words which are science (f=126), concepts (f=124), experiment (f=78), teacher (f=65) and curriculum (f=54). Each cluster included a dominant word (largest circle), science for purple cluster, concept for green cluster, experiment for blue cluster, curricula for red cluster and teacher for yellow cluster. The word of science is highly connected to the words of curriculum, teacher, concept, and

university, respectively. The word of experiment is highly connected to the words of nanoparticle, nanomaterial, and chemistry. The word of concept is highly connected to the words of scale, surface area, size and curriculum. The strength of the network among these words indicates a close relationship among them. These findings confirm the findings of Figure 2. Namely, articles focused on teaching NST concepts for undergraduate students in laboratory environments. In addition, according to these findings, it can be said that researchers frequently performed laboratory experiments (especially at chemistry laboratories) to recognize the core NST concepts (such as scale, size, and surface area) for undergraduate students.

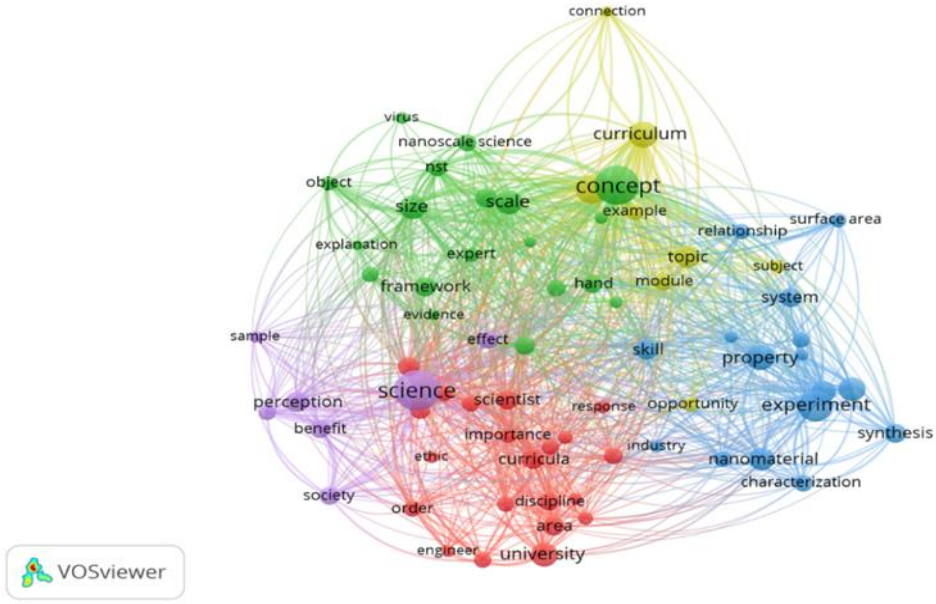

Figure 4

The Most Used Words in the Abstracts of the Articles

The distribution of the words in the abstracts by years is presented in Figure 5. Figure 5 shows that the words of nanoparticle, nanomaterial, experiment, synthesis, characterization, and undergraduate students were popular in recent years. These keywords can be indicators of the fresh research interests of researchers in the field of NST education.

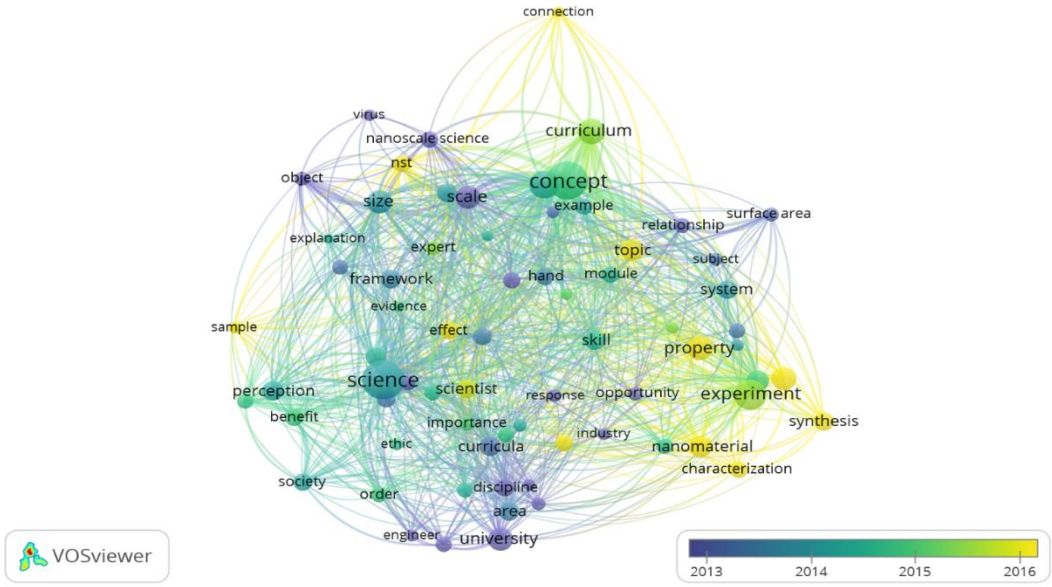

Figure 5

The Most Used Words in Abstract Sections of the Articles by Years

The Most Cited Authors

Determining the most cited authors in the articles was the third research question of the study. To determine the most-cited authors, a map was created based on text data using the VOSviewer software. Only authors with 3 or more articles were considered in the analysis. The analysis resulted in a total of 12 authors. The map is presented in Figure 6. It presents the VOSviewer visualization of the most cited authors with the circle size, the link thickness and color, while circle size, line thickness and color refer to the total number of citations, link strength and clustering, respectively. According to Figure 6, M. G. Jones (citations= 280, articles= 11), R. Blonder (citations= 143, articles= 11), and R. Taylor (citations= 134, articles= 3) are the top three most-cited authors in this field. It also shows that there are three clusters (red, blue and green) giving us information which author has cited each other. As for the link strengths, M.G. Jones has the highest link strengths with R. Blonder and A. Taylor. Also, R. Blonder has the highest link strength with S. Sakhnini. The network represents the state of citations between the most cited and productive authors. Table 2 also shows some additional information about the most-cited authors in the field of nanotechnology education.

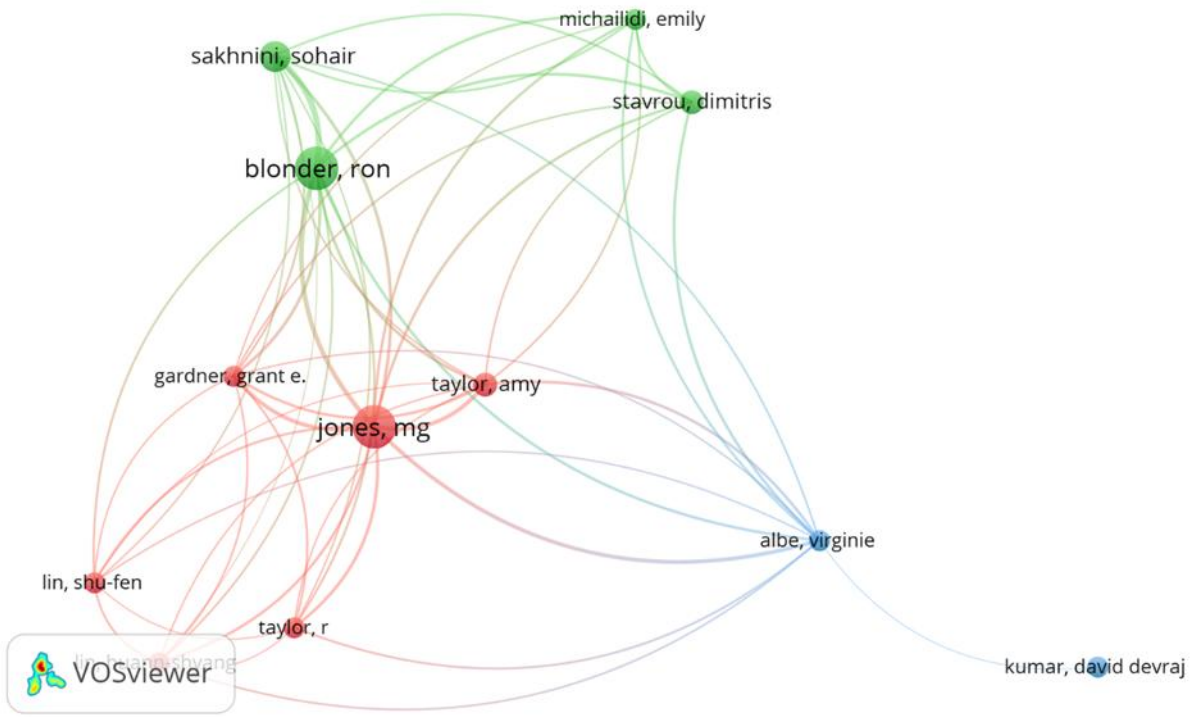

Figure 6

The Most Cited Authors

In addition, the most cited authors by years were analyzed. Figure 7 shows the distribution of most-cited authors by years. According to the figure, R. Blonder and S. Sakhnini are the authors who published the latest articles among the most-cited authors related to NST education. Their average publication year is 2015 with 11 and 6 articles, respectively. Also, Dimitris Stavrou and Emily Michailidi are two authors who have been among the most productive in recent years. They especially studied teaching nanotechnology in primary education. Besides, R. Taylor, M. G. Jones, and A. Taylor have the lowest average publication years of 2004, 2009, and 2010, respectively.

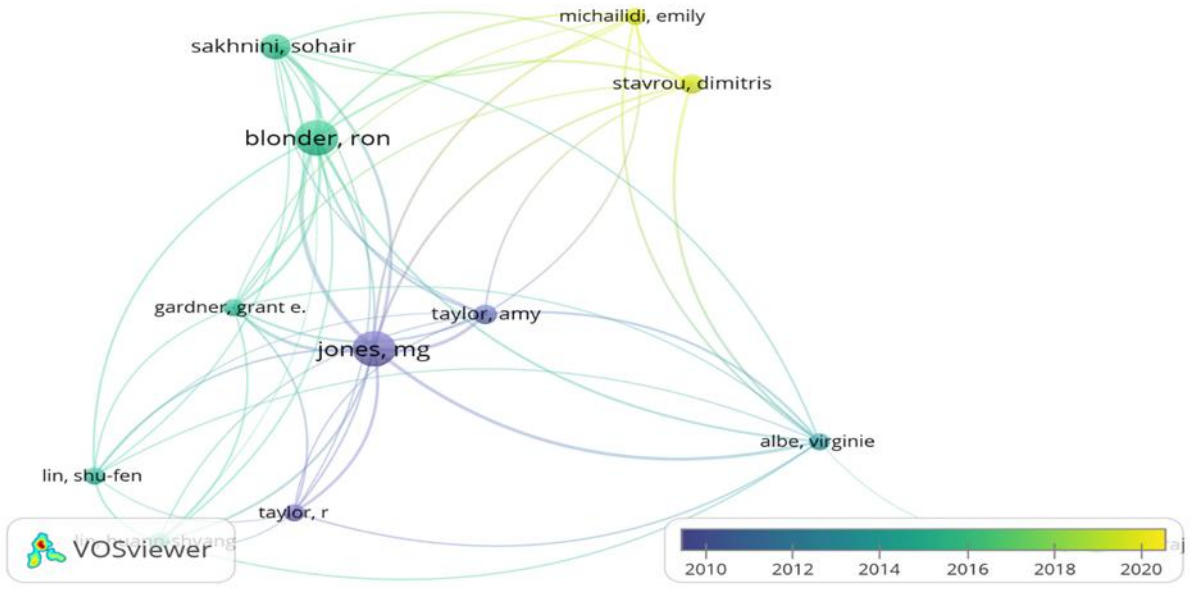

Figure 7

The Most Cited Authors by Years

Table 2

Information About the Most-cited Authors in Nanotechnology Education

Name of author	Institution	The number of citations	Average publication year	The total link strength
M. Gail Jones	NC State University	280	2009	117
Ron Blonder	Weizmann Institute of Science	143	2015	114
Russell Taylor	University of North Carolina	134	2004	35
Amy Taylor	University of North Carolina	88	2011	60
Sohair Sakhnini	Weizmann Institute of Science	76	2015	74

Co-authorship analysis was also examined to find out in the collaboration between authors. Figure 8 refers to authors with stronger connections appear grouped into clusters and represent collaborative networks of authors studying on NST education. The findings show that there are only seven authors (with three or more publications and greatest total link strengths) connected with each other. The network in Figure 8 represents that there are three clusters and a few networks of scientific collaboration

among researchers. The clusters are composed of two or three researchers. The red cluster has the strongest link strength and includes a leading researcher (M. G. Jones).

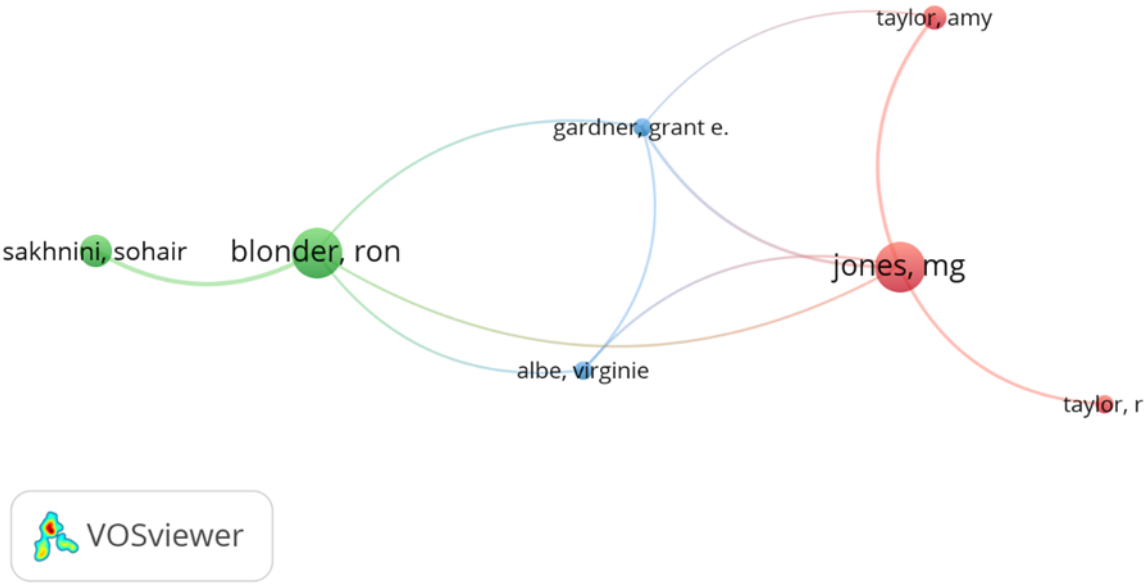

Figure 8

Co-authorship Networks between Authors

The Most Cited Journals

The fourth research question of the study was about the most active journals in the field of NST education. To determine the most-cited journals, the database file was uploaded into the VOSviewer software. Minimum number of articles published in the journal was determined as 4. The analysis resulted in a total of 10 journals. Then, a map was created based on text data for the most-cited journals. The map is presented in Figure 9. It shows that the top three journals in terms of total number of citations are Journal of Chemical Education (citations= 295), International Journal of Science Education (citations=178) and International Journal of Engineering Education (citations= 167). However, the top three journals in terms of total number of articles published are Journal of Chemical Education (articles= 47), International Journal of Engineering Education (articles= 24), and Journal of Materials Education (articles= 13). These findings show that Journal of Chemical Education is both the most-cited and most-productive journal among active journals in the field of NST. This journal accumulates almost 25% of all articles in the database. The map in Figure 9 shows that there are two clusters representing the citation networks between journals. The color of the circle in the map determines the cluster to which the journal has been assigned. Journals in the same

cluster have stronger citation relationships between them. On the map, the circles represent journals publishing research on the field, and its size refers to the total number of citations the journal had.

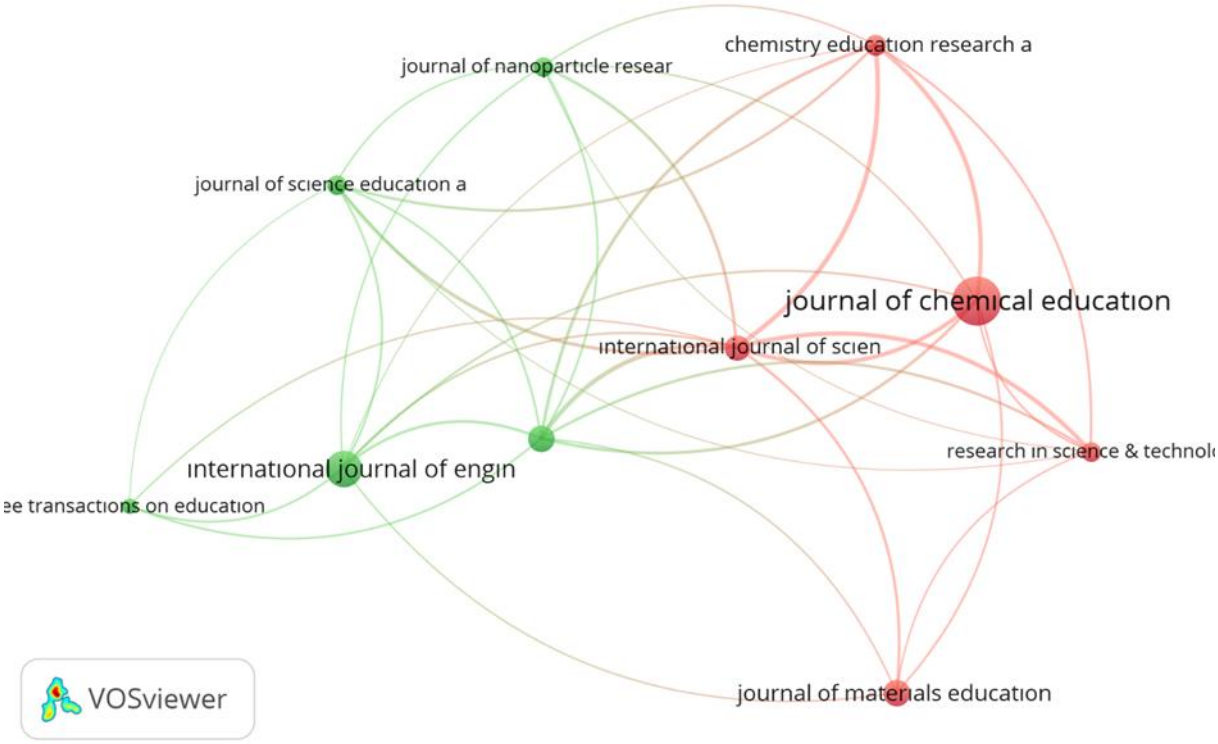

Figure 9

The Most-cited Journals in NST Education Research

In addition, the most cited journals by years were analyzed. Figure 10 shows the distribution of most-cited journals by years. According to the map in the figure, Journal of Chemical Education and Research in Science and Technological Education are the journals published the recent articles among the most active journals in the field. Their average publication years are 2015 and 2016. Besides, International Journal of Engineering Education has the oldest average publication years with 2009 among the journals.

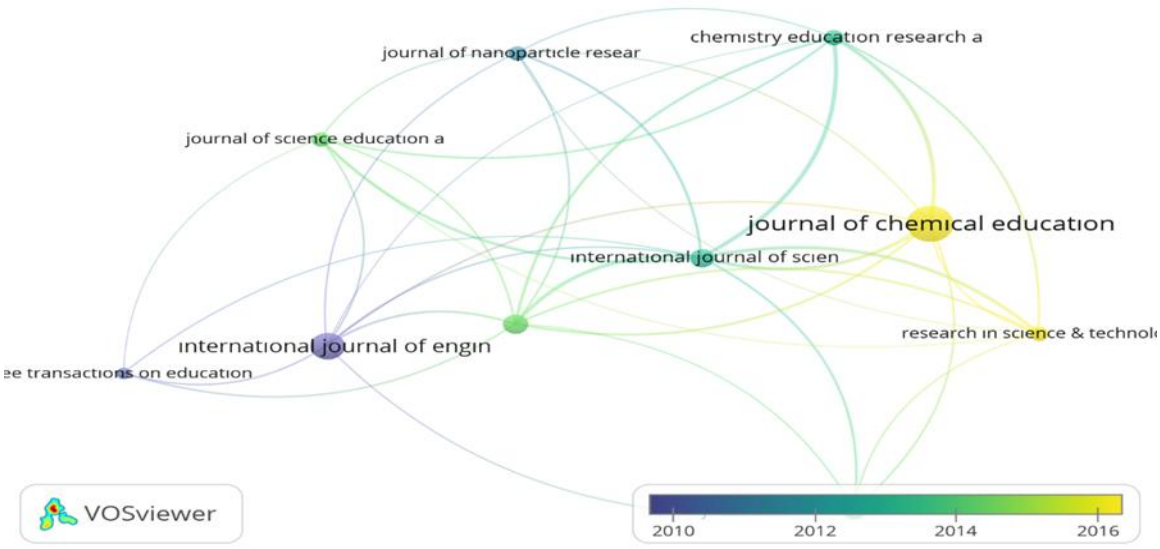

Figure 10

The Most Cited Journals by Years

The Most Productive Countries

Lastly, the most-productive countries in NST education research were determined. To determine the countries, a map was created based on text data using the VOSviewer software. Only the countries with 3 or more articles of a source were considered in the analysis. Also, the minimum number of citations of a country was determined as 10. The analysis resulted in a total of 14 countries. The map is presented in Figure 11.

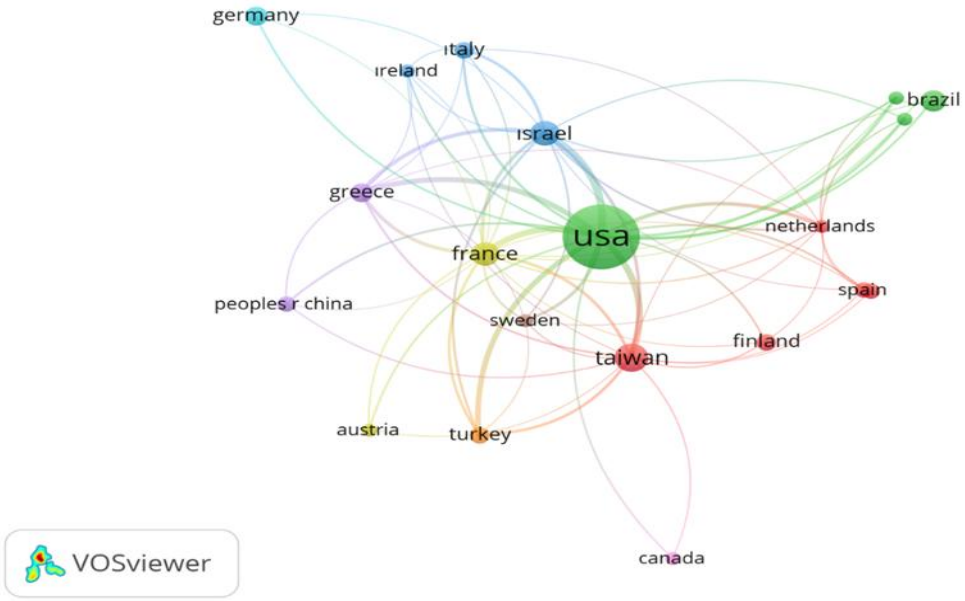

Figure 11

The Most Cited Countries

The map shows that the most-cited countries in which the authors are employed are the United States (US) (citations= 931, articles= 95), Israel (citations= 146, articles= 12), France (citations= 116, articles= 10) and Taiwan (citations= 107, articles= 15). The total number of citations of the US is higher than the total number of citations of other most productive countries. According to these findings, it can be said that the US is a leading country in the field of NST education research. Figure 11 also shows that the US has the highest link strengths with the countries of Israel, France, and Taiwan.

In addition, the co-authorship network of the most productive countries based on the total number of articles was examined. Minimum number of articles of and citations of a country was determined as 3 and 5, respectively. The analysis resulted in a total of 10 countries which were connected to each other. The map is presented in Figure 12. The map shows the state of collaboration between the most productive countries. In the map, the circle size refers to the total number of articles, while line thickness and color refer to link strength and clustering, respectively. The map reveals that there are three clusters, as follows: countries surrounding the US (the blue cluster), countries surrounding France (the red cluster), and countries surrounding Denmark (the green cluster). As for the total link strength, the US as the leading country is highly connected to Israel and France, and these three countries are the most collaborative countries among the most productive countries. According to the findings of both the total number of citations and total link strength, it can be said that the US is the most productive and collaborative country. However, Figure 12 indicates that there is a limited transnational research collaboration on NST education research.

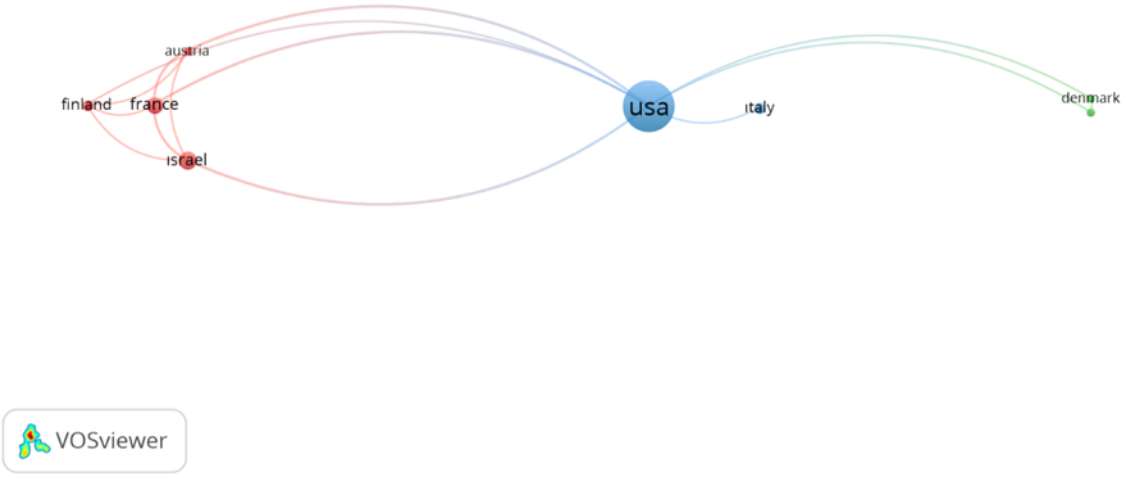

Figure 12

Co-authorship Networks between Countries

RESULTS AND DISCUSSION

This study presented an overview of the evolution and current state of research in NST education based on 196 research articles available on the WoS database. Author keywords, words in abstracts, authors, journals, and countries were used as bibliometric data of the study. The findings showed that the first article on NST education was published almost two decades ago in 2001. The author of the article is Stephen J. Fonash, and it was published in the Journal of Nanoparticle Research. He discussed the importance of education and training of the nanotechnology workforce in the article. He also advocated that the society in general, schools, colleges, and universities must contribute to developing the scientific and engineering workforce. The findings also showed that there was a relative increase in the number of articles during the period of 2001-2007. The first notable increase occurred in 2006, in which seven articles were published. Then, the peak productivity was reached in 2012 with 22 articles. However, after this year a decreasing trend was started in the total number of articles. Similar trends were observed for the total number of citations by years. According to these findings, it can be stated that the researchers were quite interested in this field till 2012, but after 2012 they relatively lost their interest in NST education research.

Findings indicated that nanotechnology, hands-on learning, undergraduate, graduate education, experiment, and laboratory instruction were the most used keywords in the articles. In addition, first-year undergraduate, hands-on learning, inquiry-based learning, and material science were the keywords frequently used in the articles published in recent studies. These findings showed that hands-on activities were frequently implemented for teaching NST related concepts. These activities were especially performed at laboratory environments to teach undergraduate or graduate students (e.g., Yueh & Sheen, 2009; Russo et al., 2011; Pavel et al., 2012). The laboratories provided appropriate environments to implement hands-on experiences, and laboratory exercises represented the hands-on learning aspect of NST related studies. In addition, there were many articles focusing the fabrication, characterization, properties, and applications of nanoparticles such as AgNPs and AuNPs through laboratory experiments (e.g., Amaris et al., 2017; Cea et al., 2016; Perez-Marino et al., 2019). The authors of these articles claimed that such efforts aimed to educate a well-trained nanotechnology workforce because of the increasing applications of nanomaterials. Most of these articles were published in the Journal of Chemical Education. Inquiry-based learning (IBL) was another keyword among the fresh research interests of researchers. According to the researchers, they have preferred the IBL to teach NST concepts since it allows students to build their own knowledge of abstract science topics while also enhancing students' interest in NST (Cheng et al., 2016; Jones et al., 2006; Paluri et al., 2015).

As for most productive authors in the field, M. G. Jones and R. Blonder were both productive and most cited authors. M. G. Jones published 11 articles with 280 citations. She worked with precollege students on teaching the concepts of size and scale. R. Blonder published 11 articles with 143 citations. She especially studied on identification of the essential concepts in NST be taught in high school science and the insertion of these concepts into school science curriculums. In addition, the collaborative research networks between authors were examined. There were three clusters, but they are characterized as small networks. The largest one is formed by three authors with M. G. Jones, Taylor A. and Taylor R., but the other two networks are formed by only two researchers each. Thus, collaboration networks are limited in number and size.

According to findings of most active journals in the field, the 196 articles were published in 53 journals between the years of 2001 and 2021, but there were five journals published more than 10 articles. Also, three of them were the most active ones with higher number of articles and citations: Journal of Chemical Education, International Journal of Engineering Education, and International Journal of Science Education. Interestingly, none of these journals is a specialized journal on NST education. Unfortunately, there is not a journal specialized on NST education research in the WoS database. In addition, Nanotechnology Reviews and Journal of Nanoparticle Research were the only two journals among most productive journals not specialized on educational studies, but they also accept studies related to NST education research.

Lastly, the most productive countries in the articles were examined. The findings showed that the US was the center of the field of NST education research. It had connections with other most active countries on the map (Figure 11). Although China is the most productive country in the numbers of articles on nanoscale science and technology in recent years, the number of articles in the field of nano education is quite limited in this country. As for research collaboration between countries, there were only 10 countries which were connected to each other, and the US was the main collaborator of the articles relevant to NST education. On the other hand, it found that there was a limited research collaboration between countries on NST education research.

In conclusion, this study aimed to reveal the trends in the field of NST education, identify influential studies, and determine the productive authors/journals/countries in the field through a bibliometric analysis. The results of the study provide a comprehensive review to understand the recent developments in the NST education research. This can be a useful source for both researchers and educators by presenting the current trends. However, new studies can be done by using alternative databases (such as Google scholar or Scopus) to expand the findings of this research.

SUGGESTIONS

This study provides an overview and effective comprehension of the present state of the literature on NST education, as well as important insights into the field's development. In light of the findings of this research, the following suggestions have been made:

- It is suggested that utilizing teaching methods like IBL or hands-on learning to teach NST concepts is effective since it allows students to construct their own knowledge of abstract topics.

- It is suggested more research collaboration between authors and countries. Researchers may be able to overcome the rising complexity and specialism of scientific study by collaborating. Collaboration may also allow researchers to handle educational issues from a variety of angles.

- Every year, a large number of articles on nanotechnology education are published. There is, however, no journal specializing in NST education research. It is thought that the establishment of a journal that publishes specifically on NST education will contribute to supporting studies in this field.

LIMITATIONS

This study also has some certain limitations. First, the bibliometric analysis included the articles published between the years of 2001 and 2021 and covered by the SCI-E, SSCI and AHCI indexes. Second, the articles published after December 2021 were not included. Third, different combinations of the terms of nanotechnology, education, nanoscience, nanoscale, and nanoparticle were used as search terms to generate sample articles for the analysis. Lastly, VOSviewer software is used to examine and visualize the relationship between the indicators of keywords, the words in the abstracts, authors, journals and countries. The findings presented in this study should be interpreted within the context of these limitations.

Conflict of Interest Declaration

The author(s) have not declared a potential conflict of interest during the research, authorship, and publishing of this article.

Support / Financing Information

The author(s) have not received any financial support during research, authorship, and publishing of this article.

Ethical Committee Decision / Permission

No data were collected from human participants during the research. The document was examined in the research. All ethical standards were taken into consideration and followed during the research.

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