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Unveiling cognitive structure and comparative advantages of countries in knowledge domains

1. Introduction

Characterizing scientific knowledge by tracking patterns, dynamics, and trends of scientific outcomes in a research field is useful for designing reliable and solid tools for science policy and science evaluation processes [1]. Through these patterns, the intellectual-cognitive structure and the dynamics of scientific fields over time can be explored [2] in order to provide an overview of emerging and/or mature research fields, and to perceive how academic knowledge flows in the form of key concepts to be shared, recombined and developed over time [3].

Nowadays, Nanoscience and Nanotechnology (henceforth NST) is an area holding vast technological and social potential for the community, presenting advancements for industry, health, the environment, and security. It therefore attracts great policy interest [4]. NST has been included as a strategic area with an innovative and economic potential in many research and development plans, even worldwide, such as the EU Research and Innovation Programme known as Horizon 2020[1], the National Science Foundation[2] and the National Nanotechnology Initiative[3].

Previous bibliometric analyses of global NST scientific production based on WoS publications have revealed the main producers and contributors in NST output. China and South Korea underwent the most rapid growth in NST output, China being close to the overall leader —the US— and outstanding in certain nanotechnology research topics [5,6,7,8,9,10]. Similar outcomes were reported by Grieneisen and Zhang [11] and Arora et al. [12], who found that the top producers of NST publications were China, the US, Japan, Germany and South Korea, although a number of Asian (i.e. Taiwan, India or Iran) and European countries have become main contributors to the NST field [13]. Recent research found that Asia as a continent was the most productive in NST from 2000 to 2016, followed by Europe, whose main producers were Germany, the United Kingdom, France, Spain and Italy [14]. The most updated NST publication dataset shows China to lead in NST output, followed by the US; although European countries such as Germany and France make the top-ten worldwide ranking, respectively 4th and 8th [15].

In addition, depending on the level of aggregation, different approaches and units of analysis can be adopted. A combination of techniques (author co-citation analysis, document co-citation analysis, co-word analysis, etc.), units of analysis (journal, publication, keyword, etc.), and actors (countries, institutions, organizations, etc.) may lend accuracy to the identification and characterization of scientific fields [16,17]. Co-word analysis can help describe, define and

[1] ec.europa.eu/programmes/horizon2020/en/what-horizon-2020

[2] www.nsf.gov

[3] www.nano.gov

identify the research topics within a field. It gathers words from publications (extracted from titles, abstracts and keywords) to capture the changes in a field over time [18,19]. Through the study of terminology corresponding to different periods, co-word analysis draws a picture of cognitive structures and their development dynamics [20,21,22]

Scientometric studies have used diverse methods to explore the disciplinary structure, dynamics and research patterns of Nanoscience and Nanotechnology. Network analysis of WoS publications and subject categories was applied to establish the main scientific and technological fields (i.e. materials science, chemistry or physics) comprising NST research [23,24,25]. Citation analysis has been employed to identify the subject categories of NST publications from WoS [12], results showing that biomedical sciences were highly cited. Term analysis (extracted from titles, abstracts and keywords) of WoS publications have been used to determine the main research topics of NST [26], to capture cutting-edge NST research [27] or to determine to what extent countries benefit from the role of their collaborators to heighten research performance in terms of citation; collaboration could help countries to leverage their competitiveness through the design of research and development agendas [28]. Hybrid methods, such as the combination of lexical mining, citation flows and mapping techniques, have been applied to nano publications from WoS in order to detect the diverse topics that comprise the NST field [29] or to explore the dynamics of knowledge integration in some NST-related research areas [30].

On the other hand, characterizing national publications profiles serve to appraise countries' research strengths or weaknesses, which complement the analysis of the intellectual-cognitive structure. Based upon the idea that research topics of a particular field signal a country´s specialization or diversification, hence its competitive advantages [31], relative indicators can be used to compare research performance in terms of the disciplinary specialization of countries. The Specialization Index (RSI), a variation of the Activity Index (AI) is an indicator that indicates whether a country has a relatively high or low share in world publications in a particular field or domain. The Activity Index has been employed to study the disciplinary evolution of some countries [32,33,34,35]. Versions of the AI indicator include the revealed comparative advance [36], the Attractivity Index [37], Document-Type variant [38] or Keyword Activity Index [39], or similarity measures applied to scientific collaboration [40]. For a comprehensive review of this indicator, we would refer to Rousseau [41].

Not many bibliometric analyses of global NST scientific production have been based on Scopus publications, despite its vast coverage [42,43]. Although the main players and contributors in NST have been explored, the national country profile in terms of specialization in NST has rarely been studied [44]. This paper updates previously published outcomes [26,45,46] by extending the time period studied, updating and refining the search strategy [4] and analyzing specialization profiles using the Activity Index based on publications and on the use of keywords at global and country levels. We combine different approaches, aiming to grasp the global and local structure of the Nanoscience and Nanotechnology research field (as a case study), and trace its dynamics over time. The objectives of this paper are to (1) keep working on the characterization of NST with a reliable and detailed search strategy, (2) discern the evolution over time of the cognitive structure of a scientific discipline, and (3) trace the specialization profile from a twofold perspective: publications and keywords. This approach could be useful to arrive at a better understanding of the field´s development and comparative advantages at the country level. To this end, we relied on the Scopus database to fill the gaps of previous studies that used WoS research topics to address the following specific research questions:

RQ1: Worldwide, which countries are the main producers, how has their output evolved, and what comparative degree of specialization have they achieved?

RQ 2: What are the main research topics in NST at the worldwide level, and how do Germany, France and Spain perform in terms of their cognitive contributions to and development of NST research topics?

RQ3: Considering the use of keywords, how specialized are countries in each research topic? How do they reflect the scientific profile of NST and its evolution over time?

2. Data and methods

Data were retrieved from Scopus database at the global and country level using an updated and refined search strategy (Supplementary Text S1) described in Muñoz-Écija et al. [4]. Following Wang et al. [15], we focus our analysis at the country level on Germany, France and Spain as the main European producers in NST, given that the United Kingdom left the European Union in 2020. Data at the global level were used to build overlay maps as a referent for the analysis of countries. We study three different time periods, summing up to a total duration of nine years (2010, 2014 and 2018), to perceive changes over time in the NST research field. The NST dataset comprises 396,250 publications, including all document types (Supplementary Information. Table S1).

2.1. Co-word maps

Co-word analysis [18] has been outlined and later substantiated [47] as the best method to identify the cognitive structure of a field at the level of research specialties. Furthermore, it is capable of revealing new developments within a research topic over time [46]. To perform co-word analysis, we used the keywords (author keywords and indexed keywords) contained in all the retrieved documents to build a proximity/similarity matrix. A threshold of co-occurrence ≥ 10 was set to generate the cognitive structure. In order to avoid synonymy and acronymy issues, we normalized the keywords by designing an *ad hoc* thesaurus (Supplementary Text S2), standardizing plural and singular, abbreviation or acronyms, as complete keywords.

Science mapping —to intuitively analyze co-word maps— consists of developing and applying computational techniques for the visualization, analysis and modeling of a wide range of scientific and technological activities [48]; it is intended to display structural and dynamic aspects of scientific research [22,42,49]. Local science maps are problematic when it comes to comparisons because their units or positions of representation are not stable. To overcome this, one can take the units and the positions derived from a global map of science, then superimpose upon them the information to be displayed and analyzed [50]. Such “overlay maps” are a powerful tool, serving to explore an activity of interest (e.g. publications of a given organization, the references used in an emergent field, co-words...) and appraise the increasingly fluid and complex dynamics of the sciences [46,50,51,52]. NST co-word maps at the global level in 2010, 2014 and 2018 were constructed, and the corresponding overlay maps for each year were derived for Germany, France and Spain, in order to explore and compare cognitive structures and main research topics.

Mapping was performed using VOSviewer [53]. Each node/circle represents a keyword. The circle´s size reflects the number of times it occurs in the document represented. The level of co-occurrence (how frequently keywords co-occur) is expressed by the distance between two keywords —that is, the closer two keywords are, the stronger their relationship is. The colors represent the different clusters (research topics) detected. Then, the keywords of high frequency were extracted as the basis for our analysis, since keywords of this nature usually coincide with research hotspots.

2.2. Activity index

The Activity Index (AI) or Specialization Index, introduced by Frame [32], is a version of the Revealed Comparative Advantage Index (RCA) used in economy as a common measure for quantifying the economic and production advantages of countries [54]. In this study, the AI denotes the relative research effort that a country devotes to a given subject field, i.e., the publication profile of national research in a given country by measuring whether "a country has a relatively higher or lower share in world publications in a particular field of science than its overall share in world total publications" [55], and is defined as:

$$\mathrm{AI} = \frac{\text{the share of the given field in the publication of the given country}}{\text{the share of the given field in the world total of publications}}$$

When AI is greater than one it means that the country's research production in a given field is higher than the world average, just as AI≤1 means lower than the world average. In order to assess each country's relative disciplinary strengths in NST, we apply the Relative Specialization Index (RSI). Thus RSI ≥0 versus ≤0 indicates scientific specialization or no specialization of a country in a given field. RSI is defined as:

$$\mathrm{RSI} = \frac{\mathrm{AI} - 1}{\mathrm{AI} + 1}$$

Hence, we calculate the AI and RSI in 2010, 2014 and 2018 to estimate their NST publication profile over time and detect changes in specialization or comparative advantages [34].

Following this framework, to estimate the comparative advantages of a country in a given research topic, the notion behind the Activity Index for publications is applied to the keywords. This index measures whether a certain country has comparative advantages in researching a given topic, so that we can select their country-specific topics [56]. The Activity Index variant based on keywords (KAI) is defined as:

$$\mathrm{KAI} = \frac{\text{the share of a given research topic in the keyword of a given country}}{\text{the share of a given research topic in the world total keywords}}$$

KAI ≥1 indicates that the topic is emphasized in the country above its average level, and KAI ≤1 indicates that the topic is underemphasized in the country. In order to assess each country's relative disciplinary strengths based in keywords, we apply the Relative Specialization Index (RSIk). Thus RSIk ≥0 versus ≤0 indicates scientific specialization or no specialization of a country in a given field. RSIk is defined as:

$$RSIk = \frac{KAI - 1}{KAI + 1}$$

Sometimes high-frequency keywords from publications are general concepts used by many researchers of a given field, and do not accurately represent details of a field, especially research topics that are the strength of a single country [39]. In turn, low-frequency keywords are related to innovative and emerging concepts, being more representative than high-frequency keywords [57]. This paper proposes an approach to identify keywords considering the frequency of their use in the world and in certain countries. In view of the science maps that display the entire NST keywords, the most relevant keywords in a country or in several countries can be identified. These specific keywords reduce the number of total keywords, and can more clearly expose the research advantages of countries with fewer keywords.

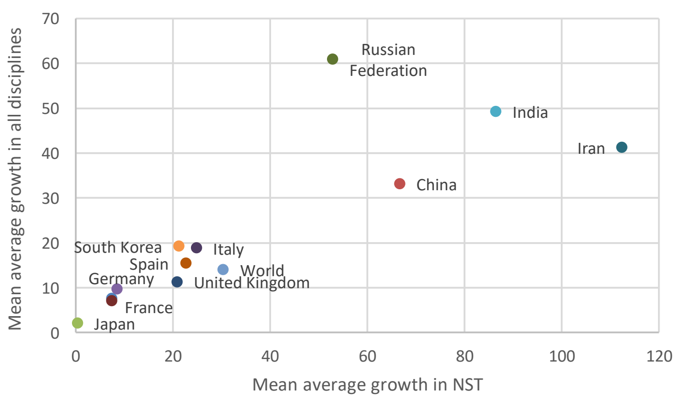
3. Results

3.1. Basic statistics

Bearing in mind the countries producing more than 50,000 documents in the period 2010-2018, among them the countries studied here, Figure 1 shows the percentage of NST documents published with respect to total output in each country and worldwide for the years 2010, 2014 and 2018 (left). The United States and China are the outstanding NST producers (22,534 and 19,883 documents, respectively), followed by Japan and Germany (7,534 and 7,322) (see Supplementary Information. Table S1).

Figure 1 Percentage of NST publications at the global and country level in 2010, 2014 and 2018 (left) and mean average growth rate in NST and in all disciplines (right)

	% NST pub		
Countries	2010	2014	2018
United States	3.70	3.79	3.67
China	5.77	7.54	8.96
Japan	5.78	6.03	5.56
Germany	4.73	4.89	4.60
India	5.40	7.33	8.21
South Korea	9.05	9.61	9.24
United Kingdom	2.64	2.96	3.10
France	4.43	4.62	4.43
Russian Federation	7.62	7.73	6.94
Italy	3.49	3.94	3.79
Iran	6.60	11.24	14.27
Spain	3.76	4.18	4.20
World	3.92	4.67	5.08



The graph on the left shows, for the same geographic aggregates, the average rate of growth for the entire period. At the global level, the share of world output reflects a steady increase in NST publications: a 30% annual growth rate over the nine years (Figure 1- right). At the country level, even though the raw number of publications increases year by year, growth is not homogenous; Iran, India, China and the Russian Federation increase their output much more than the rest of the world, or the other main producers, and well above the level of output in all other disciplines

(Supplementary Information. Table S2). These results largely agree with previous reports of how countries follow different dynamics and output processes in NST [44]. Among the three countries targeted in this study, Germany shows the highest proportion of NST output, followed by France, while Spain presents the highest annual growth rate.

3.2. Relative Specialization Index based on publications

Figure 2 presents the relative specialization index of the most prolific countries in NST considering their production in this field in comparison with the total production in all disciplines and taking the world as a standard (0).

In Germany, France and Spain, the corresponding RSI value is seen to decline after 2010. It may be that these countries are more specialized in nano applied research than in nano basic research. Similar results were divulged by Porter et al. [27], with Germany and France showing a decrease in the NST cutting-edge research activity (2006-2015), perhaps due to a growing interest in nano applications, for instance those related to biomedical research. This also means that other countries are increasing their specialization in the NST field. Indeed, Iran, India and South Korea show substantial specialization growth after 2010 (Supplementary Information. Table S3).

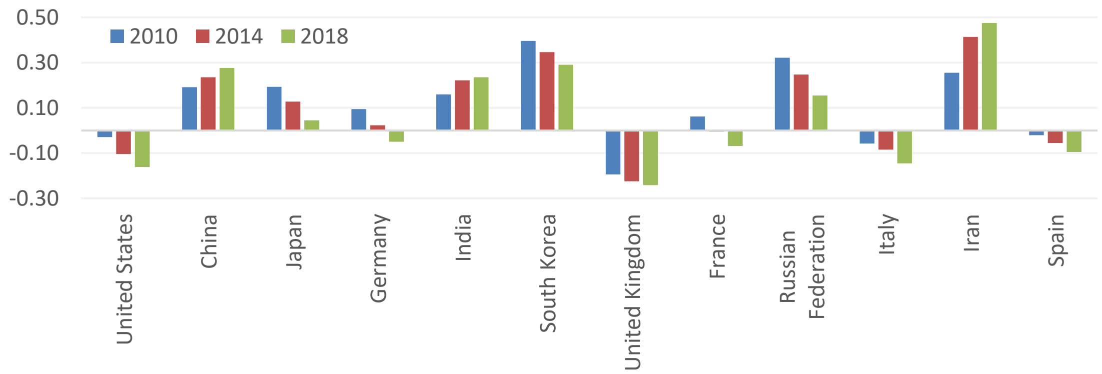
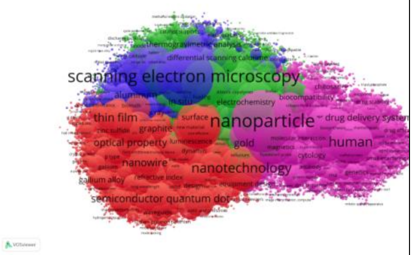
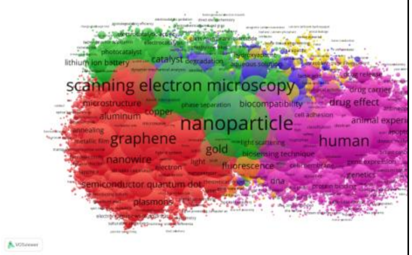
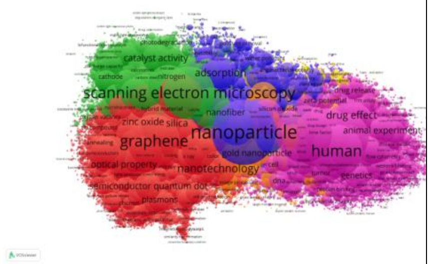
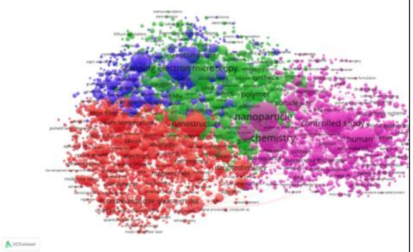
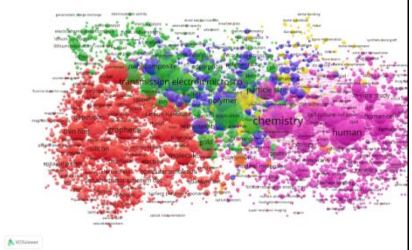
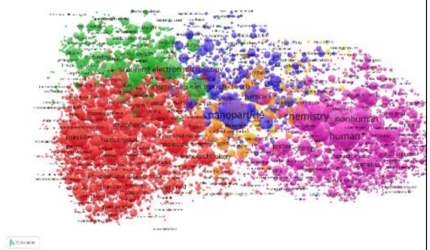
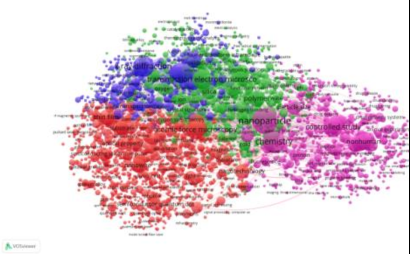
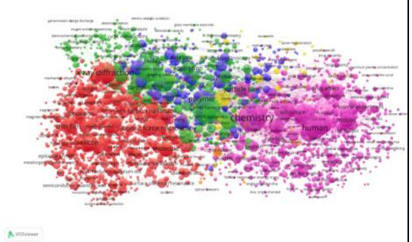
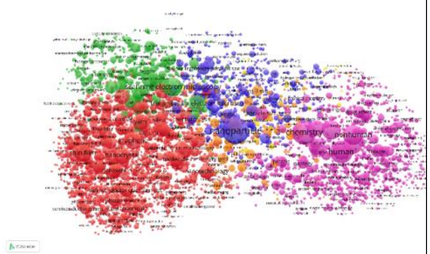


Figure 2 Relative Specialization Index in NST for the most prolific countries in the period 2010-2018

3.3. Co-word maps

Figure 3 displays the knowledge structure of NST over time using science overlay maps. At the worldwide level, the networks represent structures having different numbers of research topics and a variety of keywords in each line. All research topics identified in the world over time are transferred and represented at the country level. The number of keywords defines the disciplinary matrix calculated by co-occurrence that determines one´s position in the hierarchy. The 50 most frequent keywords occurring for the world, Germany, France and Spain —in descending order of prevalence by their occurrence and the total number of overlapped keywords per research topic— can be consulted in the Supplementary Information, Data S1, S2 and S3.

In these global maps, the hierarchical clustering shows a structure with four research topics in 2010: *Microelectronics engineering and top-down processes* (red), *Synthesis of nanomaterials and bottom-up processes + Optics and electronics* (green), *Biotechnology and Biomedicine* (purple), and *Physical and mechanical characteristics of materials* (blue). However, the research topic *Biotechnology and Biomedicine* becomes divided into three new clusters in 2014, lasting until 2018. These emergent clusters are still related with *Biotechnology and Biomedicine*, but they show greater specialization, in: 1) therapeutic applications through the distribution of medicines*;* 2) diagnostic techniques using biosensors; and 3) regenerative medicine. Thus, the specialization of the research topic *Biotechnology and Biomedicine* gives rise to the following clusters: *Biotechnology and Biomedicine: Therapeutic biomedicine* (purple); *Biotechnology and Biomedicine: Regenerative medicine* (light yellow); and *Biotechnology and Biomedicine: Biosensors* (orange).

	2010	2014	2018
World	 http://bit.ly/World-2010	 http://bit.ly/World-2014	 http://bit.ly/World-2018
Germany	 http://bit.ly/Germany-2010	 http://bit.ly/Germany_2014	 http://bit.ly/Germany_2018
France	 http://bit.ly/France-2010	 http://bit.ly/France_2014	 http://bit.ly/France--2018

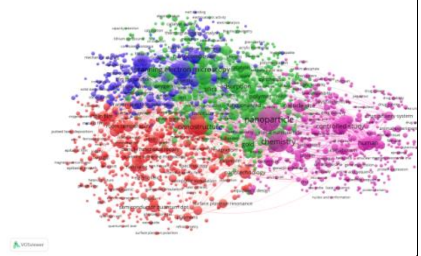
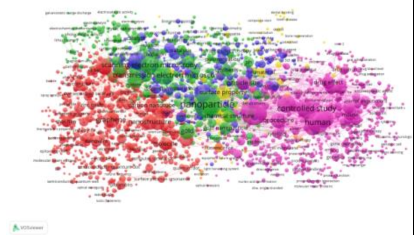
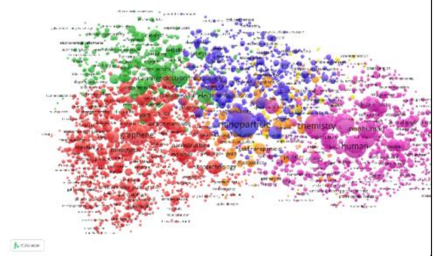
Spain	 http://bit.ly/Spain--2010	 http://bit.ly/Spain--2014	 http://bit.ly/Spain--2018

Figure 3 Global co-word maps for each country and the world output in NST. The links at the bottom of each map allow the reader to visualize the maps and the networks on VOSviewer. Please note that for very broad domains, e.g., the world map, a computer with more than 16 GB of RAM is needed.

As global co-word maps show, the development of NST has meant the emergence of new research topics related with the application of NST for the purposes of social well-being, as in the biomedical field (cluster colored in purple, orange and light yellow). The research topics of NST based on physics, chemistry, and materials science, whether theoretical or conceptual, are represented by research topics colored in red, green and blue. These three research topics are essential for manufacturing procedures involved in the development of new materials, as well as technological devices.

Over the years, NST research appears to have remained stable in Physics and Chemistry (cluster colored in green and in blue), key domains for its evolution. However, noteworthy interest in the biomedical applications (clusters colored in purple, orange and light yellow) results in a greater specialization of researchers along new research topics. In this sense, NST research related to new materials and engineering fields (colored in red) has increased gradually every year, but less than in the area of biomedical research.

At the country level, Germany focuses on *Microelectronics engineering and top-down processes* (red) and *Biotechnology and Biomedicine* (purple) research, and undergoes minor growth in research based on *Physical and mechanical characteristics of materials* (blue). France shows a pattern similar to Germany´s at first; but its trend in NST research changed in 2014 and 2018, with a remarkable increase in *Biotechnology and Biomedicine*. This development gave rise to new research topics in the biomedical and biotechnological field or increased the existing research in the case of *Therapeutic biomedicine*. Spain largely follows the behavior of Germany or France in that *Microelectronics engineering and top-down processes* (red) became the top research topic after 2010. Yet unlike the others, *Synthesis of nanomaterials and bottom-up processes + Optics and electronics* (green) decreased in the number of overlapped keywords after 2014.

Worldwide, the top keywords used in each research topic show only slight differences by year. At the worldwide level, *nanoparticle* is the keyword that tops the ranking every year along with *Scanning electron microscopy* and *chemistry*. There are some differences among the remaining top-five keywords, however. For example, *x ray diffraction* appears only in 2010 and 2014. *Human* was a top keyword in 2014, and again in 2018. *Graphene* appears as a top keyword only in 2018. At the country level, the keywords *nanoparticle, graphene, human* and *chemistry* showed the highest overlap with the world maps for Germany. In France, the most overlapped keywords were *nanoparticle*, *human*, *controlled study* and *unclassified drug.* For Spain, *nanoparticle, chemistry* and *graphene* were the outstanding keywords.

3.4. Relative Specialization Index based on keywords in each research topic

Table 1 shows the RSIk from a dual perspective. For one, the average RSIk of each cluster is calculated in terms of the total number of keywords (N terms). Secondly, the average RSIk is calculated in terms of the total occurrences (N occurrences). As can be seen in Figure 1, Germany, France and Spain show a specialization under 0 with respect to world output and to that of other countries. Because this value is lower than 0, we find specialization with values under 0 when we look at the terms of the different research topics comprising NST in the countries studied (Table 1). But if we look at specialization calculated based on total term occurrences, most values are over 0 with respect to the world. That is, after eliminating the size effect from output, we discover which countries have a research topic with a competitive edge on the global level.

This cross-country comparison regarding patterns of specialization evidences noteworthy differences. The RSIk values (total number of terms) reveal that in Spain, all the NST research topics have relative advantages between 2010 and 2018, but *Biotechnology and Biomedicine: Therapeutic biomedicine* reflects the greatest advantage. France shows a relative advantage in *Microelectronics engineering and top-down processes research*, whereas Germany evolves toward specialization in *Biotechnology and Biomedicine: therapeutic biomedicine,* as does Spain, but to a lesser extent (Table 1).

In turn, the RSIk values (total number of occurrences) (Table 1) present greater advantages in all the research topics in Spain at the worldwide level in the period 2010-2018, especially in the areas of *Biotechnology and Biomedicine* and the characterization of nanomaterials. The lowest advantages are seen for Germany, giving values of 0 in *Physical and mechanical characteristics of materials*, or under 0 as is the case of *Synthesis of nanomaterials and bottom-up processes + Optics and electronics*. France shows intermediate values, between Germany and Spain, in all the research topics, although it has a greater advantage in research related with engineering.

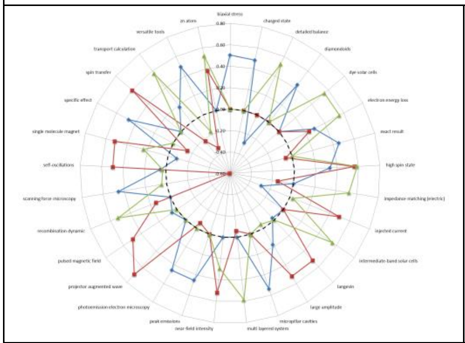
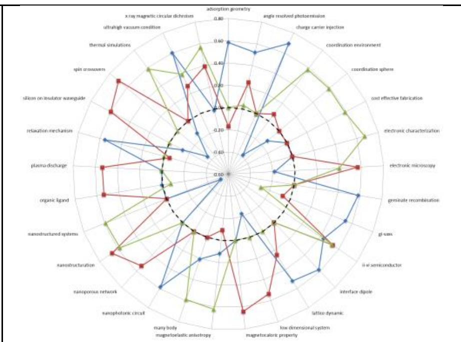
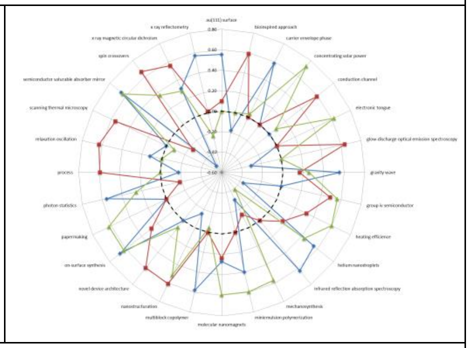
Table 1 RSI of each research topic based on keywords

		Microelectronics engineering and top-down processes			Biotechnology and Biomedicine: Therapeutic biomedicine			Synthesis of nanomaterials and bottom-up processes + Optics and electronics			Physical and mechanical characteristics of materials			Biotechnology and Biomedicine: Regenerative medicine			Biotechnology and Biomedicine: Biosensors		
		G	F	S	G	F	S	G	F	S	G	F	S	G	F	S	G	F	S
2010	N terms	-0.35	-0.33	-0.32	-0.34	-0.37	-0.32	-0.36	-0.36	-0.26	-0.41	-0.38	-0.31	--	--	--	--	--	--
	N ocurrences	0.12	0.20	0.23	0.13	0.16	0.24	0.11	0.17	0.30	0.05	0.15	0.25	--	--	--	--	--	--
2014	N terms	-0.30	-0.30	-0.30	-0.29	-0.30	-0.25	-0.41	-0.36	-0.29	-0.35	-0.31	-0.25	-0.40	-0.44	-0.27	-0.39	-0.39	-0.31
	N ocurrences	0.13	0.19	0.20	0.15	0.19	0.26	0.01	0.11	0.20	0.09	0.17	0.25	0.17	0.13	0.27	0.03	0.09	0.19
2018	N terms	-0.30	-0.28	-0.31	-0.29	-0.32	-0.27	-0.47	-0.44	-0.37	-0.43	-0.39	-0.28	-0.44	-0.50	-0.38	-0.36	-0.37	-0.30

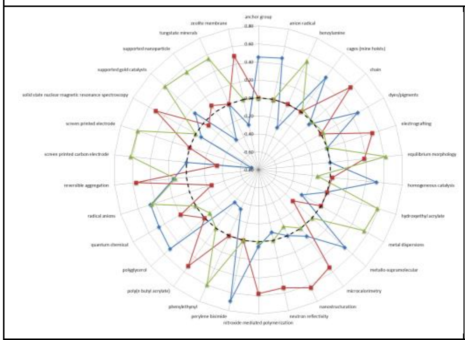
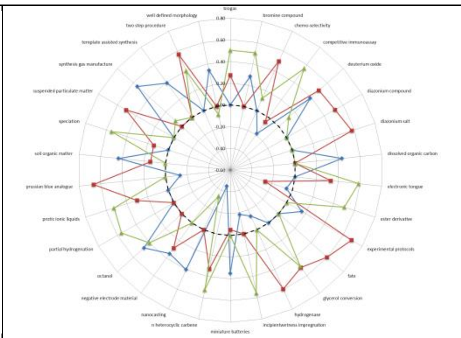
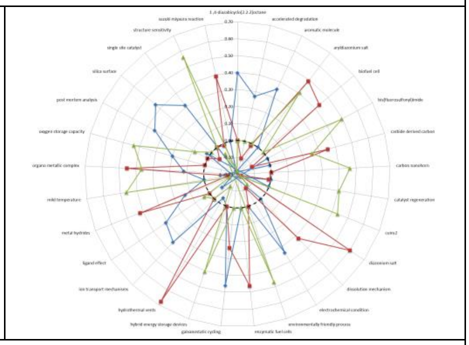
N ocurrences	0.15	0.23	0.20	0.17	0.19	0.25	-0.05	0.04	0.12	0.00	0.10	0.24	0.05	0.05	0.25	0.08	0.12	0.22

G=Germany; F=France; S=Spain. *Cell color scale red-white-blue. Red color is assigned to the lowest value, and blue color to the highest value. Other values are assigned a weighted blend of colors.

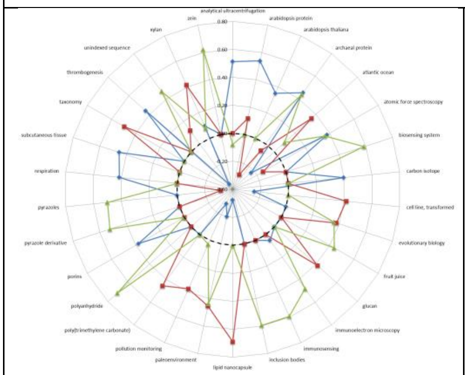
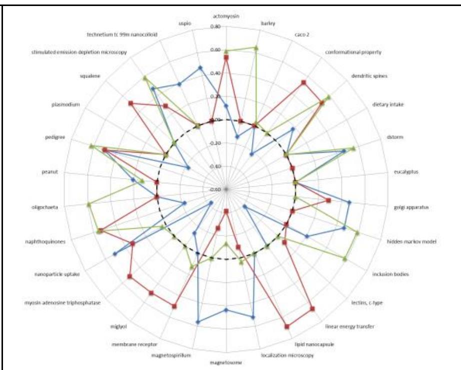
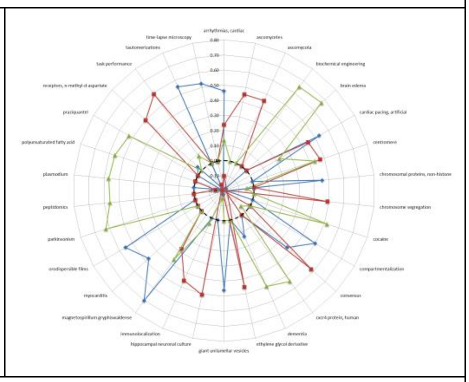
Red cluster: Microelectronics engineering and top-down processes

Green cluster: Synthesis of nanomaterials and bottom-up processes + Optics and electronics

Purple cluster: Biotechnology and Biomedicine - Therapeutic biomedicine

Blue cluster: Physical and mechanical characteristics of materials

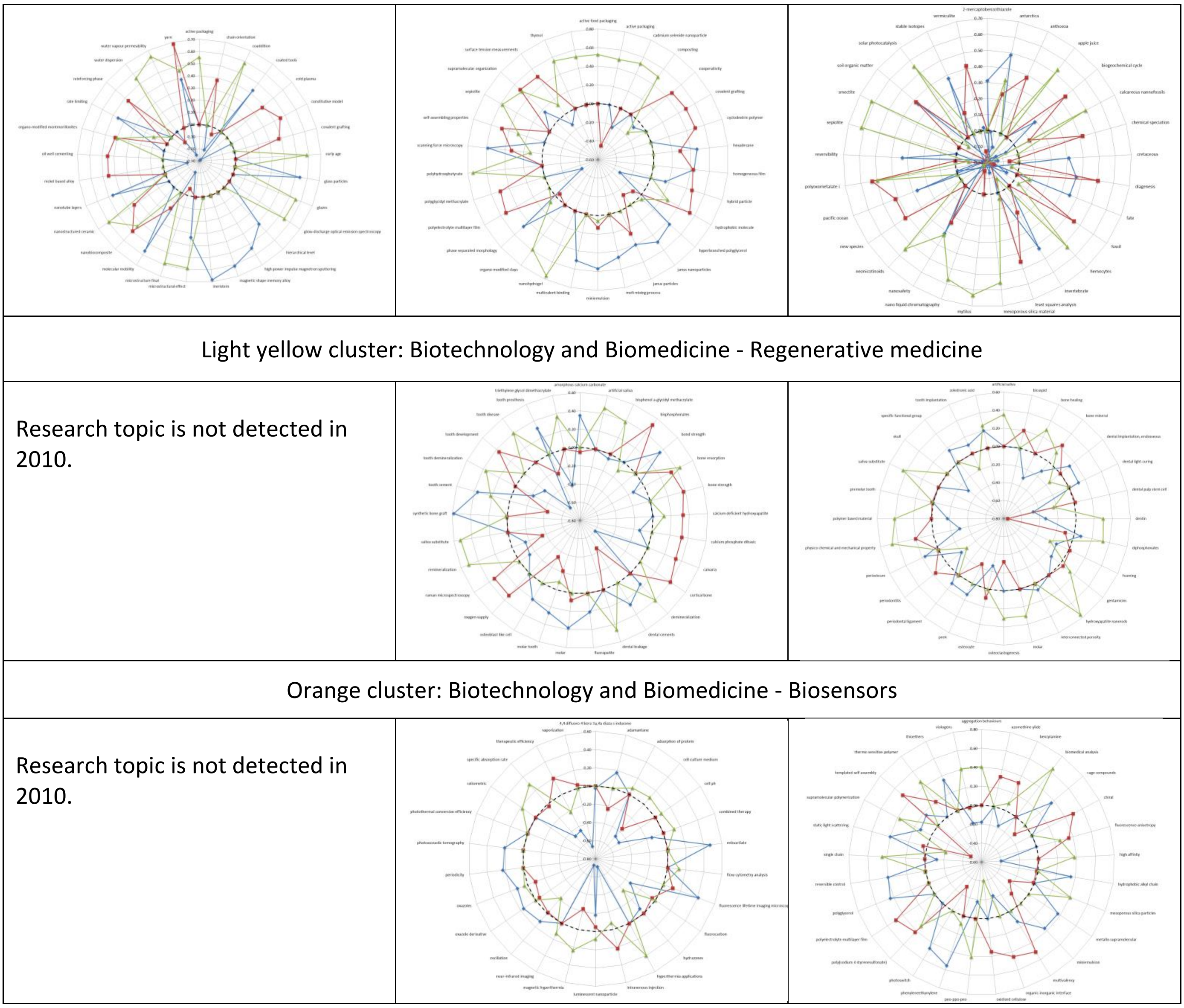


Figure 4 Top 10 *RSIk* keywords in each cluster in Germany (blue), France (red) and Spain (green)

Figure 4 shows the top 10 RSIk of each research topic. Each cluster is described below for more detailed analysis. Further details can be found in the Supplementary Information, Data S1, S2 and S3.

3.4.1. Microelectronics engineering and top-down processes – red cluster

In 2010, this research topic has a relative advantage in *micropillar cavities* and *biaxial stress* in Germany. In France, this advantage is highest in terms that include *projector augmented wave, spin transfer* or *high spin state.* The latter term, *high spin state,* coincides with one of the keywords denoting higher specialization in Spain, along with other terms, such as *dye solar cells*, that reflect intensive activity.

In 2014, the term *carrier injection* presents the highest relative advantage in Germany. The terms relative to spin, e.g. *spin crossovers*, continue to indicate high research activity in France, although other terms arise, among them *nanostructuration* or *x ray magnetic circular dichroism.*

In Spain, new terms related with major advantages include *nanostructured systems,* as well as *nanostructuration* or *x ray magnetic circular dichrois*, keywords coinciding with those of France.

In 2018, a new term signaling relative advantages is *semiconductor saturable absorber mirror.* In Francia, *spin crossovers* and *nanostructuration* continue to denote high relative advantages; and *x ray magnetic circular dichroism* shows remarkable growth when compared with 2014. Researchers in Spain funneled more effort into *concentrating solar power* and *semiconductor saturable absorber mirror;* and whereas *nanostructuration* and *x ray magnetic circular dichroism* continued to mark research activity, it was less than in 2014.

3.4.2. Synthesis of nanomaterials and bottom-up processes and Optics and electronics – green cluster

In 2010, Germany reveals major research activity in *perylene bisimide, homogeneous catalysis* and *polyglycerol,* whereas France initially concentrates more research specialization on *nanostructuration* or *nitroxide mediated polymerization.* In Spain, the term highlighting research advantages is *screen printed carbon electrod.*

In 2014, new terms appear: for example, *synthesis gas manufacture* or *octanol* in Germany. The research activity in France is more heavily dedicated to *experimental protocols* or *prussian blue analogue*. In Spain the terms vary, with the emergence of terms such as *electronic tongue* or *competitive immunoassay*.

In 2018, greater research activity is focused on terms such as *galvanostatic cycling* and *silica surface* in Germany. In France, *diazomiun salt* rises as a relative advantage keyword, and new terms such as *hydrothermal vents* or *aryldiazonium salt* mark the bulk of research activity. Spain witnesses the emergence of further keywords: *structure sensitivity* and *carbon nanohorn*.

3.4.3. Biotechnology and Biomedicine: Therapeutic biomedicine – purple cluster

In 2010, Germany exerted greater specialization in the research topic *arabidopsis protein*, whereas *lipid nanocapsule* has a higher presence in France, and *biomedicine* prevails in Spain with *polyanhydride, zein* or *biosensing systems*.

In 2014, the keywords *magnetospirillum* and *nanoparticle uptake* cover the focus of most research activity in Germany; *lipid nanocapsule* still shows the highest relative advantage in France, and *caco 2* and *plasmodium* predominate in Spain.

In 2018, *magnetospirillum gryphiswaldens* still evokes the highest research activity in Germany, together with terms such as *orodispersible films* and *tautomerizations;* in France, new terms including *hippocampal neuronal culture* or *chromosome segregation* reflect a surge in research activity; while in Spain *plasmodium*, *brain edema*, *biochemical engineering* or *parkinsonism* emerge to represent specialization in NST.

3.4.4. Physical and mechanical characteristics of nanomaterials – blue cluster

The evolution of this research topic in 2010 is highly specialized in *meristem* and *magnetic* in Germany. In France, specialization is concerned with *yarn* and *nanobiocomposite*. In Spain, the highest degree of research activity is initially represented by *water vapour permeability* and *nanostructured ceramic.*

In 2014, terms reflect lesser research efforts in Germany, when relative advantages surrounded terms such as *scanning force microscopy* or *miniemulsion.* France´s research activity revolves around terms such as *hydrophobic molecule*, *polyelectrolyte multilayer film* or *supramolecular organization*. In Spain, terms such as *nanohydrogel* and *sepiolite* underline intensified research efforts.

In 2018, NST German efforts are focused on *invertebrate* or *stable isotopes.* In France, specialization shifts to *polyoxometalate* or *diagenesis. Sepiolite* still indicates high activity in 2018, together with *mytilus* and *smectite* in Spain

3.4.5. Biotechnology and Biomedicine: Biosensores – orange cluster

In 2014, research related to *Biosensors* displays the highest specialization through keywords such as *enbucrilate* and *fluorescence lifetime imaging microscopy* in Germany; *intravenous injection* shows intensified research activity in France; in Spain, the keyword *hyperthermia applications* reflects the most NST activity.

In 2018, this research topic shows different specialized terms. For example, in Germany *phenyleneethynylene* and *photoswitch* mark the highest research activity; in France, the keywords are terms such as *multivalency*, *chiral* and *polyelectrolyte multilayer;* and in Spain, *biomedical analysis* or *thermo sensitive polymer* are the terms designating the most intensive research activity.

3.4.6. Biotechnology and Biomedicine: Regenerative medicine – light yellow cluster

In 2014, Germany put emphasis on the term *synthetic bone graft.* In France, keywords *bisphosphonates* and *cortical bone* display the highest research activity. Spain´s research activity is more focused on *saliva substitute* and *remineralization.*

In 2018, Germany´s terms reflecting the highest relative advantages are *zoledronic acid* and *periosteum.* In France, new terms emerging are *bone mineral*, *bicuspid*, *physico chemical and mechanical property.* In Spain, *saliva substitute* and *artificial saliva* still show activity, but a bit less than in 2014. The emergent terms denoting new and intensive research activity would be *hydroxyapatite nanorods* and *physico chemical and mechanical property*.

4. Discussion

This study provides an overview of the cognitive structure and the relative specialization or comparative advantage of countries at the level of publications and research topics over time in NST research. We analyzed relative strengths and weaknesses in national performance and international competitiveness. The focus is an international comparison for three European countries (Germany, France and Spain) against a world baseline. This overview proves how mapping knowledge and depicting scientific intellectual structures in NST (or any other knowledge domain) are of importance to understand how it develops and how research units relate to each other in this domain. With an intuitive “picture,” it is easy for informetricians, research assessors, and even the public at large to unveil the inner structure of this domain and extract key clusters [58].

Our results reveal changes in the cognitive structure of NST at the global level, with new research topics popping up here and there. NST research tends to explore new technologies and applications with the potential to address societal challenges, improve the quality of life, and optimize industries that might benefit society, a finding in consonance with previous studies [59,60]. Porter et al. [27] argue that the development of theoretical stages in this domain helps consolidate new research topics focused on concrete applications of NST theories, which witnessed remarkable developments in engineering, medical and biological areas of NST. The novelty of this paper is that we show differences in national cognitive structures. For example, we observe that Germany´s scientific research is more concentrated on *Biotechnology and Biomedicine* research topics and *Microelectronics engineering and top-down processes* than France or Spain, at the world baseline. Within France, *Biotechnology and Biomedicine: Therapeutic biomedicine* is well represented, although the other research topics do not suggest noteworthy strength with respect to the world. *Physical and mechanical characteristics of materials* (blue) output is lower in Spain than in Germany or France, but the frequency of occurrence of its terms *increases more at the world baseline*. These differences may reflect diverse institutional settings and hence management cultures [61,62]. Further study is needed to explore how such factors may influence a country´s output and competitive edge. The analysis presented here, highlighting the strengths of particular countries, is helpful to orient research in certain fields to gain or maintain a firm research position, create alliances or collaborative ties with other countries, or compensate for weaknesses detected.

Overall, NST publications have undergone vast development over the last decade, as evidenced by the cumulative number of publications at a worldwide level. However, this growth is unevenly distributed among countries. For example, while the number of publications in Spain is still lower than in Germany or France, its growth in the past decade is greater (SI. Tables S1 and S2). This growth does not correspond with the rate of specialization, meaning that while Germany and France show some degree of specialization with respect to the world in the early years of study, their specialization decreases when the output in NST grows at a faster pace in other countries, for instance Iran or South Korea. Specialization profiles in core NST research may be high despite a relatively low world share (see SI, Table S3). The dynamics of scientific output in every single country and interactions among countries worldwide are both determinant factors behind advances in NST or other fields of specialization.

Some countries perform more or less evenly in terms of output and specialization, while others have evident and characteristic core strengths, even in research topics where the relative investment is low [63,64]. This can be quantified in various ways. For example, the specialization index applied by Chinchilla-Rodríguez et al. [44] showed Asian countries to have a higher concentration of NST research output than the rest of the studied countries, a possible indication that NST research has become established as a scientific priority in this geographical area. In contrast, though the United States is the greatest producer overall, it only stands out in specialization in 2003, with an excellence rate above the world average. France is the 6th greatest producer of NST, with a specialization index above the worldwide level, but its excellence rate is below the global average. Institutional settings and research management may play a key role in these outcomes; further analysis is needed to explore this possibility.

In short, each country (or geographical area) has a different pattern of specialization based on NST publications, which is a potential signal of relative advantage with respect to collaborators or competitors at the worldwide level. According to Hidalgo et al. [65], in terms of 'product space', these results may have important implications for economic policy, because they point to topics where a country might promote efforts toward transformation and gaining an upper hand within a specific scientific field. Such efforts could be focused, for example, on the economic investment to be made for products (topics) of vast potential, bearing in mind the level of a country and its weight in the global realm. When economic resources destined to the sciences are scanty, knowing just what and how countries produce can be determinant for allotment. As stated by Adams [62], even if the frontiers of research are endless, each country has only a limited quantum of good research to offer. Investment beyond that point is nugatory; greater quantity inevitably means poorer quality. Despite the challenges involved, the ultimate aim is to ensure greater efficacy in the development of research and sound competition in the global realm, including collaborative efforts among different countries, aspiring to ''Smart specialization''. This term refers to a political framework of vertical orientation that reflects the priorities established at a regional level. It combines upward and downward dynamics to set priorities for public investment in knowledge. This strategy helps guarantee that governmental efforts and resources are not spread out evenly; the key question is how to select the most relevant areas deserving investment [66]. Such a diagnosis foments positive transformation, by updating neglected areas, advancing along new lines of interest, or fortifying areas already competitive at the international level. Smart specialization entails identification of national strengths and weaknesses within research fields to establish priorities accordingly. It may be a useful strategy for building scientific capacity in developing and peripheral countries [67]. Alternatively, nations may develop a consensus about investment, and develop programs to concentrate talent behind core.

There are some limitations that should be mentioned. First, the analysis and comparison of just a few European countries is an obvious geographical limitation. However, this approach could be extended to analyze any country or institution in further efforts, to study a broad set of countries across continent and/or scientific capacities [68]. Criticism of the Activity Index and its mathematical equivalents would be a second limitation. AI implies some theoretical problems due to its mathematical structure [69] and its values for a field may be affected by the output activity of other countries in other fields, so that an across-field comparison could be misleading [70]. The interpretations of results from these indicators in the realm of science policy must be addressed carefully [41]. Third, we use high-frequency keywords to illustrate the combination of co-word analysis and activity index. Other non-high frequency keywords can be selected in further studies to unveil and compare research advantages that might lead to innovative NST research if these keywords appear in all units of analysis (countries, institutions, etc.) [39,57].

In addition, for a more detailed analysis of NST research, other approaches should have been studied as well as other data sources affording broad coverage (see for example, Hook et al. 71] and Huang et al. [72]). Alternative data sources would enrich this analysis —for example, considering qualified personal in relation to the total population, or the sectors most involved in knowledge production (namely, industry, government, or higher education sectors).

As usual, this approach or any other approach can always be subjected to discussion. Its suitability for a broad array of fields suggests a diversity of outcomes that might serve as feedback to modify and/or improve its application, in search of a process that will lead us closer to consensus among the scientific community. Further work is needed to provide indicators and interpretations of NST that would lead to a profound understanding of how research is produced, shared and developed.

5. Conclusions

Despite these limitations, this research paper, and the results it projects, can be seen as a platform of evidence for supporting decision-makers in the development of new policies that favor smart specialization and good practices in scholarly communication. The analysis of research topics is relevant because it substantiates the link between scientific yield in terms of the effort and level of activity undertaken by countries against a world baseline, and brings to light relationships within the competitive structure of a domain. The combination of several techniques may be used for technological surveillance in economic research policy and technological development. Future studies could attempt to untangle these associations at higher (regions) or lower levels (institutions) of aggregation. A global benchmarking analysis would help us gain a holistic view of knowledge production and the scientific capacities of countries, sectors or institutions.

In conjunction with the research aims stated, our contribution is twofold. Firstly, we trace the cognitive structure of NST over time by updating the NST dataset as described by Muñoz-Écija et al. [4]. This comprehensive search strategy along with science mapping provides an opportunity for a full grasp of NST development, but also proves useful to quickly detect relevant research. Secondly, our modification of the AI to measure keywords helps determine the salient research topics of countries. This modification can enhance the characterization of a national or regional profile, so as to detect efficiency in terms of specialization/innovation, in a field within the overall context of research output. Shedding new light on the background and characteristics of a domain could aid researchers in their own development and potentially support collaborations, calls for grants, or mobility programs. Therefore, having this information may accelerate investment along strategic research topics, which is beneficial for all the parties involved.

Authorship contribution statement

Author 1: Conceptualization, Methodology, Data Curation, Formal analysis, Writing- Original Draft, Writing- Reviewing and Editing.

Author 2: Methodology, Software, Writing- Reviewing and Editing, Visualization, Supervision

Author 3: Conceptualization, Methodology, Writing- Original Draft, Writing- Reviewing and Editing, Supervision

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Declaration of conflicting interests

None of the authors has a conflict of interest to declare.

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