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Research activities in Nanotechnologies and Nanosciences: an analysis of Piedmont's nanotech research system

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ABSTRACT

Nanotechnologies and nanosciences are since the end of the 20th century a relevant scientific and technological field. Nanotechnologies are widely exploited in industrial innovation in several industries, due to their pervasive nature. Being a highly knowledge-content field nanotechnologies deeply rely on the results of nanoscience research. This work presents the results of a survey, conducted with both quantitative and qualitative methodologies, on the nanoscience research activities performed in the research institutions of the north Italian Region of Piedmont. In order to perform a quantitative analysis scientific products belonging to each of the Universities and Public Research Organisations have been retrieved exploiting a specific methodology, and the analysed. The qualitative analysis has been realised conducting an impressive number of interview to researchers and university professor. The aim is to present a complete panorama of researches in this specific topic, with the aim of contributing to the analysis of the local nanotechnology and nanosciences regional system of innovation. At the end of the paper, results are commented, and conclusions are drawn.

KEYWORDS: Piedmont; nanotechnologies; nanosciences; research; Regional system of innovation.

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1. INTRODUCTION

Since the end of the 20th century, scientific research in nanotechnologies and nanosciences (NST from now on) has been one of the most burgeoning fields in science and technology (Zhu, Jiang, Chen, & Roco, 2017). This is true in terms of number of publication, in number of research projects and in received financing (Jiang, Gao, Chen, & Roco, 2015). The intrinsic character of multidisciplinariety and transdisciplinariety of NST (Finardi, 2012) is certainly among the factors contributing to this growth. By one side, this allows scientists of many different fields to work and publish on NST-related fields and to increase the total publication count on this field (Munoz-Sandoval, 2013). On the other side, this is one of the causes of the relevance of NST for innovation in most diverse industries and technological fields (Grinin *et al.*, 2017; (Islam & Miyazaki, 2009).

Due to their relevance in science, technology and innovation NST are also an important field of research in social sciences. Many scientific works in fact have deepened the study of the social and economic effects of NST, as well as the characteristics of the organization of research in this field under several points of view (Roco & Bainbridge, 2005; Roco, 2003; Salerno, Landoni, & Verganti, 2008).

The present work aims at contributing to the research stream tackling the problems of research organization in local environments in nanotechnologies. It tries to perform an analysis of the NST research activities performed inside the regional research system of Piedmont, Italy. To do so, it exploits a mixed methodology. The main part of the work relies on a series of interviews to scientist of the different research labs involved in NST research activities in the various research institutions (public and private) based in the region. Then, in order to complement interviews, a bibliometric activity has been performed retrieving NST scientific publication from the different institutions.

The present paper performs a description of the research activities, and systematizes them in order to offer to the reader an instrument to better understand and exploit what is going on in this field in the Region. However, this systematization focuses mainly on the policy makers, as well as on practitioners and technology transfer scopes, it is also interesting to the scholars who wish to approach nanotechnologies.

The remainder of the paper is organized as follows. Section 2 contains a literature review on the topics of research organisation in NST and of regional innovation and research systems. Section 3 describes the adopted methodology as well as the samples of the research, while section 4 presents the results of the interviews and of the bibliometric activity. Section 5 presents the conclusion on the experimental work.

2. LITERATURE OVERVIEW

The most relevant topics related to the present research work are the studies on the research field of NST (bibliometrics, organization of research, technology transfer from public research institutions…) and the studies on regional innovation and research systems. The present literature overview presents some of the most relevant and most recent works in these two streams of literature, in order to build a background for the following experimental section of the paper.

Social science studies on NST started just after their insurgence as a scientific field, probably due to their intrinsic relevance. Yet at the end of the 2000s in fact Shapira *et al.* (Shapira, Youtie, & Porter, 2010) examine the development of social sciences literature studying nanotechnologies. Social scientists start with strong impetus reviewing hard science literature on a field (nanotech in the case) in order to build a specific on-topic literature. In a similar vein Terekhov (2017) studies nanotech literature, mainly focusing on the specific case of Russia. The analysis shows that "USA and EU-28, shifting emphasis on commercialization of nanotechnology and, on the other hand, directing its interest toward a wider range of enabling technologies, continue to lose positions in the scientific nano—race" (p. 1238). In addition, Russia is slightly declining as most government financing goes to applied research.

Another seminal work analysing social science literature on nanotechnology is that of Huang *et al.*(Huang, Notten, & Rasters, 2011). Authors review more than 120 social science studies on nanotechnologies, most part of which (90%) are studies on publications and patents. Authors do also review different strategies used to harvest publications, and conclude advocating the need for continuous studies, for instance updating the sets of nanotech keywords. Under this point of view other relevant efforts are those by Mogoutov & Kahane (2007), Arora et al. (2013), Porter et al. (2008). A more recent contribution in this research area is that of Stopar et al. (2016) who study interdisciplinariety of NST performing a complex analysis,, using citations to measure similarity. In this way, they are able to identify four different clusters of literature: the main group, materials/physics/chemistry is also the least interdisciplinary.

In their introduction to a special issue on NST, Bozeman et al. (2007) advocate the potentials of NST research "to revolutionalize many sectors of industry, in particular by fostering the convergence between previously distinct technology-driven sectors" (p. 808). But one of the first essays of analysing the global path of NST research activities is that of Miyazaki & Islam (2007). Their work categorizes the different contributions of geographic areas in terms of importance and specific topic. Porter et al. (2018) pursue a similar aim in more recent years. Though exploiting only a bibliometric methodology they are able to explore national prominence and the emergence of new topics.

Robinson et al. (2007) study clustering in nanotechnologies focusing on two specific clusters, those of Twente and Grenoble. Also Finardi (2013) and Scaringella & Chanaron (2016) study Minatec in Grenoble. This specific topic is connected to the second stream of research reviewed in the present section, which is that of regional systems of innovation and research.

A seminal contribution to this topic is the work of Cooke et al. (1997) who explore and conceptualize the topic. So does Cooke (2001) who reviews also past contribution in innovation in regional sciences. A recent contribution that analyses a case study is that of Tödtling et al. (2012). Aim of the paper is to investigate the role of geography in the knowledge-innovation-industry systemic interrelations, using an Austrian case study as an experimental basis. Authors conclude: "The results of the multivariate models have provided evidence that the use of external knowledge sources is positively related to the innovativeness of companies. […] external R&D cooperations have significant positive effects" (p. 339, *passim*). Moreover, "firms rely to a high extent on regional as well as international knowledge sources, and to a relatively small extent on national ones. In particular, knowledge from R&D organisations and universities that is highly relevant […] is sourced often within the region" (p. 342, *passim*).

Other case studies analyse regional innovation systems and their features. An interesting work, not immune of criticisms, is that of Brown (2016) who, in his investigation of the Scottish regional systems advocates the theory that the "Third mission" of universities is impossible, at least in Scotland. This is due to the attempt to "turn universities into quasi-economic development agencies" which "seems a highly reductionist policy objective" (p. 200, passim). Todt et al. (2007) describe another, least recent case. In this case the subject is an advanced field, that of biotechnology in a peripheral region, that of Valencia (Spain). Authors aim at studying the relationship existing between public sector research and the development of industry. The main gaps in these relations are those existing between strong research-oriented activities and weaker

application-oriented ones, and between predominant out-of-region interrelations versus weak inter-regional ones.

Finally, we review recent contributions discussing Italian cases of regional innovation systems. The first one is that of Addie *et al.*, (2018) who compare the urban areas of Naples, Italy and Newark, NJ, US, under the profile of the spatial development of university-led innovation. The two areas show similarities, and the main points of strengths of the Naples area are strong international collaboration of the main Naples University (Federico II) and the role of the San Giovanni University Hub in reshaping the urban development of the area it is set in. The second one of the two contributions is the work of Barra and Zotti (2018) who instead investigate the efficiency of regional innovation systems at Italian level. Their findings support the investments in R&D from public and private actors, "which benefit the most to regional innovation activities; the evidence also suggests the relevance of the knowledge context in which the firms operate as the existence of an intermediation structure, such as a university technology transfer office, has an important role on the innovation process" (p. 432).

Summing up, this short overview shows the relevance of NST, as witnessed by the reviewed studies (a small fraction of the existing ones) as well as the scientific interest existing around the analysis of regional innovation and research systems. The following of the work will present the experimental activity that is at its core.

3. METHODOLOGY AND SAMPLE

In order to perform the present analysis, I have exploited a simple yet powerful methodology. First, the research institutions based in Piedmont and involved in NST research have been identified through a bibliometric study (reported in Finardi, 2018). In particular, the study has also allowed going back to the Departments performing activities in NST, and to several of the researchers mainly involved in the activities. Thus, I identified people to interview, in order to gather information on the research activities performed in the field. Interviewees are either researchers directly involved in NST research or head of departments or other research structures. I added other people to the list after being cited by the interviewees.

Once the interviews were completed, I synthesized results in a table summarising the research topics of the studied research institutions.

In order to corroborate the analysis I performed a bottom-up bibliometric exercise aiming at confirming the results obtained by way of the interviews. In specific, the adopted methodology has some similarities with the methodology adopted in Finardi (2018). In order to obtain a set of list of nanotech papers (a list for each research institution) I performed a data retrieval activity on Elsevier's Scopus® database. Scopus has been preferred to other similar databases due to its higher completeness in terms of encompassed journals, books and series and to the ease of use for data retrieving purposes. First of all each of the Piedmont's research institutions have been searched in the "Affiliation" search mask. Then, once obtained the list of publications relative to the institution, a data mining activity was performed using the "Advanced" search feature of Scopus. Specifically, the methodology used to search for data is an adaptation of that described by (Arora et al., 2013). In order to retrieve NST publications this methodology exploits a series of queries of meaningful NST terms. I chose these terms by Arora et al. in order to retrieve nanotech scientific production with maximum precision. In fact, these terms assure both that the obtained results contain the most complete set of nanotech scientific publications and that no spurious data are present.

In the present work the methodology has been slightly modified with respect to Arora et al., (2013) and consequently to Finardi (2018). In fact the search term "AND NOT (nano*)" has been eliminated from the queries. This search term was introduced in order to remove the items containing only the "nano" term that may have led to spurious results. In the present case the term was withdrawn from the search strategy given the circumscribed search neighbourhood, though this might have led to some pollution of results. As in Finardi (2018) the queries have been performed searching on TITLE-KEYWORDS-ABSTRACT. The obtained lists, relative to

each query, were merged into one list. Then duplicates were removed, and the list was scanned manually for further duplicates.

The lists obtained for each research institution have been analysed under several points of view: time evolution of publications, authors, keywords, etc.

4. RESULTS: PUBLIC RESEARCH INSTITUTIONS

NST research activities are performed both in public research institutions and in private research bodies. The three Universities of Piedmont (University of Torino, Polytechnic of Torino, University of Eastern Piedmont), as well as INRIM – Istituto nazionale di Ricerca Metrologica, the Italian National Metrology Research Institute, one of Italy's Public Research Organisations, having its seat in Turin belong to the first group. CRF- Centro Ricerche FIAT (FIAT research centre) and Istituto Donegani of ENI – Ente Nazionale Idrocarburi, Italian national body for hydrocarbons belong to the second group

The following sections describe the NST activities of each research institution, first reporting the results of the interviews, and then reporting the results of the bibliometric analysis.

4.1. University of Torino

University of Torino (UniTO from now on) is the oldest and the largest of the three Piedmont's Universities. Rolfo and Finardi (2014) describe the case of technology transfer at UniTO (together with Polytechnic of Torino). UniTO performs research and teaching in all Italian University fields except for engineering and architecture (which are monopoly of Polytechnic). University of Torino counts as of 2018 more than 72 thousand students, and more than 19 hundred professors.

4.1.1. Qualitative analysis: interviews. NIS – Nanostructured Interfaces and Surfaces Centre of Excellence

Research activities in nanotechnology at UniTO mainly coalesce around the Interdepartment centre NIS-Nanostructured Interfaces and Surfaces[1]. NIS was founded in 2004 after receiving a government financing for the creation of an Excellence Centre. Since then, its activities have connected the University Departments involved in NST research. In fact, in particular, among its tasks there are those of connecting activities of the departments in the field, of promoting collaboration, research and education in the field of NST. Since its foundation, the members of the Centre of Excellence have belonged to several different departments of the University. In specific, these departments are nowadays the Department of Chemistry, the Department of Physics (both departments were formerly divided into three different departments each), the Department of Life Sciences and Systems Biology, the Department of Drug Science and Technology, the Department of Earth Sciences. Many professors and researchers, as well as many Ph. D. students and Post-doc, belong to the Centre of Excellence.

More recently, after Departments' reorganization following Italian law 240/2010 on University reformation, its role has changed. First, it does not receive funding anymore as a single entity, and thus its activities are mostly cultural. Moreover, most of the task pursued at its beginning and innovative at that time – mostly in terms of collaboration, sharing of facilities and labs, etc. – are nowadays among the tasks of the Departments, which are more proactive than once. Finally funding assigned in the last years for the acquisition of research instruments compel the recipients to share the use of instrumentation among departments *and* with external users such as firms (after the payment of a fee).

Notwithstanding these changes, NIS still acts as a collector for nanotech research activities in the scientific Departments: professors and researchers involved in nanotech activities are af-

[1] See http://www.nis.unito.it/ (link visited April 2019).

filiated to NIS, conferences continue being organized under the NIS patronage and nanotech scientific products are still published with the NIS affiliation.

UniTO is a generalist university, performing research and teaching in all scientific fields (excluding engineering and architecture). This variety reflects also in the main NST research topics that are undertaken in its lab. These are detailed here below:

- *Catalysis and porous materials*. This topic encompasses research on zeolites, MOFs (metallo-organic-frameworks) as well as on the novel topic of porous ionic liquids (organic ionic liquids with several specific features). These materials are used as catalysts, for their gas trapping features and for selective organic synthesis in green chemistry processes. Other subtopics are those of functionalized silica for biomedical application and of zeolites-trapped dyes. These topics are extremely relevant not only on the side of basic research but also in terms of industrial contracts.
- *Physics for neurosciences*. This topic is relative to the growth and measurement of single neurons or little neural networks on artificial supports, mainly dealing with basic biochemistry aspects.
- *Photocatalysis*. Research in photocatalysis aims both at applications for water splitting and hydrogen production, and abatement of pollutants. A joint project with INRIM has recently dealt with metrology of photocatalisys and standardization of photocatalysts.
- *Hydrogen storage*. Notwithstanding the decreased interest on the topic on the side of automotive industry, hydrogen storage is still extremely relevant mainly due to its applications in hydrogen fuel cells. Light metallic hydrides have been still explored at UniTO to this end.
- *Metallic glasses*. Metallic glasses, as well as porous amorphous metals – in particular porous gold, obtained using dealloying techniques – have been studied for their use in sensors, as well as a material for SERS (Surface Enhanced Raman Scattering) techniques.
- *Thermoelectric materials*. This research field entails the study of joint doped thermoelectric materials aiming at energetic recovery.
- *Nano-biochemistry*. The research activities encompassed under this label involve the study of modified enzymes for hydrogen production and photo-electrochemical cells.
- *Carbon-loaded composites.* This research line studies and prepares insulating polymers loaded with carbon-based materials having piezo-resistive characteristics, with electric conductivity changing according to pressure. The use of these materials is intended in automotive industry: this field has a great importance on the side of industrial cooperation.
- *Other composite materials*. Other materials for aerospace have been recently developed.
- *Diamond nanotechnologies*. Diamond is studied both as a support for neuroscience studies (see above) and to create fluidic nanodevices: these are obtained by creating nanostructured channel with atom bombardment techniques.
- *Surfactants and dyes*. Surfactant and dyes have been studied for photovoltaic cells, in specific Grätzel cells using water as a solvent. This research field has led to industrial collaboration.
- *Nanotechnologies for pharmaceutics and cosmetics.* This research area studies first the realization with novel methodologies of novel catalysts. These are based on nanoparticles obtained with a mix of ultrasound and microwaves technologies. Metal nanoparticles (in particular Palladium, Nickel and Copper nanoparticles) can be dispersed on oxide matrices such as Alumina or Ceria. This allows a greater surface area and a better activity of catalysts, employed in heterogeneous catalysis to prepare drugs and fine chemical products. A further field of research deals with modulated crystallization of organic molecules, in particular drugs, allowing a better bioavailability.

Research infrastructures are all potentially accessible to external users; in the NIS website, in fact the “Laboratories” section offers the chance of instrument booking. This is also the result of the “Open lab” policy of the University of Torino.

NIS is involved also in several collaborations and research contracts with firms. Some of them, in particular those with larger industrial groups, are multi-year contracts. Besides these

larger collaborations, other research contracts aim at solving production problems and can be framed as technical-scientific consultancy contracts. Finally, in the frame of one of the collaborations a joint research lab is going to be established.

4.1.2. Qualitative analysis: interviews. Interdepartmental Centre "Giovanni Scansetti" for Studies on Asbestos and Other Toxic Particulates.

The Interdepartmental Centre for Studies on Asbestos and Other Toxic Particulates "Giovanni Scansetti" was established in 2001 and promotes research projects, as well as other activities (schools, seminars, conferences…) on the topics of health and environmental issues caused by respirable toxic particulates[2]. Its members belong to several Departments of the University, from both fields of sciences and of medicine. The Centre performs research activities studying asbestos, silica and quartz, artificial fibres, metallic dusts, nanoparticles, as well as man-generated particulate matter. More in general any material, which could affect the respiratory system once inhaled, is the research subject of the Centre.

Among the many research topics currently studied by the researchers and professors belonging to the Centre, some are related to NST. Most part of these researches is related to the fields of nanotoxicology and safety of biomaterials, as well as to those of nanomedicine. More in specific, the most relevant the topics are: the safety and the pathogenic features of nanoparticles of different origin (such as metals, metal oxides, Silica or Carbon) as well as of nanotubes, with particular attention to the effects on the respiratory apparatus and on the skin; hazard assessment of nanostructured materials; assessment and validation of standards and tests for nanomaterials toxicology; education and updating of students and workers on the topics of nanosafety and nanotoxicity. Some of the researchers of the Centre also participate to on-topic European projects.

4.1.3. Quantitative analysis: results of bibliometric analysis

The dataset obtained following the abovedescribed methodology contains for UniTO 557 publications. These publications have been analysed under several points of view. The first one is the time evolution of NST scientific production. Table 1 and figure 1 present the number of publications in the list from 1996 onwards. The number of publications spins up from the half of the 2000s onwards (NIS was founded in 2004). A peak is present in 2014. It must be noted that data for year 2018 are forcedly incomplete.

A second analysis has been performed on the names of the scientists who published the articles in the list. Without entering in details, it is possible to say that all UniTO authors belong to NIS, to Centro Scansetti or to both.

A third analysis has been performed on author keywords of the scientific works in the list, which have been counted. Results are presented in table 3. It must be noted that Scopus does not always collect author keywords and that thus they are not present in all records of the list. The list of single keywords counts more than 1,200 occurrences.

Most keywords in the list can be grouped together under several of the research fields above described. For instance, keywords that relate to Catalysis and porous materials are Raman spectroscopy and X-ray diffraction as adopted investigation techniques, and Nickel oxide and Titanium dioxide as studied materials. To the topics of Physics for neurosciences we can relate Diamond and Epitaxy; to Photocatalysis Titanium dioxide (the most important photocatalyst); to Nano-biochemistry Cancer, Drug delivery, Cytotoxicity; to Carbon-loaded composites the carbon based materials Graphene, Carbon nanotubes and Graphene oxide; to Diamond nanotechnologies obviously Diamond. Other relevant nano materials such as Quantum dots and Nanoparticles are obviously present in the list.

Finally sources (journals) publishing the articles of the list have been counted and listed. The list of single journals counts almost 300 titles. Results are presented in table 3. In addition, in

[2] See https://www.centroscansetti.unito.it/ (Link visited April 2019).

this case the list of journals reflects the above listed research topics. A wide part of the journals is materials-related or physical chemistry-related. Other journals belong to the fields of physics and pharmacy, and also generalist chemistry journals are present, as well as specific nano journals.

4.2. Polytechnic of Torino

Polytechnic of Torino (PoliTO from now on) is the second university of Torino and Piedmont. Funded as such in the first quarter of the 20th century, it is a technical university, performing research and education solely in the fields of engineering and architecture. Rolfo & Finardi (2014) as well as Finardi and Breznitz (2017) describe extensively PoliTO activities and historical path, with a focus on technology transfer. PoliTO counts as of 2018 more than 33 thousand students, and more than 960 professors.

The main difference with UniTO from the point of view of our analysis is the fact that here no structure such as the NIS-Centre of Excellence or the Centro Scansetti exists. This fact, coupled to an extremely defined structure of the departments, witnessed by the organization of PoliTO's official website, entails the fact that a large number of researchers are involved at least partly in NST research (with some overlaps in research topics among different research groups and teams), and thus a large number of interviews has been performed. Thus, this section is considerably longer than the previous one, despite the fact that both Universities perform NST research extensively.

4.2.1. Qualitative analysis: interviews. DISAT – Applied Sciences and Technology Department

Most part of NST research activities at PoliTO are performed by several research lab belonging to the Applied Sciences and Technologies Department DISAT ("Dipartimento Scienza Applicata e Tecnologia" in Italian). The sub-sections below describe the research activities of the different research groups and research sub-teams. Some of the groups not present in this list do exploit nanostructured materials (such as catalysts) for their research activities; nevertheless, once interviewed, they stated their research as not being NST *per se*.

4.2.1.1. CHENERGY – Chemistry and technologies for energy research group

Inside the CHENERGY research group, several research teams are involved in NST research activities. Here below is a detail of the different NST research topics of each team.

- Applied materials and electrochemistry research team: the core research topics of this research team are materials for novel power generation systems. The first topic is that of materials for Li ion batteries, as well as new Na based energy storage system targeted at solar energy plants. More in specific the research topic is that of nanostructured Lithium- Iron and Phospate-based cathodes (with characters of low cost, low environmental impact and high capacity) and Titanium- and Carbon-based anodes. Carbon anodes are obtained from food waste. A second relevant topic is the study of solid electrolytes to replace less safe liquid electrolytes. To build these systems the team studies the use of cellulose nanoparticles for structural strengthening and of ceramic nanoparticles as active element to enhance ion conductivity. Finally, a third research topic is that of low cost and environmentally-friendly dye sensitized solar cells. Here the research is manifold: bio-derived nanoparticles-enhanced hydrogel for cells; perovskite-based cell to substitute Silicon; Fluorine-enhanced polymer nanofilms to enhance the device self-cleaning and UV-filter; substitution of expensive parts (such as gold electrodes) with low cost solutions.
- Surface Chemistry of Materials research team: its main competencies lie obviously around surface chemistry. The first research line deals with porous Titania, either doped or in mixed phase, obtained with sol-gel technique. The aim is the study and improvement of its photocatalitic properties. A second line deals with CoO_x/MnO_x-based catalysts for water splitting, in

particular for water oxidation. These catalysts are studied due to their low cost. A third line deals with Si-metal composite microparticles containing magnetic nanoparticles. These composites are obtained thermally collapsing metal-doped zeolites. Such materials are studied for their mechanical properties, as well as for biomedical application. A fourth research line deals with inorganic/hybrid nanotubes obtained modifying Imogolites.

- Solar fuels and functional materials for smart energy systems research team: the NST research activities of the research team deal with modification of polymers via addition of nanoparticles in the polymeric matrix. In the first years, since this research activity was initiated the materials were studied in order to improve mechanical properties as well as gas barrier and flame resistance. Then research evolved towards other functional properties, including electrical and thermal conductivity, typically with the use of carbon nanotubes and graphene-related materials. In recent years, the team started the study of nanostructured coatings on various polymer substrates, preparing either monolayers or multilayers coatings with properties of flame resistance, gas barrier or electric conductivity. The main application of these materials is in the energy field, including materials for heat exchangers operating in highly corrosive environment, flexible heat spreaders and lightweight materials for transport applications. A recent application stream for nanostructured materials is in thermochemical energy storage systems. This is obtained by the exploitation of the reversible dehydration of hydrated salts. In such systems, nanostructuration with graphene-related materials provides advantages in the active sorbent phase, exploiting the enhancement of thermal conductivity and mechanical stability, as well as in the polymer nanocomposite heat exchanger, coupling thermal conductivity with corrosion resistance and ease of processing in to complex shapes.
- Electrochemistry research team: the main research topics of the Electrochemistry research team deal with problems of innovative batteries, and with the materials needed for their development. Such electrochemical systems are obviously in a pre-market stage, and are mostly post-Li-ion batteries, such as Li-S or Li-air, having energy density from 5 to 10 times those of Li-ion batteries. The main research effort is relative to the design of cells and to the use of novel materials exploiting nanostructured materials. For instance, the team exploits nanoparticles to build porous electrodes for Li-S batteries (as Sulfur is not conductive and needs to be trapped in a specific environment) or prepares nanodimensioned carbon coatings to enhance conductivity, or hybrid polymer coatings to protect Lithium from the external environment due to its high reactivity. The study of the use these nanostructured materials (as well as the building of batteries) allows tailoring of electrodes in a very specific way, with the aim of obtaining both higher capacity and higher energy from novel design batteries. A further research topic is that of self-healing batteries, that is, batteries built with parts (such as membranes) able to self-regenerate or containing sensors that allow the interaction with security systems.

4.2.1.2. CMPCS – Condensed matter physics and complex systems research group

Inside the CMPCS research group one of the teams, the Nanophysics and quantum systems research team, deals with NST research activities. The team's research activities are mainly theoretical simulations, though it works at strict contact with experimental researchers. The team began about 20 years ago working on semiconductor-based materials, and optically active materials such as Gallium arsenide or more recently developed materials exploited for optoelectronics applications, such as graphene-based materials. The basic idea underlying the research activities is to simulate optoelectronics devices or transistors, detectors, new generation lasers and other devices studied for applications in electronics. More in specific relevant results have been obtained in the field of lasers. Traditional lasers are based on quantum wells, while recently new materials, emitting in the Far Infrared or generating radiations in the terahertz field, have been used. This has helped in the mid-2000s studying and then building the first Quantum cascade laser, emitting radiation in never explored bands. The research team performs simulations of different type (e.g. using Monte Carlo methods) reproducing with calculations what will happen in the device, and thus collecting results on its properties. The study is relative to both steady-

state and time-dependent behaviour. More recent research topics are those of topological materials (materials presenting surface behaviour different from bulk) and quantum computer applications. The research team collaborates with several national and international research institutions, while collaboration with firms is less developed due to the intrinsic nature of the research topics.

4.2.1.3. GLANCE – Glasses Ceramics and Composites research group

Among the research topics of the GLANCE research group, many are those belonging to different NST research areas. The first one of these areas is biomaterials. The research topics studied in this field are many: antimicrobial layers (based on silver nanocluster-silica matrix composites or surface nanostructured titanium alloys); multifunctional magnetic nanoparticles for health applications (generally presenting core-coated structure); surface modification of Titanium alloys in order to enhance the adhesion of soft/hard tissues; surface functionalization of different biomaterials with biomolecules; synthesis, characterization and testing of bioactive and ferromagnetic glass ceramics containing nanometric magnetic crystal in a biocompatible glass matrix; realization and study of silica-based glasses or glass-ceramics containing antibacterial elements such as Silver, Copper or Zinc.

A second NST research area of the group is that of sputtering. Research in this field is related to the design, production and characterization of thin films and smart coatings for different applications. These films and coatings are designed and produced aiming at several different applications, such as biomedical, optical, energy, resistance in harsh environment, as well as aesthetic.

4.2.1.4. MPMNT - Materials and Processes for Micro & Nano Technologies research group

The MPMNT research group deals with a series of NST research topics; the group is also involved in the local section of IIT-Italian Institute for Technology.

- *Biomedical and food*. This research line deals with two main topics: detection of biomolecules and creation and study of smart scaffolds for precision medicine. This last research topic entails the building of polymeric scaffolding where tumour cells can grow in tridimensional conformation, that is, similar to natural tissues. In this way it is possible to test on tumour avatars batches of new drugs aiming at personalized medicine. Such scaffold are micrometric *per se* but are nanometrically structured in order to allow cell adhesion. Their structures are in fact zeolite-like. This research line is novel with respect to traditional diagnostics.
- *4.0 industry*. This research line deals mainly with 3-D printing, in particular with electronics and sensors made with polymeric materials. In this field the group did participate to competitive bids on regional funding.
- *Energy, sustainability and environment.* Activities in this area are mainly focused on the study of: sensors for environmental monitoring; graphene-based membranes for water filtering; supercapacitors for energy storage. In particular, this last research line aims at studying and producing supercapacitors alternative and complementary to batteries. These are small capacitors presenting very high capacity, mainly polymer-made and flexible, and with a water-based electrolyte. The advantage of such capacitors is that they are easier in use and greener than batteries in terms of exploited materials. In these devices the nanotech side of the research lies in the study and creation of the electrodes' surface, which is nanostructured in order to increase the surface area, and made with graphene-based conducing polymers.
- *Sustainability and energy*. This research line is performed by the local section of IIT, strictly connected to the research group. Research activities in this area relate to low carbon economy: trapping of CO_2 via nanostructured materials, ionic filters, dendrimers and nanostructured catalysts for CO_2 reduction. These catalysts are mainly based on metal oxides (e.g MnO_x SnO_x CuO_x TiO_x ZnO_x) and graphene and can be used also for electrocatalysis and photocatalysis for CO_2 reduction. The aim of these processes is to transform CO_2 into raw materials. A further relevant point is the almost completed new biocatalysis lab (fully fi-

nanced by the Regional government) where the study will deal with bacteria able to digest CO_2 and to transform it into hydrocarbons, or to produce biodegradable biopolymers.

Also industrial collaboration spans across the various research topics. Regarding biomedical, most collaborations are with firms that aims at using precision medicine data rather than with those interested in developing hardware. This is due to the structure of the industrial sector in the Region. Regarding agrifood the presence of a vast number of firms makes collaboration easier, though most firms are end users interested in technological solutions for food quality monitoring, that is, checking for the presence of bacteria, antibiotics, anabolic steroids, etc. Again technology producers are absent in the industrial environment of the Region. 4.0 industry topics are of interest for several sectors, and many firms wish to innovate their production lines. Research in this field tackles the creation of non-standard hardware with *ad-hoc* nanoelectronics, more specifically to solve miniaturizing problems for instance in measuring parameters. Collaborations in the field of energy and environment involve energy managing, energy production, large players and firms interested in environmental monitoring, water supply, gas supply in need to verify the integrity of their distribution network, pollution. Thus, they need sensors to integrate in their assets. Many large players show high interest towards CO_2 abatement and reuse. The aim is to produce devices that often need specific nanostructured materials to be realized.

4.2.1.5. MUSYCHEN – Multiphase systems and chemical engineering research group

Inside the MUSYCHEN research group, several research teams are involved in NST research activities. Here below is a detail of the different research topics.

- Process system engineering research team: the main research interest of the group in NST is the production of polymer nanoparticles that are exploited as carriers. The main applications studied so far are the use as carriers of dsRNA in agro-pathology applications and as antibiotic carriers. Nanoparticles are produced and characterized in terms of dimensions distribution and surface electric potential; this last feature is essential as the presence of a positive/negative surface charge avoids the particles to coalesce and, in some cases, it is mandatory to have a positive (or negative) surface charge to get the particle interacting with the target tissue. Once the particles are produced and the active principle is introduced in the particle that shall carry it, a titration of the content is performed via spectrophotometry. A relevant part of the research activities is devoted to study and apply the best conditions to produce nanoparticles for the scope and to allow the most concentration of the carried active principle in the nanoparticles, as well as to study the release in laboratory conditions. Another subtopic is that of the conservation in time of nanoparticles, which must be stable for a certain time lapse between preparation and use. Nanoparticles are thus lyophilised, and the production process is optimized also in terms of best conservation time. Research is obviously performed in collaboration with departments and institutes interested in the use of the produced nanoparticles.
- Molecular Engineering Lab (MOLE) research team. Among the several research lines of the MOLE Lab two are fully nanotech. A first research stream involves the study and realisation of polymer nanoparticles exploited as nanocarriers for pharmaceutical use. Such nanoparticles are produced exploiting different photopolymerisation techniques: minimulsion, aerosol and microfluidic. Each technique entails the production of a different dispersed phase precursor to the nanoparticle formation. The experimental activity deals also with the control of the structure of the nanoparticles. Four different types of nanoparticle structures can be obtained: bulky, capsules, porous and porous capsules. Besides experimental activity in laboratory also computational simulations are performed in order to better study and define transport properties of nanoparticles. A second research stream studies the use of micro- and nanoparticles exploited to encapsulate ethylene gas for controlled release applications in food industry. In specific ethylene is used in fruit packaging solutions as ripening promotion agent. Nanoparticles in this case are made of Cyclodextrin extrusion complexes: gas is

trapped into Cyclodextrin crystals, and its controlled release allows controlling ripening speed.

- POLILATT (Textile Research & Process Engineering) research team. The main NST research topic of the POLILATT research team is related to functionalization of textiles. In particular the main NST expertise of the group is the production of polymer nanoparticles containing active principles and their grafting on the surface of textiles for applications in pharma, parapharma or cosmetics. Grafted nanoparticles release active ingredients for trans dermic applications (for instance to relieve skin pain in determinate conditions). Textiles can be either hospital gauzes or clothes, according to the specific application. Another research line is the surface functionalization of synthetic fibres (in specific polyester) with hydrophilic polymers (like PEDGDA or METAC). Nanodimensioned coatings, obtained polymerising the monomers directly on the surface of the fibre, confer hydrophilic properties able to mimic the behaviour of cotton. Finally, a third NST research stream is that of plasma modification of the surface of textile fibres. Plasma etching is performed in order to modify surface characteristics or to prepare fibres for following gripping.

4.2.1.6. SIMTI – Materials Science and Engineering for Innovative Technologies research group

Inside the SIMTI research group several research teams are involved in NST research activities. Here below is a detail of the different research topics.

- ALL-POLYMER research team: the main research topic of the team involves the modification of polymers exploiting nanostructured materials or coatings for different applications. Both thermoplastic and thermosetting polymers are charged with different nanostructured materials such as carbon nanofillers (such as graphene and carbon nanotubes), nanoclays or piezonanoceramics. For these latter materials, the goal is to improve thermo-mechanical or electric conductivity of the polymer matrix, or to obtain materials with energy harvesting or piezoelectric features. Nanocoatings are obtained either using sub-micro- or nanoparticles. Other bottom-up systems (namely, sol-gel processes) are exploited for obtaining flame-retarded surfaces. Ceramising layers obtained depositing nanosized precursors confer flame retardant properties to the polymer. Another studied process entails a layer-by-layer application of nanometric (almost monomolecular) layers on fabrics or films, exploiting ionic interactions of the substrate. In fact, electrostatic interactions allow applying layer over layer of a specific nanofiller, thus conferring flame retardant properties without external changes in the fabric. Finally, a further studied process is that of dispersion of nano-charges on a bio-sourced thermoplastic polymer matrix. Nanocharges are dispersed at low concentration (up to 4 – 5 %) and then the mass is extruded or mixed. The target of these technologies involve applications in the automotive industry where bio-sourced polymers allow a higher degree of recycling in a circular economy vision.
- Biomaterials research team. Among the research topic of the team a relevant NST research stream is pursued. The research has the target of preparing materials for the regeneration of living tissues, in specific to promote osteogenesis and to heal chronical wounds. To this end the group uses specific nanostructured micro/nanoparticles (around 100 nanometers diameter) called mesoporous glass, which possess internal nanostructuration. These mesoporous glasses are silica based and contains also other ions such as Calcium, Strontium, Copper and Silver. The use of a templating agent allows modulating the internal structure of the nanopores of the particles. Once nanoparticles are prepared then their surface can be modified in order to graft antibodies or growth factors. Micro/nanoparticle, due to their nanostructuration, possess a high surface area, and are thus apt at releasing molecules or ions (for instance ions possessing pro-osteogenic, antibacterial or angiogenesis-promoting features). A further studied topic is that of drug controlled release, as nanoparticles can be loaded with drugs, and release kinetics of such molecules can be controlled.
- Ceramic materials research team: the research team studies ceramic materials for several applications. Main studied applications are those in the biomedical field. Alumina-Zirconia ceramics are studied to produce femur heads prostheses, or dental prostheses and spinal pros-

theses; such materials present high mechanical properties of resistance to fractures and of biocompatibility. Non-structural ceramics, based on Calcium Phosphates, are studied as bone substitutes. Such porous materials in fact present less marked mechanical properties but in turn can induce and stimulate spontaneous bone tissue growth when implanted in human body, and are then re-adsorbed by the body itself. Nanostructuration of such materials is fundamental as working with extremely fine-grained ceramics allows maximising mechanical properties and making the material last longer. Other research lines study monophasic or composite ceramic materials presenting characteristics of high resistance to mechanical and thermal shocks, and intended for the use in the production of cutting tools. Again, nanometric fine-grained powders allow obtaining better properties. A further topic is that of transparent ceramics, joining transparency (proper of amorphous Silica glasses) with ceramic's mechanical properties. In this case, the technology entails the use of Alumina or Spinels presenting cubic structure; specific sintering technologies (pressure sintering or electric pulse sintering) are exploited.

- Materials for High Temperatures and Nanocomposites research team. The main research interests of the research team lie around the realization and study of polymers functionalized via the use of Carbon nanotubes or graphene. A recent research project did entail on the side of the team the evaluation of thermal treatments and the creep features of produced materials. Another activity is the use of graphene and Carbon nanotubes, also in addition to other fillers, to confer electric conductivity to polymer matrices. Nanoparticles, Carbon nanotubes or graphene are also used to obtain polymers apt at being worked with laser beams in order to create conductive traces via local pyrolysis. The most recent research stream is dedicated to the study of addictive manufacturing of polymers modified with nanostructured fillers. The aim in this case is to study the use of nanocharged polymers as materials to exploit in additive manufacturing processes. Both thermoplastic and thermosetting polymers are used as matrices in all the above-described researches. Besides polymer composites, another research stream entails the use of ceramic nanoparticles (Alumina or Aluminium nitrides) to improve mechanical characteristics of Magnesium alloys.

4.2.1.7. SMAC – Supercritical Fluids and Materials Chemistry research group

The SMAC (Supercritical fluids and MAterials Chemistry) research group joins competencies in Chemistry (surface chemistry and solid state chemistry) and in Chemical Engineering (supercritical fluids). Two main research topics in the group deal with NST. The first one deals with the synthesis of nanoporous aerogels with supercritical carbon dioxide. Silica and organic precursors are used to build aerogels. The second research stream (which at present is the main of the group) tackles studies on nanostructured materials for drug delivery. Two types of inorganic materials are produced and studied to this end. The first one are classical mesoporous Silica-based materials, which nanoporosity can be controlled during the production. A second material is nanostructured ZnO. These materials derive from the aggregation of Zinc oxide nanoparticles, and present disordered porosity. The advantage of exploiting Zinc oxide-based materials for drug delivery is due to its intrinsic antibacterial activity (deriving also from the presence of Zinc ions). In addition to laboratory-produced materials also commercial mesoporous Silica – yet registered as pharma eccipient – are exploited for the next steps of the research activity. These are first the drug loading, obtained with the use of supercritic carbon dioxide, and the following study of release of drugs in systems simulating the true biological environment.

4.2.1.8. SMIM – Superconductivity and Magnetism in Innovative Materials research Group

Both teams of the SMIM research group are involved in NST research. The research group deals with scientific-technological problems related to superconductivity. Part of the research topics can be labelled under "nanotechnologies" while other ones are better described as "nanoscientific". In studying superconductivity researchers exploit the nanoscale origin of phenomenon. The team more involved in basic nanoscientific research mainly tackles the realization and

the study of novel superconductor materials, either improving existing materials or studying other ones never exploited as superconductors. Research involves, among other techniques: the use of Scanning tunnelling spectroscopy to characterize materials; the introduction defects in the superconductor using strong electric fields with the aim of obtaining superconducting semiconductors. The second team mainly deals with more applicative topics such as characterization of superconducting cables, or of superconductor-based single photon detectors.

4.2.2. Qualitative analysis: interviews. DIATI – Department of Environmental Engineering, land and infrastructures

A relevant research activity exploiting nanostructured materials is conducted at the DIATI – Department of Environmental Engineering, land and infrastructures (Ingegneria dell'ambiente, del territorio e delle infrastrutture) at the Research group of Health and Environmental Engineering. This research activity is related to the use of huge quantities of nanoparticles for remediation and de-contamination. The importance of this research lies in the high number of contaminated sites: these are around 1,200,000 according to a JRC research. One should consider the fact that rivers and lakes are only a mere 1 % of total fresh water, while 30 % is groundwater (the rest of the fraction is present in polar ice). Notice that freshwater is a mere 3 % of the total quantity of water.

This technology is aimed at solving the important problem of pollution deriving from the presence in freshwater of chlorinated organic compounds, such as trichloroethylene. These compounds are heavily used as solvents in chemistry and mechanics as well as in dry cleaning. They are not miscible with water and more dense, and thus migrate in the subsoil as a separate phase until they reach the impermeable layer. Here they slowly migrate polluting the groundwater layer, as the continuous contact between pollutant phase and slowly flowing freshwater continuously strips pollutant.

Several techniques have been studied in the past, such as pump and treat techniques, vapour stripping of contaminants, microbial degradation, etc. Nevertheless no one of such techniques is satisfying either for the results or for the work safety problems they entail.

The method that has been studied in the research group in past years is that of Reactive Permeable Barriers. This technology consists in digging a trench (about 50 centimetres wide) and filling it with a powder of an oxidizing agent able to reduce the chlorinated molecules. This reaction is more efficient that biodegradation is. The usual oxidizing agent is metallic Iron. The barrier is installed across the flow of the groundwater layer and, being permeable, allows water passing through it and reacting with the oxidising agent.

The natural evolution of this technology has been going from millimetre-dimensioned particles to nanoparticles. As the reaction kinetics are obviously influenced by the specific surface of the oxidising agent, the use of nanoparticles (around 80 nanometers) allows a greater efficiency. Moreover in this case it is possible to inject Iron nanoparticles puncturing the soil and attaining directly the polluted phase. The technology allows reaching depths up to 15 meters; the quantities of nanoparticles lie around the ten tonnes.

The research interest, on the engineer's side, is that of sizing the intervention: where and how many times one should puncture the soil, which distance can iron nanoparticles attain, which quantity should one use, etc. Here lies the specific knowledge of the research group. Nanoparticles present a relevant technological problem: due to their peculiar magnetic behaviour, they tend to coalesce and, thus, to not diffuse in the polluted stream and in the pollutant phase. After several test the best solution to stabilize the iron nanoparticles has been the use of surfactant polymers able to stabilize the nanoparticles. Such polymers are biodegradable and are used also for food processing. Nanoparticles are stabilized prior to the injection, allowing the use of lower pressures. This technology attained a distance record for the diffusion of nanoparticles. After a series of laboratory trials the technology has been scaled and has been implemented in a series of European research project. The last of these ones involved the use of Iron Oxides aimed at the interaction with metals. The research activities resulted also in a number of recent patents, as well as in international scientific collaborations.

4.2.3. Qualitative analysis: interviews. DIMEAS - Department of Mechanical and Aerospace Engineering

The “Materials in Bionanotechnology and Biomedical Laboratory” research group at the Department of Mechanical and Aerospace Engineering (DIMEAS) develops degradable biomaterials of natural and synthetic origin for biomedical applications. For what concerns NST applications, the group designs synthetic materials that are processed in the form of nanoparticles in the dimensional range of hundreds of nanometers, using precipitation or emulsion methodologies. The main application is in drug delivery to tumors, where nanoparticles tend to accumulate preferentially. The group has tested both commercial and self-produced polymers to this end. Another research line deals with encapsulation of Magnetic Iron Oxide nanoparticles to obtain multifunctional nanomedicines. These systems can be directed towards the target by applying an external magnetic field and, subsequently, generate heat to damage cancer cells, or can be used as magnetic resonance contrast agents. Nanoparticles can also be surface-decorated to obtain specific circulation or target-recognition features. For instance, specific antibodies with affinity for receptors on cancer cells can be linked to their surface. These activities are conducted in collaboration with national and international hospitals, in order to investigate their perspective application in the clinics.

4.2.4. Qualitative analysis: interviews. DET – Department of Electronics and Telecommunication

Some of the research groups of DET – Department of Electronics and Telecommunication perform NST research activities. This fact is also witnessed by the relevant NST scientific production of the Department’s researchers and professors. The sub-sections below describe the research activities of the different involved research groups.

4.2.4.1. Linear and nonlinear circuits and systems (LINCS) research group

The LINCS research group performs research on the topic of the development of circuit models of nanodevices. The use of modelling is aimed at the project of biologically inspired calculation systems, such as neural networks or associative memories. In the last ten years, the most studied nanodevices have been memoristors (memory resistors). These are RAM memories based on resistors. The main interest of the group is the extraction of functional models aimed at modelling systems starting from physical characteristics of the matter and from electrical characterization. Part of the research activities are at “low level”, that is, at the device level, trying to understand the physical problems that are at the core of the functioning of the device and that allow establishing the main functioning characteristics. As an example, memoristors are able to memorize information as they change their resistive state based on electrical pulses. Once a circuit model is developed, this is inserted in a more complex system, bringing the interest to the circuit level, where circuit features are developed, studying non-linear dynamic circuit behaviour. To this end, several techniques based on non-linear differential equations are exploited in order to understand non stationary, oscillating or even chaotic behaviours. At this stage calculation units are joined in order to build a network, exploiting the above described dynamic behaviours, and trying to understand how the units should be connected in order to perform useful operations. Depending on the aim, the different behaviours can be exploited, and different operations must be combined in order to generate an algorithm. The main NST relevance is at the level of modelling of devices. As the group performs solely theoretical studies, it is interfaced with laboratories which build the devices starting from the performed measurements, and which realize the integration of the different circuits and devices.

4.2.4.2. VLSI Theory, Design and Applications (VLSILAB) research group

NST research activities at VLSILAB are essentially performed under two main topics, plus some minor ones. A first stream of activities is linked to nanocomputing, trying to exploit

emerging NST to perform non-conventional elaboration. Silicon transistors are facing nowadays the problem of a physical barrier, as their dimension (which is at present around the 10 nanometers) can't be scaled below this level of miniaturization. Thus new pathways must be followed. The group investigates emerging technologies that do not exploit MOS transistors, which are at present those exploited in integrated circuits. In specific, the group studies the application of nanomagets to elaboration of information. Nanomagnets can be used as elementary bricks of calculators in several different ways. The general mechanism is to transmit information through magnetism and no through electrical impulse. A second research stream relates to molecular devices, exploiting molecules with specific shapes that make them able to transmit information via electrostatic coupling. This second research stream is even more on the edge that the former one. Finally, a third, more classical, research stream aims at improving Silicon-based technologies with NST techniques, for instance exploiting nanotubes or nanowires. Then a NST stream is linked to sensors, aiming at the production of sophisticated and miniaturized sensors. Main industrial collaboration of the research group is outside Italy.

4.2.4.3. Semiconductor integrated optoelectronics and photonics (SIOP) research Group

Among the many research activities of the group, mainly related to optoelectronics and microwaves, one is connected to NST. The group is involved since the last ten years in the theoretical study of the use of semiconductor quantum dots for their application into photonics devices, in particular in lasers for information transmission. The group performed modelling of devices incorporating quantum dots starting from their properties and from other experimental data. Once studied a theoretical model projecting and production of the devices where realized elsewhere. In the last year, the expertise in modelling of the use of quantum dots has been exploited also for their use in photovoltaic cells.

4.2.5. Quantitative analysis: results of bibliometric analysis

The dataset obtained following the above-described methodology contains 1,177 publications for PoliTO. In addition, in this case publications have been analysed under the same points of view. Regarding the time evolution of NST scientific production results are presented in table 4 and figure 1, again showing the number of publications in the list from 1996 onwards. In this case, the growth in number of publications starts earlier, though it is less regular. The presence of peaks and lows may depend for instance by the presence or absence of financing deriving from competitive projects. In this case, too, data for year 2018 are forcedly incomplete.

The analysis of authors' names shows a good compliance with the data obtained via qualitative analysis. All the most NST productive PoliTO's researchers are among those interviewed in the above-described analysis.

PoliTO's keywords are listed in table 5 together with the number of occurrences of each one. Due to the number of groups and topics dealing with NST research also the list of keywords is rather long and complex. The keywords presenting the highest number of occurrences is "Graphene", present 63 times (together with "Graphene nanoplatelets" and "Graphene oxide"), and followed by "Quantum dot(s)", 33 and "Dye-sensitized solar cell(s)", 31. Graphene is nowadays a fashionable topic and a multi-purpose material, so its presence at the top of the list is not a surprise. Also quantum dots can be exploited for several purposes; nevertheless the number of occurrences is slightly above the half of the previous one. More in general the keywords in the list reflect the research topics described in the above presented qualitative analysis. The keywords related to the research activities in nanoelectronics are only slightly represented in the list (Semiconductor lasers, the most represented, has ten occurrences). Conversely, some of the journals related to electronics – "IEEE Journal of Quantum Electronics", or "Proceedings of SPIE - The International Society for Optical Engineering" – are at the top of the list of sources. More in general this list shows the wide number of fields touched by PoliTO's NST research activities.

4.3. University of Piemonte Orientale (UniUPO)

The University of Piemonte Orientale "Amedeo Avogadro" was founded in 1998. Since the end of the 1960s the University of Torino did activate courses in the Eastern Piedmont towns of Vercelli and Novara and, later on, of Alessandria. Once detached branches of the university were created in these towns, the creation of a novel independent university followed as a natural development. University of Piemonte Orientale (Eastern Piedmont) counts as of 2018 almost 13 thousand students, and more than 370 professors.

4.3.1. Qualitative analysis: interviews

NST research at UniPO is concentrated at the DISIT – Dipartimento di Scienze e Innovazione Tecnologica (Sciences and technological innovation Department). In specific the two research groups involved in NST are the SusMat (Sustainable development of materials) group (also involved in the Interdisciplinary Centre for Nanosciences and Technological Development of Materials nano-Sistemi) and the Macrogroup (macromolecular chemistry)[3].

4.3.1.1. SusMat research group and Interdisciplinary Centre for Nanosciences and Technological Development of Materials nano-Sistemi

In detail for the SusMat group research topics are:

- *Gas storage materials*. Gas storage materials are studied both for CO_2 trapping in environmental application and methane storage. Porous materials such PAFs ( ) are studied to this end. Such materials possess areas over 3000 square meters per gram and are thus extremely promising in terms of gas storage possibility. The group has relevant industrial collaborations in this field.
- *Materials for environmental decontamination*. In this field, the group is active in the synthesis and characterization of several types of materials: nano-porous systems, zeolites, multilayer materials are studied for the removal of heavy metals from water, as well as for nerve gas decontamination.
- *Hybrid catalysts*. Hybrid organic/inorganic catalysts are studied in order to allow industrial processes involving heterogeneous catalysis rather than homogeneous in carbon-carbon bond reactions mainly in fine chemicals/pharmaceutics industries. Such processes are less polluting than previous ones, hence the need for the development of such catalysts. The group is involved in a huge European project involving end users of the process.
- *Nanotechnologies for nanomedicine*. The study of nanotech medical applications is based on the use of nanoparticles for optical imaging applications or multidimensional photodynamic therapy, where nanoparticles release singlet molecular oxygen which is cytotoxic.

4.3.1.2. Macrogroup research group

At the Macrogroup research group, research topics are instead:

- *Block copolymers for nanostructured surfaces*. Such surfaces are exploited in various applications, such as nanolithography to build microelectronics and mask for Silicon doping. Such techniques enable building circuits down to 10 nanometers.
- *Block copolymers for the production of nanospheres*. This activity is conducted in collaboration with INRIM (see below).

4.3.2. Quantitative analysis: results of bibliometric analysis

Data for UniUPO publications are reported in table 7 and figure 1. The total number of publications in the list is 155. In this case, publications start from 1999, just after the foundation of UniUPO. Data show that the number of publications rises slowly but steadily, though not regularly. Most productive authors belong to the above described groups and departments. Coming

[3] See https://www.disit.uniupo.it/ (link visited December 2018).

to most used keywords, these are reported in table 8. Again, these are strictly connected with the topics presented in the qualitative analysis: Self-assembly, Block copolymer(s), PS-b-PMMA, Polymers, PTFE relate to the research on block copolymers, Raman spectroscopy and X-ray diffraction are common investigation techniques, Biomaterials and Cytotoxicity are connected with research on nanomedicine, Nanoparticles and Graphene are widely studied nanomaterials. Finally, coming to the publications' sources, reported in table 9, the journal containing the highest number of publications is ACS Applied Materials and Interfaces; this and the other journals present in the list fit with the above described research topics.

4.4. INRIM – National Institute for Metrology Research

INRIM (Istituto Nazionale di Ricerca Metrologica) was founded in 2006 merging two research institutes, Istituto Elettrotecnico Nazionale "Galileo Ferraris" and Istituto di Metrologia "Gustavo Colonnetti" of CNR. Its main mission is realising, maintaining and developing the national reference standards of all measurement units. The metrology activity is enhanced by basic and applied research in several fields: materials sciences, optics, physics and obviously NST.

4.4.1. Qualitative analysis: interviews

In the last decades of research activities INRIM researchers have studied several NST topics, always keeping in account specific metrological applications. In particular, before and around its foundation (years 2000-2007, that is at Galileo Ferraris Institute and Gustavo Colonnetti Institute) the main research topics were those related to: the applications of porous Silicon in photonics and in gas sensing, in particular in its interactions with NO_2 and other gases; nanostructured semiconductors; magnetic materials; superconductors and Josephson junctions. The first clean-room labs were founded back in the 1990s and enabled the production and study of such materials and devices. Moreover, at the beginning of the 2000s a novel research line on nanolithography was established.

These research topics continued being followed until, at the end of the 2000s, INRIM received a consistent financing to support (Compagnia di San Paolo Foundation) the creation of a nanofabrication laboratory, the Nanofacility INRIM. The instruments present in the lab (mainly electronic microscopes) allowed the use of several manufacturing techniques: Focused ion beam, nanomanipulation, ionic and electronic nanolithography. The instruments of the facility are all available to external users.

Besides these topics the main research theme are nowadays (since the half of the 2000s):

- *Nanosphere lithography*, resulting from self-assembly of polystyrene or silica beads, and diblock co-polymers self-assembly. Such nanospheres are deposited on Silicon surfaces from a solution by various approaches, like Langmuir Blodgett or spin coating. Polystyrene nanospheres have dimensions ranging from few micrometers to 100 nanometers, while to reach dimensions around 50-10 nanometers block co-polymers morphologies (tipically polystyrene plus Polymethyl methacrylate) are exploited.
- *Metamaterials*. These materials possess peculiar optical properties, presenting effects similar to those of photonic crystals in systems with thickness of few atomic layers.

INRIM scientific collaborations span across several European and national bodies, with a specific focus on metrology; the presence of nanofabrication laboratory in a metrology research body is almost an unicum in Europe. Industrial collaborations involve large industrial groups involved in microelectronics and aerospace, as well as other firms.

4.4.2. Quantitative analysis: results of bibliometric analysis

Quantitative analysis has been performed following the same methodology of the universities. The dataset contains a total of 168 publications. Figure 1 and table 10 present the time evolution of the number of publications of INRIM. Data start from 2006, the year INRIM was created. The number of publications per year grows slightly across time, though ups and downs are present. Table 11 contains the occurrences of author keywords. The above reported comments

hold true also in this case. Also publication sources, listed in table 12, are aligned with the above described research topics.

4.5. CNR – National Research Council of Italy

CNR is Italy's largest Public Research Institution. The over 90 institutes (each counting several territorial articulations) that form its research network are spread all over the Country. Some institutes hosted in Piedmont perform research in NST; their activities are described here below.

4.5.1. Qualitative analysis: interviews

4.5.1.1. CNR-IMEM

A small section of CNR-IMEM, the Institute of Materials for Electronics and Magnetism of the National Research Council of Italy, is hosted by the Politechnic of Torino. More in specific its activities are linked to the research lab ChiLab, which is managed by the CNR researchers[4].

The research activities of the group span across micro- and nanotechnologies. The nanotech research topics are many and are synthetized in the following list.

- *Microfluidic devices and Lab-On-Chip for healthcare, environmental monitoring and industrial application*. Fabrication of microfluidic devices, provided with customised functionalizations and integrated with micro & nano structured materials and sensors for several application fields.
- *Electronic biosensing*. This research area aims at developing novel typologies of transistors such as Organic Electrochemical Transistor (OECT), Graphene Field Effect Transistor (G-FET) and Electrolyte Gated Organic Field Effect transistor (EGO-FET) either through the development of novel clean room processes or via the use of graphene or polymeric materials.
- *Supercapacitors*. In this field different kinds of nanostructured carbon-based electrodes are studied with the aim of increasing the performance of supercapacitors.
- *3D printing technologies*. this research activity aims at developing a multi scale (from micro to nano) and multi-functional system for micro- and nano-prototype creation of devices. This system should be based on polymeric materials which should guarantee the integration of nanostructures into micro manufactured parts and components.

4.5.1.2. CNR-IMAMOTER

IMAMOTER, CNR's Research Institute for Agricultural and Earthmoving Machines, has a section hosted at Turin's CNR Research Area. A group of researchers of the section perform NST research following two main research streams:

- *Materials for biomedical applications*. The research stream involves the study of the features of materials built with alumina-zirconia nanoparticles in a polymer matrix. Such materials are studied for their possible use in biomedical field. The research group at IMAMOTER is in charge of synthesis, mechanical tests and physical-chemical analyses. The research is performed in collaboration with researchers of Polytechnic of Torino (branch of Alessandria) and the Dental School of the University of Torino).
- *Friction materials for automotive*. The subject of this research stream are nanoparticles of different nature, studied for their influence on friction behaviour of mechanical parts. This activity is carried out in collaboration with NIS-Centre of Excellence of University of Torino and a company operating in the field of friction materials for automotive.

[4] See https://areeweb.polito.it/ricerca/micronanotech/main-page and http://www.disat.polito.it/the_department/internal_structures/department_labs/laboratori_area_fisica_e_fisica_della_materia/chilab_laboratory_chivasso (links visited December 2018).

4.5.1.3. CNR-STIIMA

CNR-STIIMA (the Institute of Systems and Intelligent Industrial Technologies for the Advanced Manufacturing) has a branch in Biella. This section is devoted to research activities in textile materials. Among the many research topics of this branch, a relevant one is in NST. This research deals with the fabrication of nanofibers from natural polymers. The nanofibers are produced starting from a polymer solution, exploiting an electrospinning methodology. The most relevant material for this fabrication related to the final properties of the final product are keratins, the protein of wool. Nevertheless any polymer soluble in a volatile solvent can be electrospun: for instance polyamide or polymer blends. Electrospun nanofibers self-organize themselves in a random structures producing membranes. This material is at sight compact, but it is formed by nanofibers of 100-200 nm diameter. The aim is to obtain nanofibers of smaller diameter. Such nanofiber-made membranes have different applications. The first one is in filtration. Membranes are a mechanical filter, apt at filtering very small particles. On the other hand, the specific surface is very high and thus it is possible to enhance material exchange properties and adsorption capacity. Filters can be used to remove heavy metal ions and dyes from water, or formaldehyde and VOCs from air, thanks to covalent bonding and chelating property of keratin. Other applications are in the biomedical field. The nano-sized structure mimics that of human tissues, and biopolymers and keratin promote cellular growth. Thus, they could be used as scaffolds to create in vitro cellular cultures or as implants to heal burn wounds. Nanofibers could also be functionalized with nanoparticles (for instance Silver nanoparticles for antibacterial effects) or drugs, or with Titania nanoparticles for photocatalytic applications. The use in dental applications is at present studied actively by the group.

4.5.2. Quantitative analysis

In the case of CNR institutes, publications are reported under the general affiliation of the National Research Council of Italy. Thus, it was not possible to carry on the bibliometric activity using the same methodology of the other institutions. Thus the activity was performed prior selecting the names of the researchers involved in the above described research activities, and then performing the NST queries.

The obtained dataset contains 32 scientific products. Table 13 and figure 1 present the time evolution of CNR publications. Table 14 contains the occurrences of author keywords. The above reported comments hold true also in this case. Publication sources, too, listed in table 15, are aligned with the above described research topics.

5. RESULTS: PRIVATE RESEARCH

In order to complement the above presented description of NST research in the Regional Innovation and Research System, this section presents concisely two cases of private relevant research institutions. While in the first case research activities are described thanks to the help of an interviewee, the second case is only sketched.

5.1. FIAT Research Centre

Fiat Research Centre (Centro Ricerche Fiat, CRF from now on) has been founded in the 1970s as a reference centre for research and innovation of the then-Fiat group. It is nowadays registered as a Consortium Stock Company, whose main stockholder is Fiat Chrysler Automobiles N.V. (FCA). Its yearly turnover lies around 100 million Euros, and it employs around 800 persons. CRF is nowadays a large enterprise, and a large research centre, with strong competencies, in particular in the automotive sector, and a portfolio of over 2,000 patents, as well as many scientific publications.

Materials sciences are the target of the “Group Materials Lab” (GML), CRF’s materials laboratory, which did originate in 2010 from the union of all materials research labs in the then-FIAT group. This new unit had around 200 staff at the time of its creation and is the global FCA centre for materials, performing both applied research and problem solving at production level.

Core activities have shifted in the last years leaving more basic research and going towards engineering of production solutions. This caused, among others, a diminishing interest towards NST. Nevertheless, at GML several high level laboratory assets are available (e.g. dynamometers, microscopes, analytical chemistry instruments, hardness and viscosity meters). Finally, it is important to notice that activities are both "coupled" (that is, linked to specific products) and "decoupled", that is not connected to specific existing products and, thus, having a greater scientific-innovative character.

5.1.1. Qualitative analysis: interviews

Research activities lie between engineering, testing and materials' performance. In detail:

- The first activity of GML is scouting of nanomaterials. This involves choosing materials for new models, standards creation and performance testing of materials. An example in this are hollow spheres: these are nanoparticles incorporated in polymers in order to lighten the weight of the cast parts. In aesthetic solutions nanotechnologies are less relevant, though avant-garde solutions exists for instance in envelopments using magnetic particles.
- Among functional materials, it is important to highlight the study of additives for polymers, aiming at improving their thermal and electric conductivity, as well as mechanic and flame resistance. Other studies concern functional coatings aiming at improving abrasion resistance and conductive coatings aimed at realising touch screens. In particular, graphene is studied to these ends.

5.1.2. Quantitative analysis: results of bibliometric analysis

The queries rendered 58 publications for CRF. The evolution across time of the number of publications is presented in table 16 and in figure 1. The number of publications grows until the half of the 2010s, then decreases, according to the results of the interview, reporting a slow decrease of "target free" research activities. Nevertheless, numbers are not high all along the series. Also the analysis of keywords, presented in table 17, shows results in agreement with those of qualitative analysis. Graphene oxide is at the top of the list together with Zinc oxide, followed by Electrical properties. These topics are presented in the qualitative study.

Together with scientific publications also patents have been analysed, being CRF a case of industrial research. In specific the patents are those retrieved within the research performed in Finardi (2018a), that is, Italian patents in CPC class B82, "Nanotechnologies"[5]. Patents have been retrieved on EPO EPO Espacenet Database[6]. The database query rendered a total of 7 B82 Italian patents: in one of these ones the patentee is FIAT AUTO SpA (this is an extension of a British 1993 patent) while in the other 6 the patentee is FIAT RICERCHE (Italian priority, dates of publication between 2003 and 2012. In this case the analysis has been performed on accessory patent classes. The most represented one is G02F (OPTICS; DEVICES OR ARRANGEMENTS) with 11 occurrences. The second position is that of G02B (OPTICS, OPTICAL ELEMENTS, SYSTEMS, OR APPARATUS) (5 occurrences) and the third one is H01L (BASIC ELECTRIC ELEMENTS; SEMICONDUCTOR DEVICES; ELECTRIC SOLID STATE DEVICES NOT OTHERWISE PROVIDED FOR) (4 occurrences). Thus, it is likely that the CRF B82 patents are mainly related to inventions of optoelectronic mechanisms exploiting nanotech inventions.

5.2. ENI Renewable Energy & Environmental R&D Center (former Ist. Donegani)

The ENI Renewable Energy and Environmental R&D Center (in Italian Centro Ricerche per le Energie Rinnovabili e l'Ambiente ENI) was founded in 1941 as "Centro Ricerche e Speri-

[5] CPC – Cooperative Patent Classification patent classification system is active since January 1st, 2013. It is a bilateral classification system jointly developed by EPO – European Patent Office and USPTO United States Patent Office. It is the main EPO classification system.
[6] https://it.espacenet.com/ (site accessed July 2018).

mentazioni Chimiche Istituto Guido Donegani" (Chemical Research and Trial Centre). It has been owned by different industrial actors as Montecatini, Montedison, Enichem, Polimeri Europa, and is nowadays owned by Italian hydrocarbon and energy industrial group ENI.

Its main research fields are nowadays mainly linked to environmental technologies, renewable energy, as well as health, safety, and environment physical chemistry.

The scientific publications of the centre have been extracted exploiting the usual methodology. This resulted in a list of 19 scientific products. Table 18 presents the time evolution of publication activities. In accordance with the scope of the institute, the most recent publications deal with research in the field of dye-sensitized solar cells.

6. CONCLUSIONS

The results of this wide survey on Piedmont research on nanotechnologies and nanosciences show a rather varied and complex state-of-the-art. In the region, the public research-performing institutions (three Universities and two national Public Research Institutions) form a widespread network both in terms of geography and in terms of research fields. Though Turin is obviously the centre of the network, and the most populated area in terms of institutions, also western Piedmont University and CNR are in the picture with relevant research activities.

In order to show the complexity and the extent of the NST research fields touched by the Region's laboratories, the topics presented in section four are resumed and synthesised in table 20. The table is built following the empirical classification devised by Islam & Miyazaki (2010). NST research topics are divided into four different categories: Bionanotechnologies, Nanoelectronics, Nanomanufacturing and tools, Nanomaterials. It must be noted a difference in reporting topics existing between PoliTO and the other research bodies. Topics in the PoliTO columns have been conflated and reported only once in case of duplications. This is due to the large fragmentation of NST research activities in many different research groups and teams. The other institutions instead are either smaller (INRIM, UniUPO, CNR institutes) or more centrally organized from this point of view (UniTO). These facts resulted in the need for PoliTO to partially reorganize research topics in order to avoid duplicates.

It is easy to notice that the four categories are not equally populated. The only one of the four to be present in all institutions is that of Nanomaterials. Several research topics are tackled by more than one research institutions. Both structural and functional materials are studied extensively.

Bionanotechnologies, too, are widely studied in the Region. In this case, research lines are less overlapped that in the prior one, and the research profile of each institution is more defined. Conversely Nanomanufacturing and tools are the sole domain of PoliTO and of CNR institutes. In this case, there is some overlapping between the two; this may be due to the fact that one of the CNR institutes present in the survey is physically based inside PoliTO's structures and collaborates intensively with some of its research groups. It must be noted here that some of the CNR research topics in the "Nanomanufacturing and tools" category are very close to, or might be shared with, the last one of the categories: Nanoelectronics. Besides CNR "shared" topics (like supercapacitors) Nanoelectronics is the sole domain of PoliTO.

NST research in Piedmont is well represented across all research institutions of the Regional System of Innovation. The number of publications has been growing steadily across time, though a slight decrease in the last two-three years is witnessed. All the research institutions collaborate in a balanced way to the Regional scientific production.

The lists of NST research topics show a wide variety of research activities, though some overlaps across institutions exist. All four categories are represented in the Regional research system, with many different topics each. In order to add more details to the picture, the keywords relative to the research institutions and reported in tables 2, 5, 8, 11 and 14 have been summed. The results are reported in table 19. At the top of the list is Graphene, with 91 occurrences. The second one of the list, Quantum dot(s) presents 48 occurrences, which is slightly above the half of the previous one. More in general, browsing the keywords' list one can easily understand the wide number of topics tackled in research and, on the other side, some degree of

specialization in specific technologies (solar cells) or materials (carbon based materials such as nanotubes and graphene, quantum dots, nanostructured surfaces – thin films, coatings – etc.).

Summing up the results of this descriptive analysis, one can conclude that Piedmonts' research/innovation system in NST is lively and active, presenting a production able to keep the pace with time and widely engaged in many research interests.

Eventually, a further relevant point contributing to the image of a lively and active environment is relative to new NST research structures that are being realized. During 2018 Regione Piemonte funded PiqueT – Piemonte Quantum Enabling Technology, an ambitious project for the realization of a new centre of micro- and nanofabrication concentrating all the human and technological resources devoted to nanotechnologies of the Piemontese public research centres and Universities. The new centre involves INRIM, together with PoliTO and UniTO departments. The new infrastructure will join research and firms, with the presence of pilot production plants. Research infrastructures will be empowered and shared between institutions, with the aim of obtaining a larger research critical mass. White rooms (around 1,000 square metres of white rooms, plus 1,500 square metres of offices and other labs), as well as electronic microscope facilities and other infrastructures will be present in the centre.

A second relevant project, again funded by Regione Piemonte, is SAX – Advanced Instrumentations for Complex Systems. The project involves UniTO and PoliTO, and in specific NIS – Centre of Excellence and DISAT. The aim of the project is creating an *open lab* via the acquisition of a series of high-end instruments, such as a FEG-SEM, an X-ray diffractometer, an X-ray micro-tomography apparatus. The *open lab* is intended as a structure able to perform studies apt at enhancing the regional (and national too) innovative thrust. Such instruments are in fact of scientific relevance at European level. The projects aims at incentivizing the collaborative network existing between the Universities and their Enterprise Incubators, opening up the path towards a Regional Competence Centre.

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8. TABLES AND FIGURES

Table 1. UniTO publications per year

YEAR	N°
Before 1996	20
1996	8
1997	6
1998	3
1999	5
2000	6
2001	6
2002	5
2003	13
2004	10
2005	14
2006	18
2007	21
2008	20
2009	27
2010	21
2011	26
2012	37
2013	35
2014	59
2015	50
2016	53
2017	50
2018	43

Source: Elaboration from Scopus data.

Table 2. UniTO keywords

KEYWORDS	N°
Diamond	11
Thin films	11
Self-Assembly	10
Block Copolymers	9
Graphene	9
Quantum dots	9
Carbon nanotubes	8
Epitaxy	7
Ultrasound	7
Adsorption	6
Cancer	6
Drug delivery	6
Dye-sensitized solar cells	6
Graphene oxide	6
Nanoparticles	6
Nickel oxide	6
Raman spectroscopy	6
X-ray diffraction	6
Cytotoxicity	5
Density functional calculations	5
Langmuir-Blodgett	5
Titanium dioxide	5

Source: Elaboration from Scopus data.

Table 3. UniTO publications' sources

SOURCE	N°
Journal of Physical Chemistry C	20
Sensors and Actuators, B: Chemical	13
Physical Chemistry Chemical Physics	11
Surface Science	9
Thin Solid Films	8
Journal of Physical Chemistry B	8
Langmuir	8
Carbon	8
RSC Advances	8
Crystal Growth and Design	7
Journal of Chemical Physics	6
Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms	6
Journal of Materials Science	6
Materials Research Society Symposium Proceedings	6
International Journal of Pharmaceutics	6
Dalton Transactions	6
Applied Surface Science	6
Journal of the American Chemical Society	5
Journal of Nanoscience and Nanotechnology	5
AIP Conference Proceedings	5
Chemical Communications	5
Analytical Chemistry	5
Biosensors and Bioelectronics	5
Journal of Alloys and Compounds	5
Nanoscale	5
Crystals	5

Source: Elaboration from Scopus data.

Table 4. PoliTO publications per year

YEAR	N°
Before 1996	27
1996	8
1997	9
1998	5
1999	15
2000	18
2001	20
2002	26
2003	31
2004	38
2005	35
2006	33
2007	36
2008	63
2009	55
2010	52
2011	51
2012	87
2013	95
2014	93
2015	111
2016	84
2017	100
2018	85

Source: Elaboration from Scopus data.

Table 5. PoliTO keywords

KEYWORDS	N°
Graphene (nanoplatelets, oxide)	63
Quantum Dot(s)	33
Dye-sensitized solar cell(s)	31
Photopolymerization	20
Carbon nanotubes	19
Thin films	19
Nanocomposites	17
Polymer electrolyte	16
Mechanical properties	15
Thermal conductivity	13
XPS	13
Electrochemical impedance spectroscopy	12
UV-curing	12
Reduced graphene oxide	11
Sol-gel	11
Microcantilever	10
Semiconductor lasers	10
UV curing	10
Zinc oxide	10
Coatings	9
Modeling	9
Molecular dynamics	9
Coating	8
Light-emitting diodes	8
PECVD	7
Sputtering	7
Thin film	7
X-ray diffraction	7
Biosensor	6
Cationic photopolymerization	6
Cotton	6
Flame retardancy	6
GaN	6
Layer-by-layer	6
Mode-locked lasers	6
Molecular QCA	6
MWCNTs	6
Oxygen reduction reaction	6
Passive mode-locking	6
Quantum-dot cellular automata (QCA)	6
Raman spectroscopy	6
Semiconductor laser	6
Surface modification	6
TEM	6
Thermal stability	6
Tissue engineering	6
ZnO	6

Source: Elaboration from Scopus data.

Table 6. PoliTO publications' sources

SOURCE	N°
Proceedings of SPIE - The International Society for Optical Engineering	26
Applied Physics Letters	21
Journal of Applied Physics	20
Physical Review B - Condensed Matter and Materials Physics	20
IEEE Journal of Quantum Electronics	19
Electrochimica Acta	18
Polymer	17
Applied Surface Science	16
Optics InfoBase Conference Papers	15
ACS Applied Materials and Interfaces	14
AIP Conference Proceedings	12
IEEE International Conference on Emerging Technologies and Factory Automation, ETFA	11
Macromolecular Materials and Engineering	11
RSC Advances	11
Journal of Physics: Conference Series	10
Macromolecular Chemistry and Physics	10
Thin Solid Films	10
Diamond and Related Materials	9
Journal of Applied Polymer Science	9
Journal of Magnetism and Magnetic Materials	9
Optics Express	9
Physica B: Condensed Matter	9
Physical Chemistry Chemical Physics	9
Physica E: Low-Dimensional Systems and Nanostructures	8
Physica Status Solidi (C) Current Topics in Solid State Physics	8
Applied Physics A: Materials Science and Processing	7
Conference Digest - IEEE International Semiconductor Laser Conference	7
IEEE Transactions on Nanotechnology	7
Journal of Nanoparticle Research	7
Physica A: Statistical Mechanics and its Applications	7
Progress in Organic Coatings	7
Semiconductor Science and Technology	7

Source: Elaboration from Scopus data.

Table 7. UniUPO publications per year

YEAR	N°
1999	1
2000	1
2001	1
2002	2
2003	3
2004	3
2005	4
2006	6
2007	2
2008	4
2009	9
2010	7
2011	3
2012	18
2013	12
2014	17
2015	20
2016	15
2017	9
2018	18

Source: Elaboration from Scopus data.

Table 8. UniUPO keywords

KEYWORDS	N°
Self-assembly	14
Rapid thermal processing (RTP)	13
Block copolymer(s)	10
PS-b-PMMA	10
Core-shell nanoparticles	5
Nanoparticles	5
Polymers	4
Raman spectroscopy	4
X-ray diffraction	4
Biomaterials	3
Cytotoxicity	3
Dye-sensitized solar cells	3
Ferrocenes	3
Graphene	3
PTFE	3

Source: Elaboration from Scopus data.

Table 9. UniUPO publications' sources

SOURCE	N°
ACS Applied Materials and Interfaces	11
Nanotechnology	6
AIP Conference Proceedings	5
Journal of Biomaterials Science, Polymer Edition	3
Vaccine	3
RSC Advances	3
Chemical Communications	3
Journal of Materials Chemistry C	3
Solar Energy	3
Nature Medicine	3

Source: Elaboration from Scopus data.

Table 10. INRIM publications per year

YEAR	N°
2006	2
2007	9
2008	9
2009	13
2010	10
2011	16
2012	13
2013	9
2014	20
2015	23
2016	16
2017	13
2018	15

Source: Elaboration from Scopus data.

Table 11. INRIM keywords

KEYWORDS	N°
Self-assembly(ng)	10
Thin film(s)	10
Magnetic (thin) film(s)	9
Magnetic force microscopy (MFM)	8
NanoSQUID	6
Diamond	5
Focused ion beam	5
Graphene	5
Porous silicon	5
Magnesium diboride	4
Magnetic nanoparticles	4
Nanostructures	4
Silicon	4
Spin sensitivity	4

Source: Elaboration from Scopus data.

Table 12. INRIM publications' sources

SOURCE	N°
Journal of Magnetism and Magnetic Materials	10
IEEE Transactions on Applied Superconductivity	8
IEEE Transactions on Magnetics	8
Journal of Applied Physics	8
Scientific Reports	6
Applied Surface Science	5
Applied Physics Letters	4
Journal of Nanoparticle Research	4
Materials Research Society Symposium Proceedings	4
Physica Status Solidi (A) Applications and Materials Science	4
Superconductor Science and Technology	4

Source: Elaboration from Scopus data.

Table 13. CNR publications per year

YEAR	N°
2003	1
2004	3
2005	1
2006	1
2007	3
2008	3
2009	2
2010	1
2011	1
2012	2
2013	3
2014	0
2015	0
2016	2
2017	1
2018	6

Source: Elaboration from Scopus data.

Table 14. CNR keywords

KEYWORDS	N°
Microcantilever	4
Biosensor	3
Graphene	3
CVD	2
flexible electronics	2
G-FET	2
Graphene transfer	2
Hot Embossing	2
Keratin	2
MEMS	2
Nanobiosensors	2
Polypyrrole	2

Source: Elaboration from Scopus data.

Table 15. CNR publications' sources

KEYWORDS	N°
Biosensors and Bioelectronics	3
Materials	2
Microelectronic Engineering	2
Synthetic Metals	2

Source: Elaboration from Scopus data.

Table 16. CRF publications per year

YEAR	N°
1996	0
1997	1
1998	0
1999	0
2000	0
2001	1
2002	0
2003	1
2004	2
2005	2
2006	3
2007	3
2008	4
2009	1
2010	1
2011	2
2012	5
2013	4
2014	7
2015	8
2016	5
2017	5
2018	3

Source: Elaboration from Scopus data.

Table 17. CRF keywords

KEYWORDS	N°
Graphene oxide	5
ZnO	5
Electrical properties	4
Electron microscopy	3
Optical properties	3
Reduction	3

Source: Elaboration from Scopus data.

Table 18. Istituto Donegani publications per year

KEYWORDS	N°
Before 1996	5
1996	1
1997	1
1998	0
1999	0
2000	1
2001	0
2002	0
2003	0
2004	1
2005	0
2006	0
2007	0
2008	0
2009	0
2010	1
2011	0
2012	2
2013	1
2014	0
2015	0
2016	4
2017	0
2018	2

Source: Elaboration from Scopus data.

Table 19. Piedmont's keywords

KEYWORD	N°
Graphene (nanoplatelets; oxide; transfer)	91
Quantum-dot (cellular automata)	48
Thin film(s)	47
Dye-sensitized solar cell(s)	40
Self-assembly(ng)	34
Carbon nanotubes	27
UV-curing	22
Photopolymerization	20
Block Copolymers	19
Coating	17
Nanocomposites	17
X-ray diffraction	17
Diamond	16
Polymer electrolyte	16
Raman spectroscopy	16
Semiconductor lasers	16
Zinc oxide	16
Mechanical properties	15
Microcantilever	14
Rapid thermal processing (RTP)	13
Thermal conductivity	13
XPS	13
Electrochemical impedance spectroscopy	12
Reduced graphene oxide	12
Nanoparticles	11
Sol-gel	11
PS-b-PMMA	10

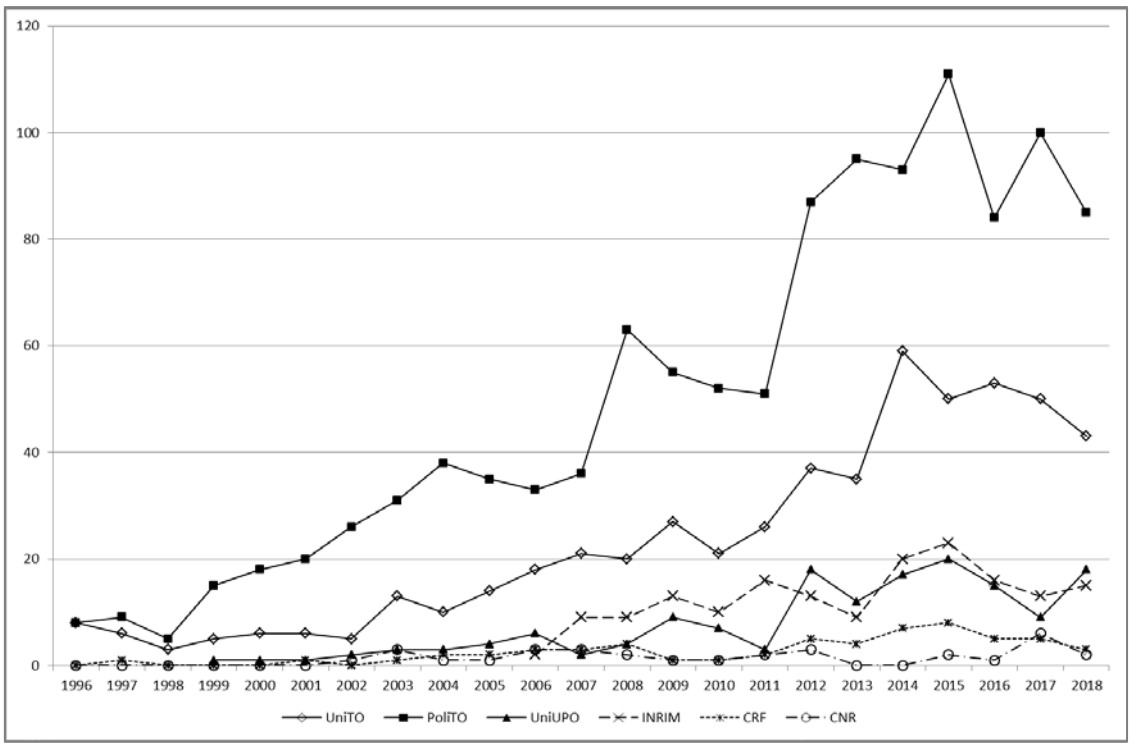
Source: Elaboration from Scopus data.

Table 20. Public research NST topics

	Bionanotechnologies	**Nanoelectronics**	**Nanomanufacturing and tools**	**Nanomaterials**
UniTO	Nano-biochemistry; Nanotechnologies for pharmaceutics and cosmetics; Nanotoxicology; Nanosafety; Nanomedicine.			Catalysis and porous materials; Photocatalysis; Physics for neurosciences; Hydrogen storage; Metallic glasses; Thermoelectric materials; Composite materials, carbon-loaded composites; Diamond nanotechnologies; Surfactants and dyes.
PoliTO	Bionanomaterials, degradable bionanomaterials; Detection of biomolecules; Smart scaffolds for precision medicine; Polymer nanoparticles carriers; Materials for the regeneration of living tissues; Nanostructured materials for drug delivery.	Circuit models of nanodevices (memoristors); Emerging technologies for nanocomputing (nanomagnets, molecular devices); Quantum dots application in photonics devices.	Simulations of semiconductor-based materials; 3-D printing; Sensors; Graphene-based membranes for water filtering; Supercapacitors for energy storage; Low carbon economy solutions; Nanoparticles for food industry; Functionalization of textiles; Nanoparticles for water remediation.	Materials for novel generation and smart energy systems and innovative batteries; Modification and functionalization of polymers with nanostructured materials; Novel catalysts and photocatalysts; Ceramic materials for biomedical and mechanic applications; Nanoporous aerogels; Superconductor materials.
UniUPO	Nanoparticles for optical imaging and photodynamic therapy.			Gas storage materials; Materials for environmental decontamination; Hybrid catalysts; Block copolymers for nanostructured surfaces and nanospheres.
INRIM				Porous Silicon applications; Nanosphere lithography; Metamaterials.
CNR	Electronic biosensing; Materials for biomedical applications.		Supercapacitors; 3D printing; Microfluidic devices and Lab-On-Chip for healthcare, environmental monitoring and industrial application; Fabrication of nanofibers for filtering applications.	Friction materials for automotive.

Source: interviews

Figure 1. NST Publications per year



Source: Elaboration from Scopus data.