Systematic Literature Review on Quantum Applications in Nanotechnology

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Abstract: The review of progress in quantum computing (QC) is very pertinent nowadays. There is a remarkable challenge in terms of the contributions that this field can provide at the level of improvements in computing time, but perhaps more importantly, in terms of how to rethink the way in which many of the current problems can be approached. Thus, the objective of this work is a Systematic Literature Review (SLR) that basically revolves around two questions: How does nano-assembled technology affect quantum computing? And what advantages does quantum computing offer to the advancement of nanotechnology? Therefore, this work analyzes how the advance of quantum computing has been influenced by nanotechnology and vice versa; and How quantum computing affects nanotechnology itself. In this way, this article clarifies the paths at which nanotechnology and quantum computing are connected on the route to future technologies in society. In conclusion, we found out that nanotechnology is crucial for the advancement of QC due to the quantumness stands in the nanometric size and the QC based-industry relies on the solid physics state nanoassembly, while on the other hand, QC significantly increases the performance of nanotransistors, imprint better sensibility features on nanosensors, among other things.

Keywords: Nanotechnology, Quantum computing, Systematic Literature Review.

1. Introduction

The world nowadays is defined by a tendency to miniaturize everything, which is aligned in practical words with nanotechnology. The sense of the nano is already a concept that represented a niche since the 80s, and it still now is crucial in the assembly of new technologies. From a certain standpoint, nanotechnology is the entrance to atomic manipulation, so scientists and technologists play out with nano world at the level of atoms, molecules or nanoparticles to build up optimized technologies such as an assembled transistors network in a tiny surface area [1], or a nanocantilever for generating nano-dropping of liquids and producing nanopatterned surfaces [2].

The reason for this deals with the fact that this technology parallelizes the computation capabilities, allowing not 2 states as classical computing, but states between 0 and 1. Thus, QC assumes that the particles are in a state between 0 and 1, meaning it has a fraction of both states, hence implying they are superposed. Also, individual states can also entangle, and this is the big property of QC because as many states are entangled, then the parallelized calculation power is increased [3]. However, in the implementation view, setting the QC for any use is not an easy task, among other things, because a qubit (basic unit of information created in QC, equivalent to the bit in the classical computers) generation is not still yet standardized. In this sense, QC arises as a very promising field that is expected to incise first in saving time for calculations, and secondly in allowing to covert complicated problems with multiple variables, into manageable problems resolvable in a few seconds or a few minutes.

There is a clear implication of nanotechnology in QC but still is not clear how QC affects nanotechnology. The nanodesign, for instance, is participating in the generation of structures that allow controlling the lasers used in the generation of qubits [4], or qubits existence can be described as a nanoparticle moving between two states 0 and 1 [5]. However, the QC influence in nanotechnology is not quite clear given that the QC is evolving in the sense of tangible applications regardless of the nanotechnology implications, even though it makes use of nanocomponents.

A recent SLR in nanotechnology mainly highlighted 2 research areas that are risk management in the nano-based industry and nanotechnology in economics interrelation. The authors found a conclusive result dealing with an improvement in the oil recovery rate based on the control of nanomineral complexes by inducing the effect of capillary value change, which induces a modification in the behavior of the clay mineral [6]. On the other hand, regarding QC there are reports of several SLR's but they range mostly in quantum machine learning and its applications [7], cloud QC [8], or data routing problems [9], and none of them touch the interrelation Nanotechnology-QC that we are approaching in this publication in our SLR proposal. For example, Laucht, A. et al [9] emphasize solid phase physics by mentioning materials such as graphene, Si, and SiC where the scientists are expecting to instantiate the qubits generation for allowing miniaturization in the upcoming years.

Thus, to our knowledge, there are no SLR priors that analyze the relationship between QC and nanotechnology. The objective of this work is to establish the connection points between QC and nanotechnology through a SLR that analyzes advances in each area individually, and how they affect each other. The main contributions of this paper are:

- To know how nanotechnology is employed to make QC advance exponentially.
- To connect the physical relationship b QC between and nanotechnology
- To know the interconnection between QC and nanotechnology applications.

In this sense, we analyze through this SLR the interconnections of Nanotechnology and QC by answering 2 questions, how does the nano-assembled technology incise in QC? And, what advantages offer the QC to the advancement of nanotechnology?

This work is organized as follows, section 2 shows the SLR methodology used; then, we carry out the literature review for the 2 questions in section 3. Section 4 presents a general discussion, with an emphasis on an overall analysis. The paper finalizes with the challenges in section 5.

2. Methodology

This section presents the methodology for carrying out the SLR that will allow determining the interrelationship between QC and Nanotechnology. The methodology is based on the works [10, 11] and includes the identification of the need to review the literature, then continues with a definition of the article search protocol, and then, with the review of the selected articles, to end with an analysis of current challenges.

Following this methodology, in the first section, the need for this SLR has been identified/motivated, because there are no previous works that analyze the relationship between nanotechnology and QC. This section describes the article search protocol and concludes with the selection of the articles to be analyzed but will previously reiterate the need for this work. The following section presents the analysis of these selected works, to conclude with the most relevant findings according to the interest of this work, which has to do with the relationships/interconnections between QC and nanotechnology. Thus, this SLR aims to lay the foundations for how to integrate both domains, given that, as highlighted in preliminary results, there are no previous SLRs that discuss this aspect.

2.1. Identification of the need for revision

To elucidate the relationship between QC and nanotechnology, we will perform an SLR giving answers to 2 specific questions:

Q1. How does the nano-assembled technology affect QC?
Q2. What advantages offer the QC to the advancement of nanotechnology?

Q1 and Q2 are pertinent because, first they encompass the understanding of nanotechnology and QC common points. By answering Q1 and Q2, we will discover how the 2 areas are connected and how we can contribute to their advancement.

Q1 and Q2 are relevant because, first of all, they cover the understanding of advances in nanotechnology and QC, but also, the common points between them. Thus, by answering Q1 and Q2 we will discover how the 2 areas are connected and how we can contribute to their advancement.

2.2. Definition of a review protocol

Based on Q1 and Q2, specific keywords are defined that describe them in **Table 1**. This table is constructed using the PICOC method, which allows the questions to be described using keywords that define the Population (which defines who is involved), Intervention (which indicates what it affects), Comparison (defines what it can be compared against), Result (which points to the objectives achieved by answering the question) and Context (describes the environment) of them. Not all of these aspects are necessary to fill out to describe each question [26].

Particularly, in this case, the C of comparison is not relevant, which is why it was not considered in **Table 1**. Additionally, in this table is supposed that Nanotechnology is the Population because it represents the natural origin of any technology as QC (see Q1). Also, we suppose that QC could affect the nanotechnology, and try to prove this in the SLR (see Q2).

Table 1. *Keywords found by applying the PICOC method to each question.*

Initials	Keywords
P	→ Nanotechnology
P1	Nanosensors OR measuring OR monitoring
P2	Buckyballs
P3	Graphene
P4	Nanoclusters
P5	Nanoparticles
I	→ Properties of nanomaterials
IJA1	Improvement of NS/NC/Graphene/buckyball/NP by QC [*1]
IJA2	Acceleration of NS/NC/Graphene/buckyball/NP by QC
IJA3	Impact of NS/NC/Graphene/buckyball/NP in QC
O	→ Quantum properties or nanoobjects interdependence
O1	NS/NC/Graphene/buckyball/NP functionality in QC
O2	Nanoprocessing speed up by quantum computing

C	→ Quantum Computing
C1	Quantum entanglement OR Quantumness
C2	Coherence time
C3	Number of Qubits
C4	Quantum error correction

[*1] NS: nanosensor, NC: nanocluster, NP: nanoparticle

The keywords identified through the PICOC method in **Table 1** are combined through logical AND and OR operators to describe each question as logical statements. **Table 2** shows the logical sentences that describe questions Q1 and Q2. These sentences are the basis for searching in search engines for articles on the Internet.

Table 2. *Research Equations*

Q1	(P) AND IJA3 AND (C)
Q2	(C) AND (IJA1 OR IJA2 OR O2) AND (P)

Figure 1 shows how the selection of articles is carried out. 3 levels of exclusion were used during the search. Initially, using only the logical sentences in **Table 2**, a total of 243 articles were obtained using the Google Scholar and Scopus search engines. Of this total, a first filter was applied, leaving only the publications from 2018, then the publications that really made a contribution to the questions once the entire article had been analyzed, and finally, if the publications clearly detailed said contribution (quality). Based on this, as noted in **Figure 1**, we obtained 65 publications for Q1 and 23 for Q2 after the first filter. Then we found 21 publications for Q1 and 13 for Q2 after the second filter. Finally, 14 publications were selected for Q1 and 7 for Q2 as the final result.

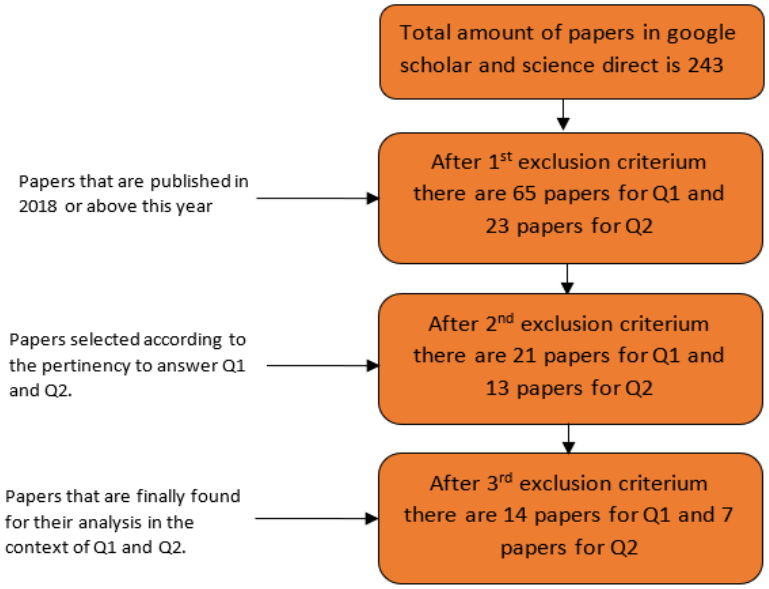

Figure 1. *Publication selection process*

2.3. Preliminary Result Analysis

A general review of the articles found for the two questions is presented. It represents an overview based on **Figure 2** that shows the region where the research was made and the kind of research made. In the figure is highlighted that the prevalence of quantum research is located at countries that count with economic resources devoted to the fact that QC research is costly. Among the first positions, we find the USA, Italy, Australia, India and Singapore, which are focusing their interests in areas connected to quantumness and the fundaments giving rise to it. Nonetheless, there is a diversity of countries in the world.

On the other hand, in the right-handed part of **Figure 2**, we can find a varied kind of areas where the quantum interest is spreading, demonstrating that the applications are not only in generating a computer based on qubits, but also, taking advantage of the quantumness to exploit applications in sensing, cryptography or photonics. Some of the domains of research are quantum biology, which deals with understanding the occurrence of reactions in nature, as for instance in the photosynthesis process, and *quantum technology-based architecture*, which refers to software architectures for quantum algorithms. Other domains are *superconducting quantum devices*, which comprehend the devices based on the graphene properties, *quantum nanophotonics* that signal the different effects of the light in quantum-based systems, or *quantum for military applications* such as quantum clocks and sensors of the earth magnetic field. Also, the domains linked to quantic communication are *wireless sensor networks* with qubits, or quantum cryptography. Finally, some of the domains linked to nanotechnology *are nanoparticle properties* at the quantum level, or *graphene-based quantum materials* that are implemented for quantum approaches in reason to their hardness and electrical conductivity.

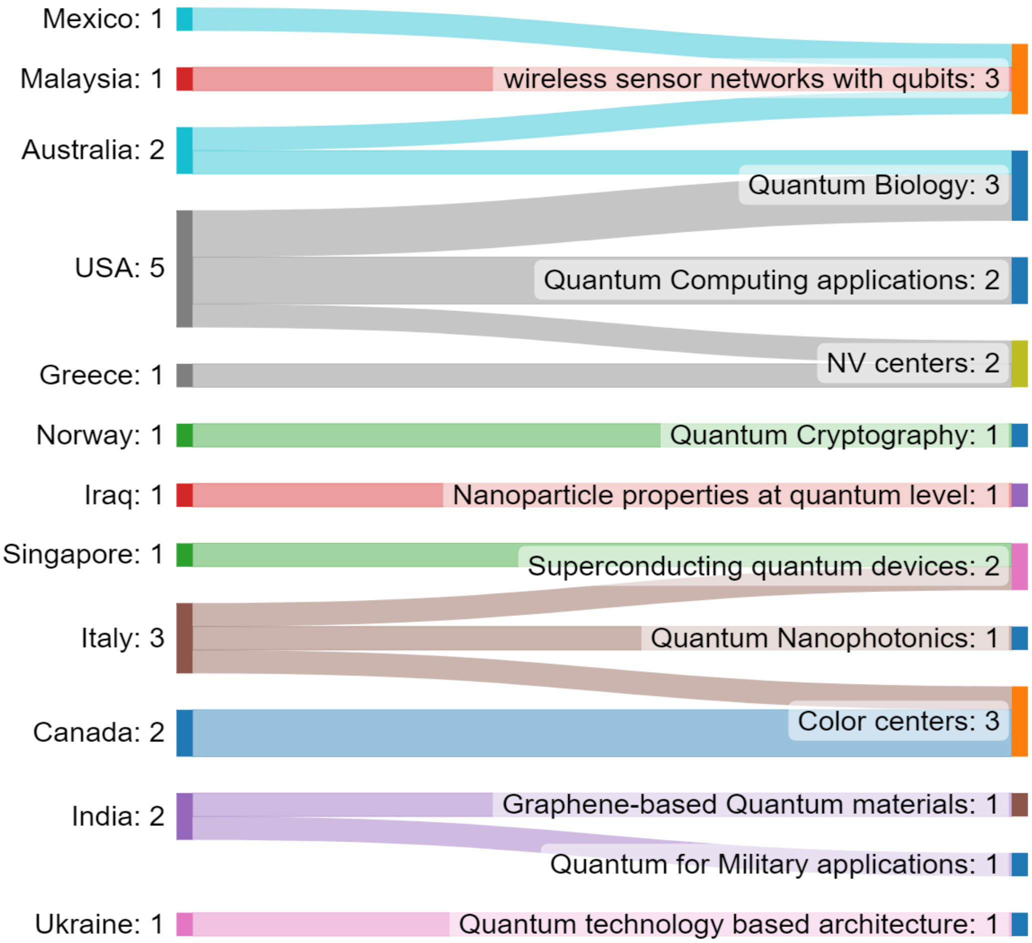

Figure 2. *Diagram of the results found after the 3rd exclusion criterium*

3. Literature review

3.1. How does the nano-assembled technology affect quantum computing?

In the following, we will instantiate a summary of the main information from the selected papers, in order to answer question Q1. Nimbe et al. [12] have highlighted that nanodevices making entanglement by using photons can generate information selectively that permits to perform calculations devoted to the parallelization that allows the quantum systems. According to these authors, the output data can migrate to classical-based treatment (classical means based on bits, while quantum means based on qubits) so this is managed in a typical computer. In this sense, Nimbe et al [12] have settled on a methodology to go from classical to quantum and from quantum to classical, but in a statement, which exists still as a proposal. For instance, in going from classical to quantum, the path of data treatment indicates first a 1. framework for classical program compilation, 2. framework for classical-quantum conversion, and 3. framework for quantum program decompilation. On the other hand, the process to go back from quantum to classical, sets algorithmically a 1. framework for quantum program compilation, 2. framework to quantum-classical conversion, and 3. framework for classical program decompilation. Nurtayeva et al [13] have stated that nanoparticles and nanostructures in general present different properties in the nanoworld compared with their macro-reality. For instance, they mention that the gold nanoparticles which appear red in an aqueous solution, have a yellow color in the macro world. Thus, the nature of the material turns different if the size of their particles is radically changed as signaled in Figure 3 where the energy levels distancing is remarkable for nanoparticles, and very close to each other for the macroworld. It demonstrates the fact that the nanoparticles absorb, emit and transfer energy internally or to other molecules. Contrarily, in the macroworld the light can be diffracted, refracted, or reflected, but not emitted. The macro or nano properties change according to the energy level distance. For this reason, nanostructures such as electrons or ions are involved in nanoassembled quantum systems, because these light-based properties are actually quantized. Quantization is a very crucial phenomenon in the nanoworld and explains the fact that electrons are located in orbitals and modify their state by the effect of light of the appropriate wavelength, among other things.

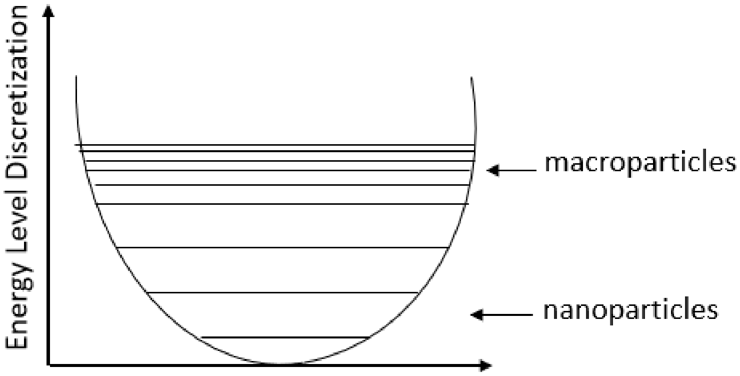

Figure 3. *Energy level distribution (source [11])*

Vettoliere et al [14] have reported the use of NanoSQUID or Nano Superconducting Quantum Interference Device whose properties are employed in the sensing field due to the high sensitivity to low magnetic flux measurement. The NanoSQUID is based on the Josephson Effect, which states that the current can be transported through an insulator located between two superconducting structures due to the overlapping of the wave functions, meaning there is a tunneling for the electrons. This fact is inexistent in the classical theory, but in the nanoworld it happens, and is predicted by the Schrodinger function. The use of NanoSQUID is crucial for magnetometry, to monitor the earth magnetic field, or for applications in Magnetic Encephalography (MEG) where small currents circulating in the brain are monitored. The Nanodevices based on the SQUID property change the output when the magnetic field is sensed in a NV quantum sensor due to the coherence is sensible to this, so the quantum state oscillates according to the magnitude of the field. Goh et al. [15] highlighted the participation of different types of materials in quantum computation. In this sense, there are superconducting circuits that rely on different properties such as a. those invoking the Josephson Effect like in [14], where a current starts flowing through an insulator; b. photonic systems, which make use of lasers to put photons or vacancies in superposition or entangled with photons far from them; and c. quantum dots-based quantum computers. Thus, for each of them, there are specific nanomaterials that require a purity of up to 99.99% in their solid phase. These materials are refined also topologically to delete the edges that alter the quantum state formation while still being in their nanosize, as well as to keep the surface uniformity and absence of defects in the nanometric constitution in order to allow the quantum state and the entanglement state generation in a reproducible manner. This nanotested surface system approaches a high qubit fidelity, low noisy context, and low quantum error correction which are ideally the conditions in any quantum system.

Aslam et al. [16] mentioned that there are two quantum sensing platforms which are Optically-Pumped atomic Magnetometers (OPM) and nitrogen vacancy centers in diamond lattice-based ones. Both of these applications require a nanostructure arrangement of the solid-state quantum surface where the nanodiamonds or related assemblies are formed. The topology of these surfaces is crucial, incising in holding longer coherence time. For instance, the OPM due to their high sensitivity is ideal for macroscopic detection of weak magnetic fields like those from the brain or the heart; meanwhile, NV centers are appropriate to sense variables at short distances, making them with high spatial resolution and high sensitivity to weak microscopic signal. The NV centers can also detect AC and DC electric fields and temperature. In this sense, there is a big impact on quantum nanobiosensors that can be applied for the structure determination of single molecules. Thus, the miniaturized arrangement holding nanocomponents sets the possibility to impulse the quantum sensing applications. In [17] is mentioned that quantum cryptography typically arising from nano-constituted quantum emitters obeys several modes of implementation. First, the quantum emitters can be rare earth ions that in an excited state over a nanoparticle emit pulses of light while keeping a spin-photon superposition state, or simply a semiconductor artificial device emitting monochromatic pulses. The emitted photon knows the information of the spin state, but it has to be read just by the single photon photodetector that has not been previously intercepted. The quantum cryptography modes stated in the article for this kind of system are the regular quantum cryptographic theory, the quantum key distribution over free space, and fiber quantum key distribution. In this way, the photons emitted by the nanosystem are protected by the physical effect.

Bradac et al. [18] mentioned that the solid-state quantum generation from different types of vacancies could be now a reality. There have been implementations in color centers (general term to define the divacancies existing in carbon-based diamond lattices holding quantum properties, and keeping different M in the MV pair of the arrangement), beyond the Nitrogen Vacancy (NV, where M is represented by N, and is the most commonly used) center that equally shows a quantum state formation. These surfaces are functionalized with nanodiamond-based carbon, holding different kinds of defects and electrical properties. This nanostructure order incises in a varied degree of sensibility for instance in the application of M-V vacancy sensors in the low current detection or in the track of low magnetic fields, as part of the biggest targets in quantum sensing applications. Also, Choi S. et al [7] mentioned the enhancement by a factor of 8 of the photoluminescence response of nanodiamond pyramid (NDP) prepared with silicon vacancies. The enhancement was tested by the use of an Atomic Force Microscopy (AFM) tip that made the readout at the spot on the NDP with the silicon vacancy (Si-V), where, as the product of a quantum effect is produced this enhancement in the Si-V, named as quantum nanosensing. The methodology comprised the preparation of Si-V instead of nitrogen (NV) and demonstrated that there is a quantum effect that favors the optical response, especially in the increase of its sensibility. The NDP was prepared by microwave-controlled Chemical Vapor Deposition (CVD), but the atmosphere was not nitrogen but a compound of Si and V (vanadium) that generated the NDP imprinted onto the Si-V that conformed to the base of the pyramid.

Castelletto et al. [19] highlighted that the silicon carbide (SiC) materials have excellent quantum properties that can be exploited for studying the solid-state generation of qubits and visualized a future integration of the quantum computers to the regular existing fabrication line of mobile devices, computers, tablets, among other devices. Some of the optical features as the quantum effect on the SiC material are devoted to a nanoassembled layer formation of double vacancy SiC superposed spin state with a coherence time of up to 1 ms. On the other hand, for NV diamond nanosurfaces are around 1 s, and for the InAs/GaAs Quantum Dots (nanostructures which are cero dimensional) are 3-10 s. In another publication, Sarantopoulou et al. [20] affirmed that the color center process either in the classical or in the quantum world depends greatly on the topology of the surface. For classical processes, this fact could imply just an increase of entropy according to the second law of thermodynamics, but for changes in the nanoworld in the quantum states generation, it suggests an increase in the degree of complexity in the surface features where there is an oscillating electron or photon in the quantum superposition. It indicates that solid state surfaces are changing because of quantum computing demands, in the provision of molecular holes, charged molecular materials, or stable quantum emitters, for instance. It is mentioned that the quantum effects in solid surfaces are due to the increase of degeneracy in the micro- or nano-cavities provided to the system through the bombarded electrons or ions. This leaves the surface with a negative charge, and allows contributing with improved nanostructured photodetectors as part of the optical signal detection afforded in quantum optical nanosensors.

At the level of wireless sensor networks with qubits, Rivero [21] highlights the possible constraints that could exist in Wireless Sensor Networks (WSN) that handle qubits instead of bits. The author mentioned the case of the agreement of satellites between the USA and China where the information faced a remarkable transmission trouble due to having a very low qubit rate coming from the nanoemitter system of photons out of the earth. The nanoassembled system sent the photons to be read out hence testing the capabilities of the quantum wireless network. The low rate of photons demonstrated that is not feasible unless you just look at a long-distance working system reporting a Yes or No answer, which can be for instance, if an event is occurring in galactic space, and we have a watcher satellite out in the space reporting what they get. In this case, a fiber optics path can provide a solution, nonetheless, it turns the system sensible to factors such as weather, ground earth surface, and any external perturbation imprinting error.

The current advances in QCs and processors make it difficult to fit with the WSN as we know it due to the high cost, dimensions and stability conditions to operate the machine. This author mainly focuses on the Quantum Wireless Sensor Network (QWSN) by proposing a scheme in which the system should work. It sets that there is a hybrid approach of classical and quantum sensors. Classical ones report to a single radio frequency node (RF-node) for transmitting it in long distances, whilst the quantum ones transmit separately their measurement to an assigned processor and then, individually each of them reports to an RF-node that transmits through a long distance to an RF-node receiver. It passes the information to a processor and subsequently to a quantum processing grid that understands the measurements, and translates the output of the QWSN and the WSN.

In the Quantum Nanophotonic field, Wang et al. [22] mentioned that in a nanoscaled system, meaning that is composed of nanocomponents, 2 kinds of entanglement can occur, they are discrete variables entanglement (DV), where the quantum state is described by a polarization of the photons or the photon number of the photonic field; or continuous variables entanglement (CV), where the quantum state depends on the quadrature (position and momentum) of the optical field. Thus, due to their own feature, the discrete features in the nanosystem apply where the components are nanometric. On the other hand, a continuous entanglement takes place in macro-composed systems. The entangled photon pairs have been measured successfully on the ground from the Micius satellite and distributed to the 2 grounded stations. Through this, they could prove indeed that entanglement was possible in the nanostructured systems due to they detected the values sent from the satellite in the ground. On the other hand,

Lay-Ekuakille et al. [23] have mentioned the advances in optical nanosensors such as plasmon-based made by gold nanoparticles, thus generating useful functions relying on quantum nanophotonics. Quantum nanosensors relying on plasmons have been formed and tested with a very low limit of detection while attenuating the noise, which is advantageous for tracking specific macromolecules or molecules in the blood vessels for in vivo or in vitro applications, given the previous functionalization of the gold nanoparticle. Bhardwaj et al. [24] have shown that quantum effects basically arrive when the material is below 5 nm because is the regime of energy discretization. These quantum effects modulate therefore the design, manipulation, building, production and applications of nanotechnology in those dimensions. Optical transitions of photons between internal levels of energy is devoted to an interrupted degeneracy of the orbitals, so the nanomaterials can be designed based on the control of shape, size and composition, in order to obtain appropriate energy levels distribution that provide materials with the expected properties.

Finally, Sahoo, S. et al in [8] have highlighted the quantum nanophotonics effect relying on color centers (MV) highly coupled to nanodiamond surfaces. They said that strong embedded color centers in a distance of 100 nm or less to the surface permit a more stable and coherently attached superposed state of photon-photon interaction, as well as for spin-photon superposition state in NV centers in conditions very close to room temperature. These facts allow the manipulation of an array of coherent photons in a very reliable manner over a nanodiamond (ND) surface, thus being affected by external magnetic or electrical fields in diverse applications such as nanosensors or nanoemitters based on quantum. In this sense, the nanophotonic application is proved from the manipulation of an ND on which they are attached to an MV defect by the inclusion of an impurity in the surface, that ideally should be with a negative charge. The ND-MV system is then transferred to a surface and disposed of regularly to allow them to perform the photonic light emission, taking advantage of the MV quantum system resonating as long as they receive the light. The formed array for the nanoresonator permitted a manipulable control of light emitted quantumly acting as a waveguide across varied kinds of material surfaces.

In **Table 3** there is a summary of the manner nanotechnology is incising in the QC evolution, to provide the answer to Q1. The nanodevices can use entanglement to generate information selectively or to perform calculations, such as in regular QC, but also, nanostructures can act generically in quantum systems to improve the calculation power, optimizing among other things, the qubit generation and the coherence time. To this end, nanoparticles present different properties in the nanoworld radically different from the macroreality, especially related to energy discretization, which attributes to the possibility of quantization. Nanoassembled structures use electrons, ions, nucleus and photons to generate the different kinds of qubits employed in quantum computing. For instance, nanoassembled chips use the D-wave applications in networks of more than 60-qubits by using special algorithms making possible that silicon-based nanochips experiment with the quantum entanglement effect which can pave the migration into quantum-based processors. Also, Nano-constituted emitters through earth ions activation over nanoparticles, can send pulses of light while keeping the spin-photon superposition state, hence possibly setting the basis for quantum cryptography. Likewise, nuclear spin from the NV vacancy in nanodiamonds can experiment with coupling of spin-spin or spin-electron, which differ slightly from those involving photons, and are employed more frequently for sensing, constituting the quantum nanosensing. These nanosurfaces can enhance the photoluminescence response prepared over silicon vacancies, changing the N vacancy by Si-based with different properties in the photon emission. Materials such as SiC can exploit their properties over the solid-state generation of qubits, foreseeing the future of the integration to QCs. The nanoassembled systems in the out space are set to send the photons of information in a row hence probing the capabilities of the quantum wireless network. The distance between nanoparticles or the nanoparticle distribution on a surface can optimize the optical sensing, thus nanophotonics by the incorporation of particles less than 5 nm can be better arranged to the quantum exploitation due to the energy discretization, coming from the addition of nanoclusters, quantum dots, or NV centers as abovementioned. Nanomaterials can be designed based on the control of shape, size and composition to have customized optical transitions in the quantum-based applications.

Table 3. *Summary of the main statements that answer to Q1*

Sub-item	Statements to answer Q1
QC Applications based on Nanotechnology	• Nanodevices can use the entanglement of photons to generate information selectively and perform calculations. • Nanostructures are generic to any computing system, so they permit quantum data handling to generate structured information.
Nanoparticle properties at the quantum level	• Nanoparticles and nanostructures present different properties in the nanoworld compared with their macro-reality. • Nanoassembled quantum systems use electrons, ions, nucleus and photons that have a quantized energy distribution.
Superconducting quantum devices	• The Nano Superconducting Quantum Interference Device uses a nanoinsulator sandwiched between superconductor layers. • The superconducting nanocircuits possess magnetically sensible coherence.
Quantum Cryptography based on nanotechnology	• Nanochips use the D-wave applications in networks of more than 60-qubits by using special algorithms. • Silicon-based nanochips have experimented quantum entanglement effect which could allow the migration to quantum-based processors. • Nano-constituted quantum emitters are possibly setting the basis for quantum cryptography. • Rare earth ions quantum emitters over a nanoparticle can send pulses of light while keeping the spin-photon superposition state.
Nitrogen Vacancy (NV) Centers	• Nuclear spin from the NV vacancy in nanodiamonds can experiment coupling of spin-spin or spin-electron.
Wireless sensor networks with qubits	• The nanoassembled systems in the space sent the photons in a row hence probing the capabilities of the quantum wireless network.
Quantum Nanophotonics	• The distance between nanoparticles or the nanoparticle distribution in a surface can optimize the quantic sensing. • Nanophotonics exist when particles are scaled in 5 nm or less due to this regime is rich in energy discretization.

- Nanomaterials can be designed based on the control of shape, size and composition to have customized optical transitions.

3.2. What advantages offer quantum computing to the advancement of nanotechnology?

We will find several sub-fields where there is a greater impact of the QC into nanotechnologies. Laucht A. et al. [9] have demonstrated that large-scale quantum computing employing quantum error correction can address the migration of current technology to quantum nanoassembled processors. For instance, the silicon quantum dots (QDs) have a strong potential to generate pairs of spin-photon with high stability and entanglement, hence constituting the base for the actionable boards in upcoming quantum-based computers enabled for large calculations. The similarity with current technology is in keeping the same silicon ground but changing the physical fundament of the machine that now possesses a quantum transistor sending entangled photons.

Xavier et al. [25] signaled that quantum technology explains naturally occurring facts that rely on photosynthesis, brain activity, annual birds' orientation or enzymatic catalysis which imply quantum mechanical processes in the nanoconstitution of plants, brain, birds and porous solids, respectively. At the very molecular level, the quantum mechanical processes are occurring according to the interplay of superposed photons or electrons constituting the quantum biology basis. In this sense, we are founding our understanding of the nano-governed world by going deeper into the incorporation of the technology of concepts such as superposition, entanglement, or coherence. An example in this line is the demonstration of quantum tunneling in enzyme catalysis, where there is a coupling of electrons and protons to mediate in charge transport and facilitate some reactions over others. This quantum governing behavior mediates the design of the nanotechnology in the future making it more responsive and adaptable, like nature is. The responsiveness can incise for instance, in emulating the vibronic quantum coherence to improve the photosynthetic process; or creating an artificial photosynthetic nanomaterial to generate an artificial O2 surface producer; or generate phototunnelling nanostructures to produce artificial enzymatic catalysis; or even better, to nanodesign electron spin quantum entanglement nanostructures to allow optimized navigation devices without the use of GPS and based on the earth's magnetic field measurement. Baiardi et al. [27] stated the advantages of QC in modelling typical problems from the biological field relying in protein folding and drug design. Basically, the quantum calculation makes large calculations faster thus allowing that interaction among macroproteins can be modelled massively, changing the way these nanostructures are analyzed. In this sense, the nanosurfaces-based platforms can now adapt to the properties measured in the macromolecules and refine the strategies for the observation, measurement and modification of these proteins from a bulk view.

Kumar et al. [28] stated that QC is setting the next generation of cyber security data, dominating in this sense the form algorithms are presented and the form they execute in the nanostructured devices. It assures that the information is saved in the quantum internet, in the encryption of nanosystems, in the assurance of new protocols for data storage, and other things. Finally, Ferry [29] stated that the trend towards miniaturization results in increasingly smaller devices, while keeping the same functionalities. Some of the main companies like IBM and Microsoft are devoted to the working in nanoassembly of these functional devices such as chips that hold millions of nanotransistors assembled in a nanoarray that interferes negligibly among them, and possesses a potentiated processing power. These nanotransistors are regularly assembled very precisely by the use of a Scanning Tunneling Microscopy (STM) device in the waffle. The net result brings up advantages in the ever-smaller technological device, which now has a bigger processing power based on the nanotransistors array satisfying Moore's law. Moore's law typically outlines that the number of transistors in a ship duplicates every 2 years, nonetheless, this apparently linear trend is getting to an end, which justifies the importance of QC due to its high processing power joint to its capability to generate a cryptographic unbreakable information transmission.

In **Table 4** there is a summary of the manner QC is incising in the nanotechnology, to provide the answer to Q2. With the migration of current technology to quantum nanoassembled processors, thus we can study processes like photosynthesis, brain activity, birds' orientation or enzymatic catalysis by incorporating nanomechanical systems. Elsewhere, quantum tunneling in enzyme catalysis involves coherence of pairs that incises in the surface nanoparticles optimization for facilitating some reactions over others, and also, QC has been tested to model biological proteins for an optimum preparation of nanoparticles-based treatments of diseases, because of its greater calculation power. This permits among other things, the generation of cyber security data, dominating the algorithms executed in nanostructured board devices. Quantum communication-based interferometry in telescope imaging acts based on shared entangled pairs to avoid the synchronization of nanostructured clocks that were required before, and there are also effects in the quantum signals increase to generate a safe communication distance that meets the requirements of information encryption, thus refining a nanobuilt data center architecture for observations from the space.

Table 4. *Summary of the main statements that answer to Q2*

Sub-item	Statements to answer Q2
QC	• Large-scale quantum computing employing quantum error correction can address the migration of current technology to quantum nanoassembled processors.
Quantum Biology	• Processes like photosynthesis, brain activity, birds' orientation or enzymatic catalysis regulate the nanomechanical systems for studying quantum biology. • Quantum tunneling in enzyme catalysis involves coherence of pairs that implies surface nanoparticles optimization to facilitate some reactions over others. • QC in modelling biological proteins can modify nanoparticles-based treatments of diseases.
Quantum for military applications	• QC is setting the next generation of cyber security data, dominating the algorithms executed in nanostructured board devices. • Quantum communication-based interferometry in telescope imaging shares entangled pairs to avoid the synchronization of nanostructured clocks.
Quantum technology-based architecture	• Quantum signals increase the safe communication distance to meet the requirements of information encryption thus improving nanobuilt data center architecture.

To conclude this section, some technical aspects regarding quantum state stability and error correction mechanisms can be mentioned from the point of view of nanotechnology and QC. On the one hand, quantum state stability [55] refers to the superposition time of ions, electrons, photons or any particle, which means that it has a large coherence time. The more superimposed qubits there are around, the more errors may occur in the system, because there are interferences between them. This is the difficulty of parallelizing qubits in QC to increase the computing power, because depending on the mechanism to create the superposition state, the efficiency of charge transport and interference from electric or magnetic fields may involve an error. In this sense, quantum error correction tries to establish an algorithm that can predict how the qubit result is biased [56], thus balancing the result and attenuating the error, or adapting physical conditions such as those mentioned above, to increase the coherence time [57].

4. General Discussion

4.1. General Analysis

Herein we state the summary of the reviewed works as well as the scientific opportunities in the publications reported in this SLR. In the **Figure 4** appears the amount of publications made in different sub-fields to cover the questions Q1 and Q2 in the range of time from 2022 to 2024 according to Google Scholar and Scopus.

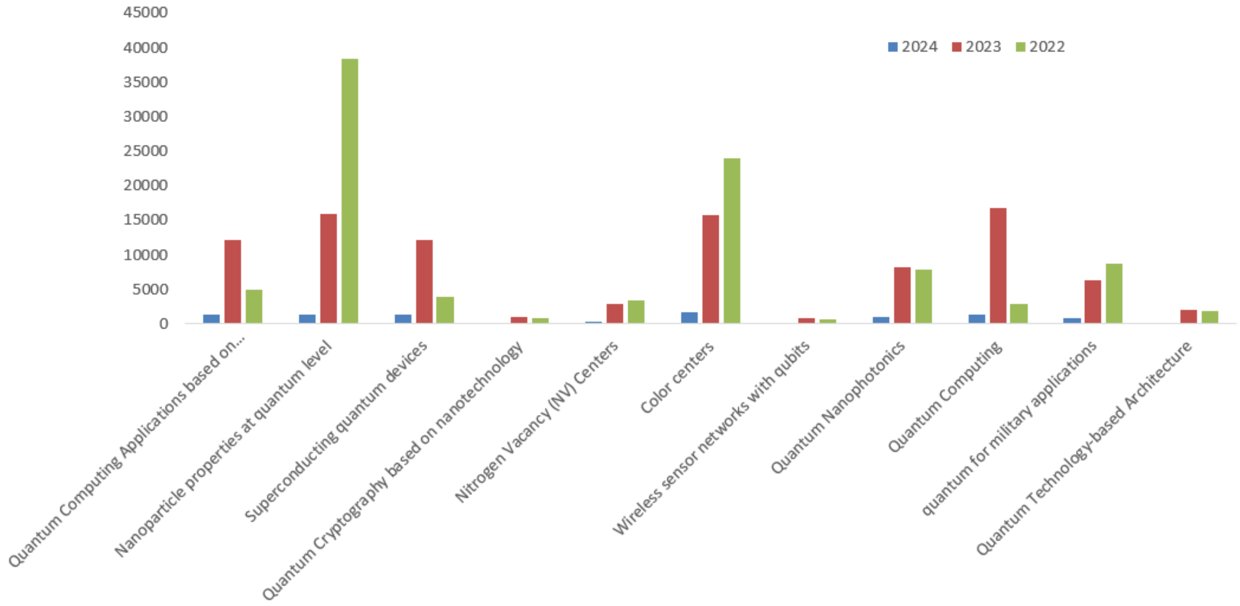

Figure 4. *Number of publications in the last 3 years for different subfields for Q1 and Q2.*

In this sense, we find in **Figure 4** that QC applications based on nanotechnology, superconducting quantum devices, and quantum computing have the same relevance according to the frequency of publications obtained from Google Scholar and Scopus. For instance, in 2024 these items have less than 1000 publications, with a top in 2023, and then, not so frequent in 2022, maybe due to some of these sub-fields are very recent, given the novelty of the quantum theory and applications. The sub-fields of research with the most relevance according to the amount of publications are nanoparticle properties at the quantum level and color centers, which are 2 fields very well disseminated in some countries such as Canada, Italy and Iraq, as shown in **Figure 2**. Then, in the middle interest fields of research are quantum nanophotonics and quantum military applications which are very linked to optical fields taking advantage among other things, of the very efficient quantum emitters and the Purcell effect-based research which is crucial for the quantum internet. Finally, are the less frequent fields that probably are arising lines in the present years, such as quantum cryptography-based nanotechnology, nitrogen vacancy centers, wireless sensor networks with qubits, and quantum technology-based architecture which provide less amount of publications.

On the other hand, we state a dichotomy where both research lines are faced, so we aim to elucidate common and different points among them. The older existence of nanotechnology will tilt the balance to have more incidence of nanotechnology to the advancement of QC. The most remarkable link between these areas is due to the fact that quantum effects are watched only in the nanometric size, thus by definition, it is a nanometric-originated consequence. Discretization of energy levels does not occur in the macroworld but in the nanometric world or below, thus we see the miniaturization of the devices to make them propensity to have quantum behavior, and therefore, to evidence the quantum properties in them. In this sense, quantum technology as a whole is supported by nanotechnology.

The modes for generating the quantum superposition are for instance by bombarding with electrons or ions a solid surface, so there are formed vacancies of a specific size and negatively charged for the superposition state in the formation of NV-centers, MV centers/color centers depending on the ion that was used for making the molecular hole. As this is made in a nanodiamond (ND), then the molecular holes can be regularly distributed, to have a reproducible size and features, and to allow the qubit formation in conditions different from absolute zero K, and on a solid surface. The qubit in solid surfaces is crucial due to it makes feasible the building of functional solid boards, for generating circuits of PCs, laptops, tablets or mobiles, and even better if this solid surface is Si, due to the current transistor classical technology relies on Si material.

Some aspects of QC such as photon coherence, decoherence, and entanglement, are imposing a big challenge to migrate the existing transistors-based technology to a quantum-based technology. Nonetheless, there are remarkable advances in the quantum adaptations involving Si such as is shown in **Figure 5** for the sub-field “Quantum Computing Applications”, which highlights an investigation in [27] employing “entanglement”, supported on Si and ND, and working on a photon-photon coupling, where the beneficiary is nanomaterial users. In Figure 5 there are other applications using Si such as “wireless sensor networks with qubits” and “superconducting quantum devices”, where both of them collide in the kind of superposition generated which is “spin-hole” and is aimed for “QC users”. It is notable that these 2 applications are very different since one is relying on communication from satellites and the other is assuming magnetic-based qubits.

In the same line of nanomaterial, a derivative of Si such as SiC has been involved for applications of color centers, meaning there is a great potential for SiC-based sensors, given the sensibility of the kind of qubit formed to measure very low currents like in the brain, the heart or even, to track the gravitational field for out of space applications. In Figure 5, most of the sub-items are referred to the ND, due to their features generate a stable qubit, with long coherence time, less error, hence becoming well adapted for sensing. As watched in this Figure, the sensing approach is useful for satellite users to improve its imaging of bodies or very far events, for medical personnel to track low potency signals, given the low limit of detection and enhanced sensibility, and for QC users, to follow up events relevant to prove the sensor in any of their forms, and suggesting that nanostructured materials like ND are key for the QC advances [30, 31]. The applications of ND materials in order to answer Q1 include the superconducting quantum devices, color centers, quantum nanophotonics, and NV centers, indicating diversification of fields using the same physical effect. “Nanoparticles” and “nanosurfaces” materials are also included as materials for the instantiation of quantum effects in QC implementations. In **Figure 5** we see applications with these materials that come from “quantum nanophotonics” and “quantum cryptography”, and also another one from “NP properties at quantum level” where the photon emission of these NPs is so stable and regular that, they can be used as quantum photon emitters. The beneficiaries of nanoparticles-based applications are typically “satellite users” and “QC users”, and they are supported on spin-hole or photon-photon superposition. By the other hand, insulator and superconductor nanomaterials are employed for superconducting based qubits generated by the Josephson effect, so its application is very active for measuring very low potency currents.

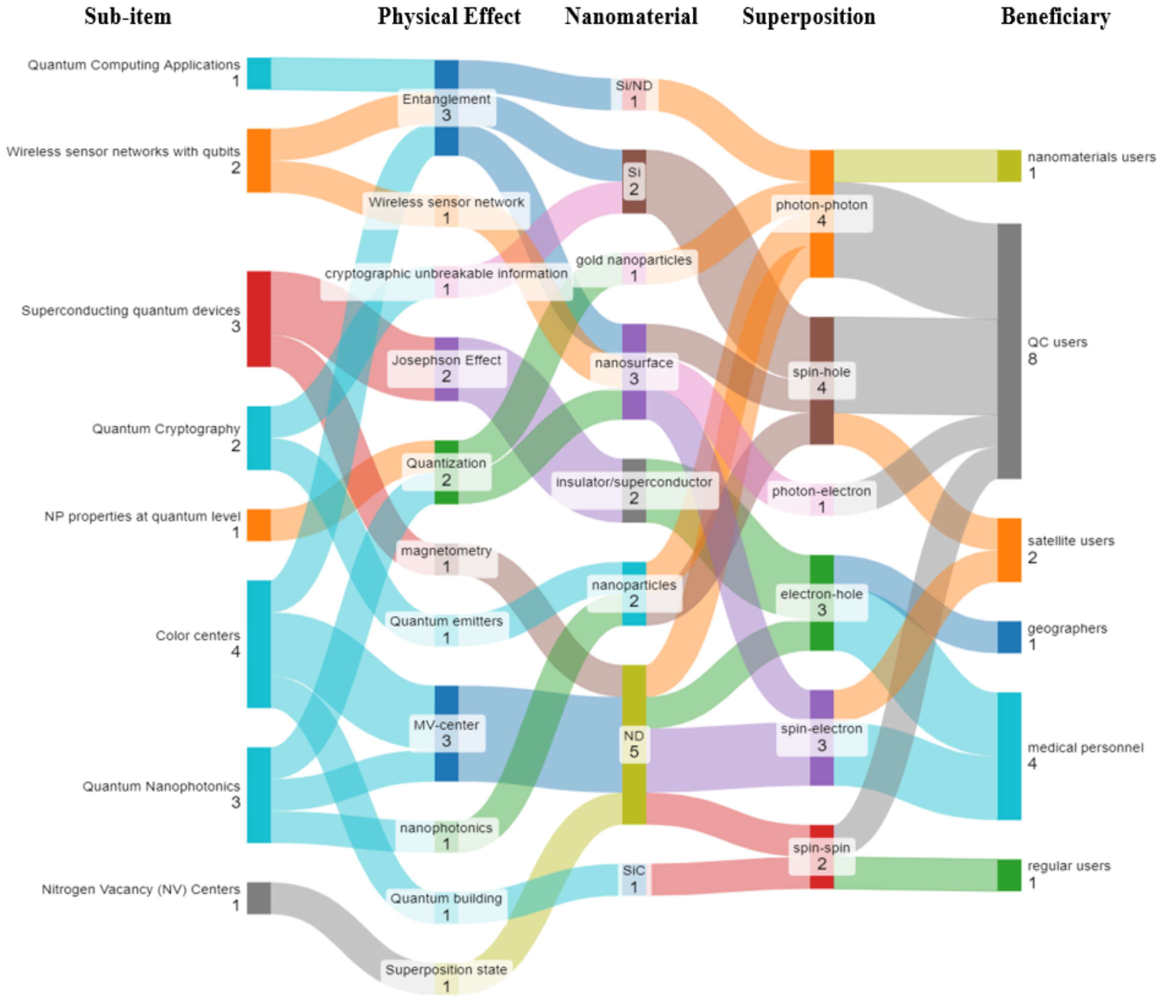

Figure 5. *Diagram of Sankey for the interrelation among the features relative to the sub-fields in Q1.*

With respect to **Figure 6**, the greater interest is for the nanomaterial Si/QD, which comes from the applications of QC, quantum technology-based architecture, and quantum for military applications, indicating its employment is diverse. Nonetheless, they all use the photon-photon superposition type for scientific purposes merely, due to the beneficiary are the QC users. Nanosurfaces are the second most frequent nanomaterial, where the applications are from quantum biology and for military purposes, and addressed for QC users. As it is palpable the scientific purpose reigns in the search for quantum computing affecting nanotechnology, indicating that still is a field where people look to explain the evolution of nanotechnology. Si/graphene, Si and nanoconstituted systems are the rest of the nanomaterials employed for the aimed applications in the publications for Q2 [32, 33]. All of these were focused on QC users, except 1 for satellite users, meaning the interest of nanosurfaces in the observation of objects out of the earth by using quantum technology. There are several physical effects invoked for the applications, which rely on entanglement and cryptographic unbreakable information, which indicates that the quantum systems advance in their lines to propose improvement in the nanosurfaces when applying these effects. Cryptography highlights the fact that quantum transmitted information cannot be hacked unless, and if trying it decoheres, so you need to have the key for reading it; and the entanglement is the property that allows connecting 2 or more qubits without attention to the distance among them. Thus, the scientists look mostly to improve these 2 techniques in the aforementioned nanomaterials, as well as, nano-assembling processors, quantum interferometry and quantum tunneling, to which they incise in Si or a combination of Si based materials as shown in **Figure 6**.

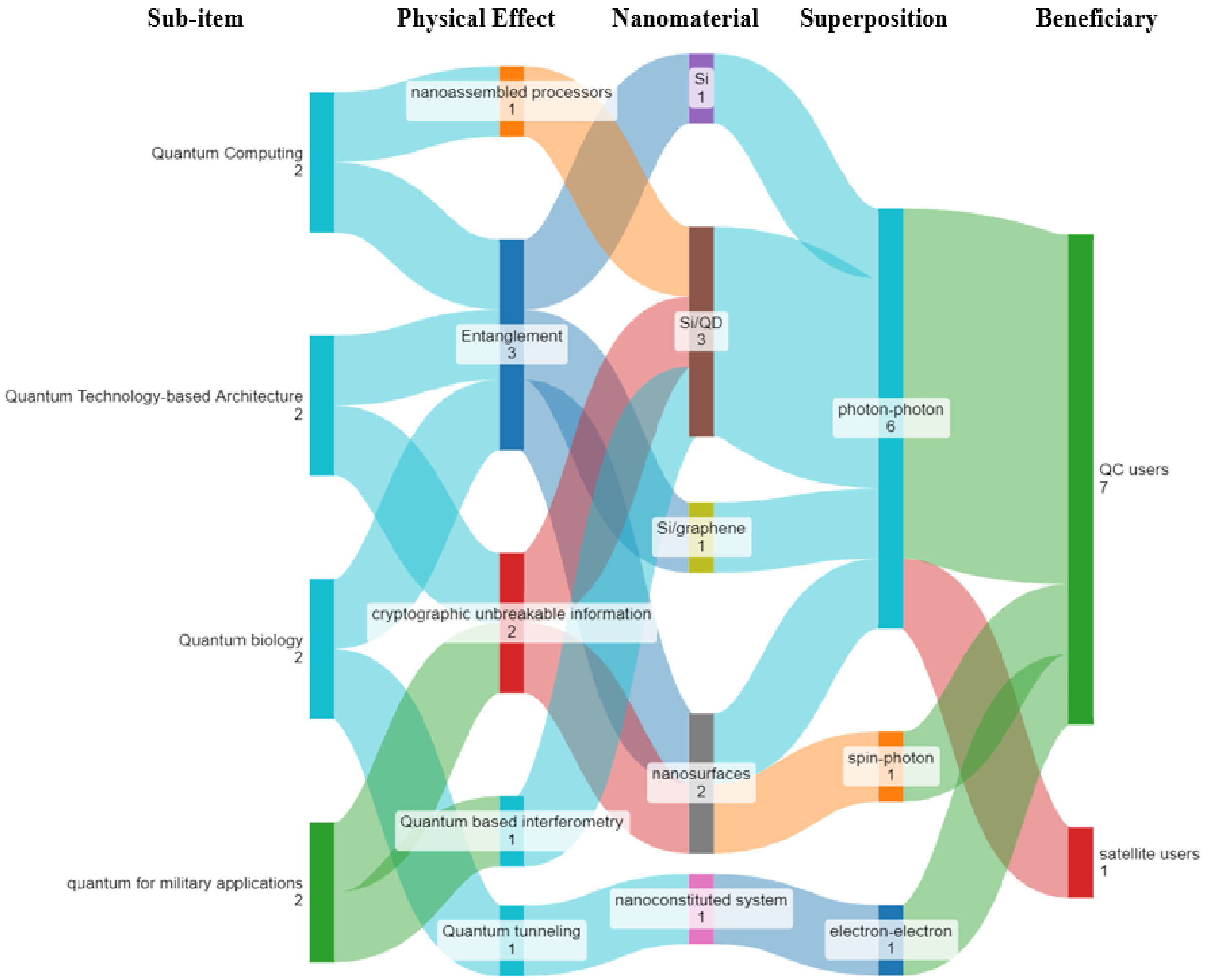

Figure 6. Diagram of Sankey for the interrelation among the features relative to the sub-fields in Q2.

Finally, some recent examples of case studies where quantum nanotechnology (fusion of both domains) has been appearing are: Brijwani et al. [46] present concrete examples of the use of quantum computing in cybersecurity advances. Some of these examples show the use of nanotechnology orchestrated by quantum computing to solve highly complex mathematical encryption problems. Pau and Borza [47] built a qubit flow architecture to imitate the behavior of synapse signals, and from there they performed an analysis of how to model the brain with nanotechnology. In the opposite sense, Mimona et al. [48] define nanoassembled wires to accelerate the computing power of quantum computers, thus creating a fault-tolerant and scalable quantum system.

4.2. Analysis based on categories

In this section, we want to highlight the main aspects of the selected publications for the SLR development for each question, distributed by three categories, "Nanomaterial", Type of

"Superposition" and the "Beneficiary", using the keywords of each category. For example, for Q1, the most demanded nanomaterial is the nanodiamond (ND) with 29%, followed by nanosurfaces with 17%, and less frequent, nanoparticles and insulator/superconductor with 12% [34, 35, 36]. This fact indicates the high interest in solid surface generated qubits using extremely ordered structures such as ND, that are devoted mostly to sensing. Nanosurfaces and nanoparticles are very similar, but they provide characteristics to the generation of qubits that are not necessary, as occurs with ND. Nanoparticles can be useful on a surface while nanosurfaces already have the features to host the qubit. Also, the superpositions most frequent are the photon-photon and the spin-hole, with 23%. The photon-photon senses properties with quantum nanosensors, and the spin-hole uses nanoparticles-based quantum properties to emit entangled photons that transport information. Finally, it is clear that the beneficiaries are the scientists (identified as "QC users"), with 47%, "medical personnel", with 23%. In general, the incidence of QC is remarkable for diagnosing purposes mostly, and "satellite users" [37, 38].

Analyzing **Figure 7** for Q2, there is a tilted interest in nanomaterials such as Si/ND, with 37%, meaning QC advances will affect most, this material. It signifies in looking up for the new generation of sensing techniques relying on quantum they optimize aspects regarding the nanosurface preparation, setting properties like regularity, layer-by-layer disposal, among others. Second place is for nanosurface having 25% of employment, and third, with 13%, the Si/graphene and nanoconstituted systems. It is clear that greater affectation is on the regularly distributed nanomaterials with crystalline properties, given the robustness and reproducibility of this nanomaterial in the solid surface qubit generation. The most common superposition is photon-photon, with 75%, indicating that the QC applications want to improve these surfaces in the handling of light (photons), due to it is the qubit start point. If the system works with light, then another kind of superposition such as electron-electron (13%) and spin-photon (12%) can provide other applications [39]. As well, it is remarkable that for the type of beneficiary, the target is the scientists, occupying 87%. This indicates that the improvement of QC over nanotechnology (Q2) is an interest merely from specialized labs [40, 41, 45]. Secondly, is located satellite users, with 13%, and this interest belongs to a profitable industry such as Aerospatiale.

The most relevant relations between nanotechnology and QC are [21, 25, 42]:

- The employed nanomaterials in QC are SiC, Si/ND, Si, Gold Nanoparticles, ND, Superconductors, and Si/graphene.
- The types of superposition for the qubits generation on nanosurfaces are the following: spin-spin, photon-photon, spin-hole, photon-electron, electron-hole, spin-electron, spin-photon, and electron-electron
- The general beneficiaries of QC by using nanotechnology are nanomaterials users, medical personnel, geographers, and satellite users.

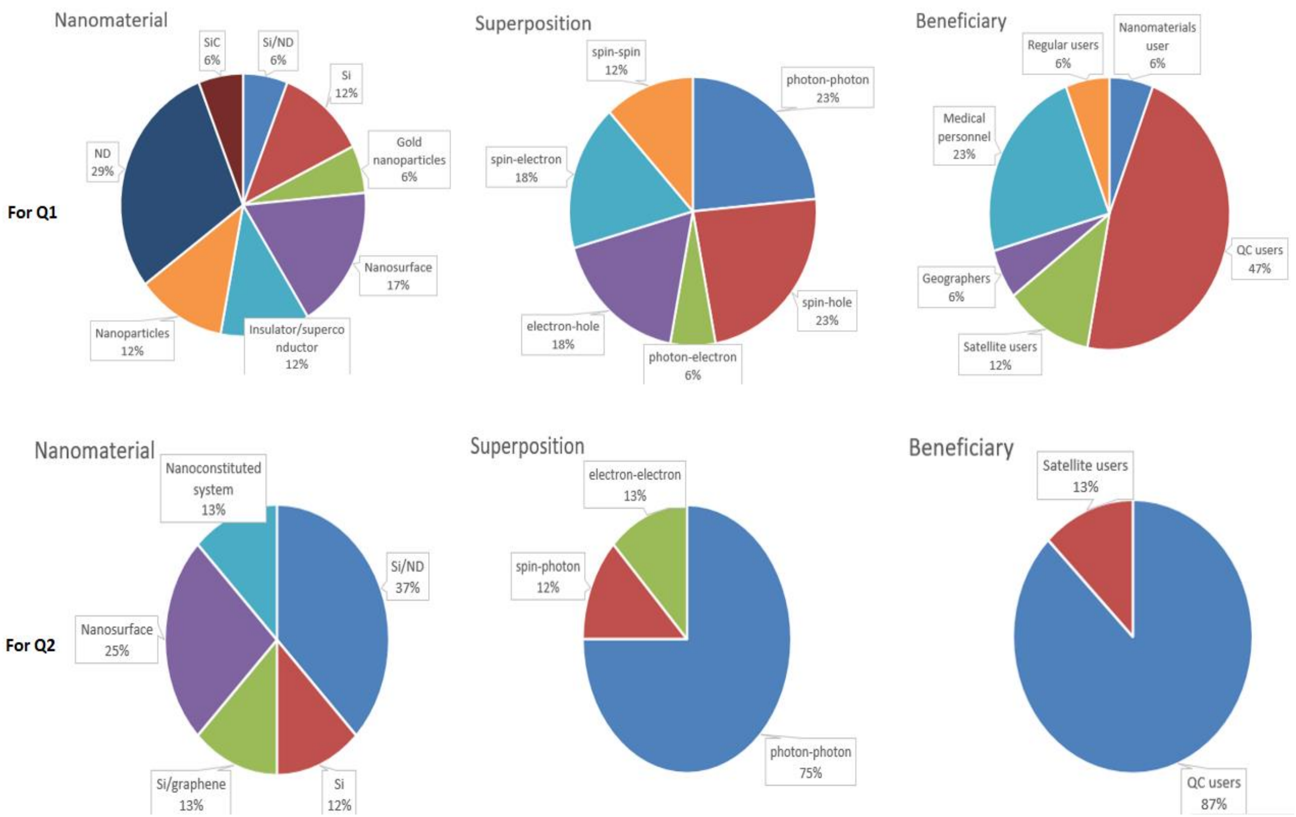

Figure 7. *Classification of articles by categories and subcategories.*

Despite the advantages mentioned above, there are also aspects that are negatively influencing the progress in both areas. In this paragraph, we will discuss some of them. For example, as Tsimvrakidis et al. [54] comment, there are problems in the integration of nanowire quantum dots (NWQD), which generates failures in the single photon source. This problem has been attempted to be solved with laser writing that modifies the refractive index and, therefore, improves the adjustment of NWQD, but improvements are still needed. In addition, there are incompatibilities of the NWQD for its integration in a quantum circuit, as indicated by Hadi et al. [53]. They have proposed to solve it by using Si or silicon nitride surfaces, but these are very preliminary results. These are examples of some problems that are appearing with the integration of these technologies, with very incipient initial results.

Now, nanoassembly in particular is not the only technology that is impacting QC. Table 5 shows some of the technologies that are impacting QC and, in general terms, how they impact them.

Table 5. Comparison of technologies affecting the QC

Reference	Technology	Impact
[49]	Nanoassembly	2-dimensional materials such as graphene, transition metal dichalcogenides, and nanosheets are vital for the advancements of QC. These materials are key due to the chance of miniaturization and the reducing energy consumption.

[50]	Molecular Dynamics	Provide better accuracy and efficiency in the simulations of big datasets, in order to improve the achievements in predictive force fields, adaptive algorithms, and in general quantum based methodologies.
[51]	Advanced photonic	Improving photonic emissions and laser performance will allow for quantum dots adapted to light wavelengths. This will speed up quantum computers.
[52]	Classical fusion of matter	Classical fusion capabilities can be integrated into the Qubernetes platform. This will allow mapping resources onto quantum environments, enabling quantum simulators at the hardware level..
[53]	Gold electrodes	A theoretical study revealed that gold electrodes and nitrogen exchange permits an improvement in the charge transport capability as part of the quantum electronic properties of the system.

Thus, Table 5 shows how various technologies are impacting QC [49-53]. Notable are the contributions of molecular dynamics to simulate nanodata sets, how lasers can be used in quantum dots, the integration of classical matter fusion with QC to accelerate the computing power of QCs, and gold electrodes to enhance quantum charge transport.

5. Challenges

From a general view of the published research, we can note that nanotechnology is crucial to QC advancement and establishment since the nano-assembly and properties are involved in the quantum capabilities [43]. Quantumness arises up when the highest internal levels of an atom are shown, hence by going through the involvement of nanoparticles or nano-instanced structures the system starts oscillating between two states [44]. Next, we will describe the present challenges to adequately answer questions Q1 and Q2, which allow us to establish the interrelation between both paradigms in the coming years.

Below we will describe the current challenges to adequately answer questions Q1 and Q2, which will allow us to establish the interrelationship between both paradigms in the coming years. In addition, we propose some possible future work/research based on these challenges.

The findings identified for question Q1 are listed below, with some possible future research,

1. To build a faster qubit-based computer relying on parallelized calculation of photon-photon entanglement and goes far beyond compared to the capabilities of classic computing. Thus, specific future research is to study the parallelized calculation of photon-photon coupling in solid state chips by implementing metal-vacancy technology specialized software.
2. Use an array of arranged nanoparticles patterned over a surface to generate well-ordered qubit states fault tolerant. Thus, specific future research is to simulate the formation of patterned qubits over a surface to see the decrease in error and increase the coherent time.
3. To vary among ions, electrons and photons to perform a most optimized solid state-based QC enabled for miniaturization. Thus, specific future research is to study different types of surfaces to see the better coupling on it, by comparing the qubits formation between ions, electrons or photons.

4. Use the nano-superconducting capabilities to perform noninvasive nanosensing of very low signals of magnetic fields from the heart or the brain of people processed in QC. Thus, specific future research is to model the multi spot analysis of brain studies to be allowed in performing the simultaneous understanding of extended zones in the brain.
5. Use D-wave-based nanochips to make portable nanodevices that process a high volume of data in a QC. Thus, a specific future research is to model the yield of the best performing nanochips regarding its surfaces doped differently with semiconductors.

The findings identified for question Q2 are listed below, with some possible future research,

1. Set the requirements of QC to realize the assembly of quantum nano-processors enabled for entangling as many qubits as possible in a high parallelized power. Thus, specific future research is to simulate to maximum entangling capability of Si based nanochips to estimate the quantum nanoprocessing
2. Study the biological-inspired process such as the birds' orientation and the plant photosynthesis to replicate artificially these processes in the nanoworld using QC. Thus, specific future research is to use real data of animals to model for instance the birds' orientation patterns, which is a property they use to travel in mass in specific seasons of the year.
3. Understand the quantum tunneling enzyme catalysis to emulate the lowest state energy optimization at which the reactions take place in mild conditions in a high rate of occurrence to be implemented in nanodevices. Thus, specific future research is to simulate high volume data nanoprocessing to shows up the quantum capability for applications such as enzyme performance in different chemical conditions.
4. Use the quantum cyber security capabilities such as KDP, to increase the secureness of nanodevices. Thus, specific future research is to test the unbreakability of KDP systems in existing computers, and foresee possible weaknesses.
5. Make nanodevices with quantum communication capabilities, to accelerate and secure communications. Thus, specific future research is to test quantum devices interconnection as an instantiation of the Quantum Internet of Things (QIoT).

In general, as a fact, the key to QC advances, as stated in [24, 15, 9], stands in the qubit stability and lower costs. On one side, the qubit is so sensible that it lasts 10^{-3}s in coherence, which in the quantum time is a lot, but in the macro time, is negligible. If a millesimal of a second is significant for calculation purposes, reaching at least 1s of coherence would be the panacea. Thus, some of the big challenges for the QC and Nanotechnology interconnection are:

A. Increase the coherence time with nanoassembled bottom-up machinery using QC.
B. Increase the number of entangled qubits in a nanosurface.

Conflict-of-Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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