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Extending Learning and Collaboration in Quantum Information with Internet Support: A Future Perspective on Research Education beyond Boundaries, Limitations, and Frontiers

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Abstract: Quantum information is an emerging scientific and technological discipline attracting a growing number of professionals from various related fields. Although it can potentially serve as a valuable source of skilled labor, the Internet provides a way to disseminate information about education, opportunities, and collaboration. In this work, we analyzed, through a blended approach, the sustained effort over 12 years to involve science and engineering students in research education and collaboration, emphasizing the role played by the Internet. Three main spaces have been promoted, workshops, research stays, and a minor, all successfully developed through distance education in 2021–2022, involving students from various locations in Mexico and the United States. The success of these efforts was measured by research-oriented indicators, the number of participants, and their surveyed opinions. The decisive inclusion of the Internet to facilitate the blended approach has accelerated the boost in human resources and research production. During the COVID-19 pandemic, the Internet played a crucial role in the digital transformation of this research education initiative, leading to effective educative and collaborative experiences in the "New Normal".

Keywords: research education; internet-supported education; blended learning; educational innovation; quantum information education; impact on research; higher education

Citation: Delgado , F. Extending Learning and Collaboration in Quantum Information with Internet Support: A Future Perspective on Research Education beyond Boundaries, Limitations, and Frontiers. *Future Internet* **2023**, *15*, 160. https://doi.org/10.3390/fi15050160

Academic Editors: Claude Chaudet and Laurent Moccozet

Received: 22 February 2023
Revised: 16 March 2023
Accepted: 7 April 2023
Published: 26 April 2023

1. Introduction

Quantum mechanics, a science that emerged in the early twentieth century, underwent a slow incubation of concepts and development throughout the century. Its notable applications include transistors, lasers, magnetic resonance, and electronic microscopes, leading to remarkable technological developments as a result of the research. However, the field did not take a fundamental step toward technological development until Richard Feynman's statement [1] that quantum systems could perform a type of computational processing unachievable by classical systems. By exploiting the central properties of quantum mechanics, such as superposition and quantum entanglement, a new development trend has emerged, resulting in real-world applications ranging from cryptography, novel communication systems (teleportation), and quantum processors.

1.1. From Quantum Mechanics toward a Quantum Industry

The emerging areas of quantum information, communication, and processing are no longer confined to physicists, mathematicians, and computational scientists. Instead, these fields increasingly influence various disciplines that address complex phenomena, including chemistry, biology, economics, and even sociology. As a result, a new generation of professionals with varied interests and an inclination toward innovative scientific solutions is being called upon to contribute to develop quantum technologies and solutions.

Based on a classification agreed upon by several authors for the evolution of quantum technologies and the role of education [2], Figure 1 shows the three outstanding branches in applied quantum information, quantum processing (quantum computation and algorithmic processing), quantum sensing (measurement, metrology, and quantum sensor development), and quantum communication (quantum processes to generate, store, transmit, and receive quantum information). The diagram highlights emblematic applications in each branch and the classically associated disciplines where professionals are likely to originate.

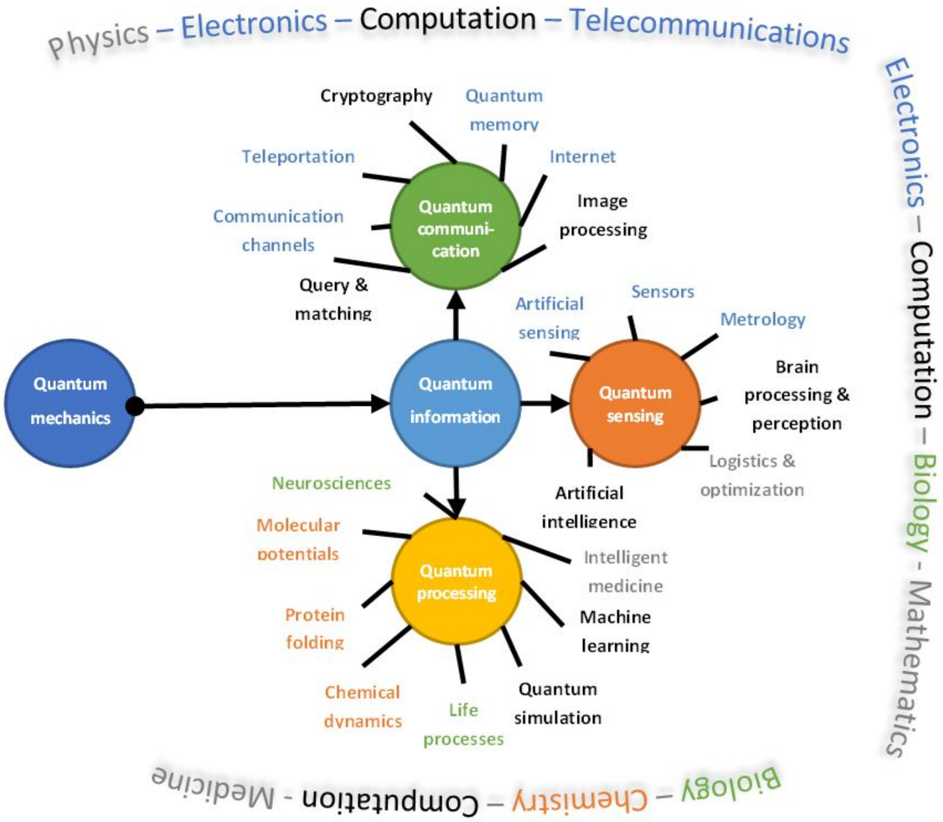


Figure 1. Three well-identified branches of quantum information science with some associated quantum emblematic technologies. The classical areas related to each branch are the same color as the corresponding emblematic application, framing the central diagram.

It has taken approximately 75 years for the development of the ENIAC to attain our current computational level. The term quantum 1.0 revolution has been coined for the typical quantum applications of today. For quantum information technologies based on quantum processing, the term quantum 2.0 revolution is used. Developed countries have prioritized the development of quantum technologies in all possible spheres, seeing them as a focus of wealth, development, and well-being in the next few decades [3]. However, there is still a divide between the primary physical and mathematical domains required to train professionals and fuse with other disciplines properly. Nonetheless, efforts are being made to synthesize these domains and shorten the training time to allow more professionals to become involved [4].

1.2. Research Education and Human Resources Increasingly Being Requested for the Future Quantum Industry

The development of the quantum revolution requires more human resources, yet the traditional curricula of bachelor's programs do not adequately prepare students for independent self-learning in this field [5]. Nevertheless, it is expected that a significant number of skilled professionals in various disciplines will be needed in the coming years [2] to achieve the global construction of a quantum computer. Most of these efforts are currently developing in a limited number of countries, such as the United States, Canada, Europe, Australia, Japan, China, and Russia [3].

This report presents a research-based educational program in quantum information, developed as a research subject since 2010. The program focuses on education and student attraction programs intending to foster an interest in frontier science and technology. Our university is a nationwide system with campuses throughout Mexico; it is the second-highest-ranked university in the nation. The research structure is based on strategic research groups (GIEE in Spanish) spread across several campuses in the system. Our leading group, photonics and quantum systems, consists of several subgroups related to optics, photonics, and quantum applications. Our branch, the Quantum Information Processing Group (QIPG), mainly focuses on theoretical and simulation-based quantum developments, collaborating with other research branches for experimental research. Our educational efforts have a nationwide scope, reflected in the current educational research report.

One of the main interests of this report is accounting for the overall educative evolution of attraction spaces and derived research outcomes. In research, the outcomes should be linked to research products as a central component of that education and human resources development. Without a doubt, through 12 years of evolution, the central role of the Internet was identified, mainly, but not exclusively, boosted by the COVID-19 health confinements. It generated a perceived transition in terms of scientific products and human resources. Thus, the interest in assessing the Internet's impact on our educative effort is inescapably present. Including students in research is a pyramidal effort, first disseminating the research with medium size groups of students, then attracting a reduced group of them to research; thus, populations are commonly small. In addition, the assessment should be constructed on a research basis centered on scientific production quality and quantity, human research development impact, and collaboration, some non-standard variables in education. This sets limitations for the scope of this research. It implies using non-conventional analytical methods based on useful indicators and correlational information analysis. Thus, a diagrammatic analysis was selected as a preferred method for some of the objectives in the current research.

The aim of this work is two-fold. First, it accounts for the achievements of 12 years of institutional efforts in quantum information education in terms of initiatives, innovations, and human resources development. It also analyses the decisive impact of the Internet on global initiatives. Thus, the second section develops a brief review of quantum information as a research area and the associated human resource development, presenting the digital evolution in research education supported by the Internet. Some other notable and comparable educative experiences in quantum information education around the world are reported as a comparison. Section 3 reports the research objectives, materials, and methods followed, together with the data collection description. The fourth section recounts the essential elements presented in the initiative, their evolution, and their integration with several Internet-based innovations. The fifth section chronologically analyzes the educative elements and outcomes appearing in the different stages of the initiative, particularly distinguishing the digital transformation period. They present the type of students, grants, achievements, innovations, research collaboration, and research products. Scientific research outcomes are chronologically analyzed with their metadata, such as from students, collaboration, and scientific publications. The analysis uses graph analytics among those variables, particularly their chronological development. Section 6 briefly discusses the outcomes with additional contextual information provided by the author. The last section presents the conclusions of the report.

2. Theoretical Background

Nowadays, quantum mechanics courses for physicists and mathematicians have been transformed into a diversity of courses with remarkable specialization, such as Information, Communication, Measurement, and Processing [6]. The audience has also changed with students coming from several science and engineering programs, including Computer Science, Chemistry, Chemical Engineering, Material Sciences, Nanotechnology, and Electronic Engineering [7]. Another trend is an exponential increase in educative resources provided by the Internet, such as video conferencing systems, diversified digital learning resources, and specialized tools [8,9]. Due to these, science has a charming attraction that was hidden before. Those public and innovative resources are reaching young people interested in research, with different focuses based on their academic interests. Students' increasing interest in science has been sparked by the Internet and the perception of having greater job security than other sectors [10]. Unfortunately, students' interest in science does not guarantee their automatic selection of a career in Science or Technology, so additional interventions should be made [11]. In any event, it can be said that the Internet is facilitating things previously popularized in specialized books. Science is becoming more open and approachable.

2.1. Quantum Information as an Attractive Life Plan for the Development of Quantum Industry

The boom in quantum information development has been sparked by its perceived potential impact on human society and the undeniable boost that the Internet has provided through scientific dissemination to everyone using their devices. The Internet has generated an intangible impulse for scientific development in the last 25 years, attracting and involving new human resources in research [12].

After decades of theoretical and experimental work, quantum technologies are a reality, currently crossing a period of emerging growth in a well-identified global industry. Although the most notable goal is the creation of a quantum processing device emulating and improving the capabilities of current computing technologies, other developments are proceeding from different fronts, including quantum processing algorithms, user interfaces with these technologies, the development of quantum sensors, and the associated metrology to measure related systems [13]. These are commonly classified into three significant developments, computing and simulations, communication and networks, and quantum sensors and measurements. Blocks of countries in North America, Europe, and Asia, have detailed medium-term strategies, roadmaps, and prioritized investments in those technologies as a line of economic development [14].

As a result, the quantum industry is growing exponentially, transitioning from quantum mechanics, as noted in several prospective references [3,7,14,15]. Figure 2 schematically shows the exponential growth as a function of time, estimated by research discovery facts and data. The color code marks three different, well-stated developmental stages of that industry. The horizontal axis divides the quantum revolution since its dawn in 1900 (with the Max Planck hypothesis of quanta) as the beginning of quantum science (blue), going through the era of electronics with the development of the semiconductors around the 1960s marking the beginning of the quantum technology stage (orange). Then, the beginning of the quantum industry era (green) was marked by the first commercial quantum computer available, the D-Wave, and 2030 is a planned horizon in the roadmaps of several countries blocks [3]. Vertical legends refer to applications that appeared or are expected to appear in each stage [3,7,14,15]. The vertical axis indicates the number of quantum scientists involved in the field; mainly, the number of new employments related to quantum information in the current decade ranges in the tens of thousands yearly [16]. Otherwise, the leading global industries currently have employees ranging in the millions [17]. Those values barely set the number of people involved for each stage of the vertical axis, especially for the quantum industry.

Thus, by surpassing the theoretical and basic experimentation of the last century, quantum science is evolving first in the current intermediate stage of quantum technologies to arrive in the following decades in a global industry of quantum applications [15]. In the future, several applications are expected to be developed involving an increasing number of professionals [18].

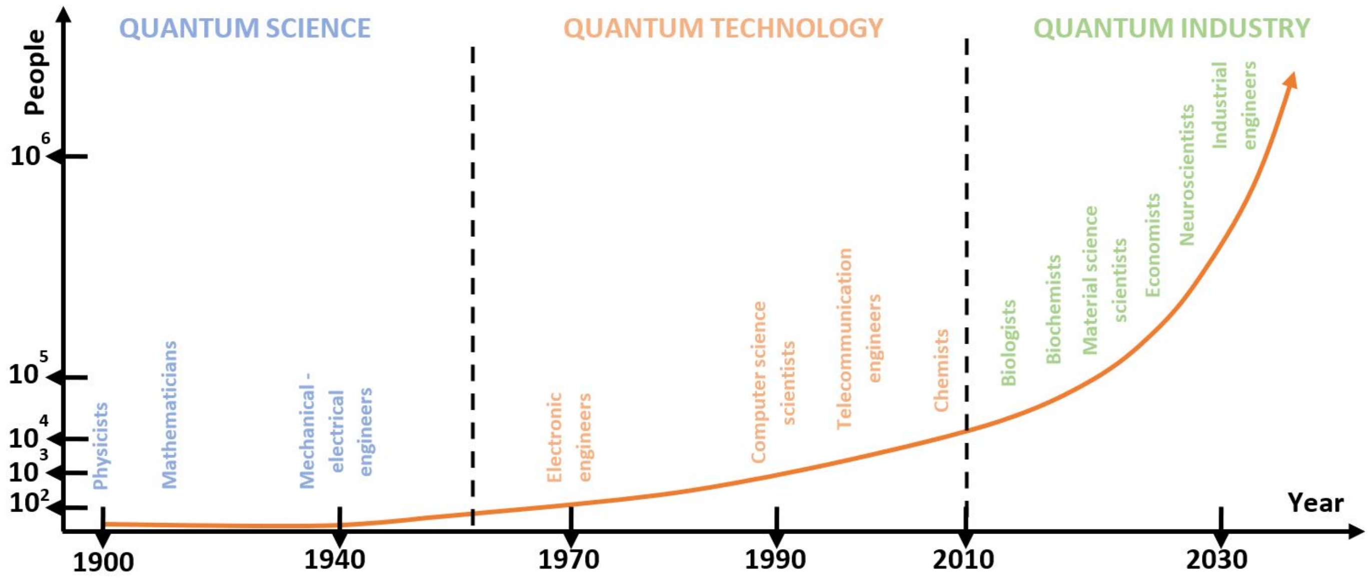


Figure 2. Evolution in quantum science applications through disciplines involved and the number of professionals to trigger an impact on global transitions quantum industry.

2.2. Quantum Information Education: A Wider Initiative around the World

The attraction of new human resources to forge and promote disciplines, such as quantum information, requires early actions. Thus, STEM (Science, Technology, Engineering, and Mathematics) educative initiatives provide early approaches for their inclusion [3]. Those initiatives seek to include, attract, and train students in scientific research first, and then the areas of quantum information as motivating life plans. Quantum information can promote and contribute to scientific interest because it is a disruptive discipline [2]. Nowadays, specialized groups and institutes use this approach to introduce this discipline in early courses, attracting students through workshops, professional stays, scientific graduate courses, and academic degrees [3,6,7].

The quantum industry comprises an emerging, commercial, and scalable development of quantum technologies [2]. The industry has produced massive products and services, such as quantum cryptography devices. Such an effervescent development of potential products and services requires a plethora of qualified human resources for their development and implementation [19,20]. Today, many commercial initiatives are already developing and improving existing quantum technologies in fierce competition. Thus, IBM, Google, D-Wave, and Amazon Braket are emerging pioneers in developing quantum processors. Meanwhile, MagiQ, AgilPQ, Anametric, and QuantumXchange develop applications and quantum encryption devices. In a disruptive direction, Atom Computing, EeroQ, and IonQ develop solid-state-based processors. ColdQuanta develops various quantum devices for communications and storage. Those companies are examples of quantum products' accelerated development and commercialization as part of an emerging market on which several developed countries partially bet their global leadership and economy [14,18].

Those opportunities in the scientific profession have motivated the development of this type of learning experience and training in research for Higher Education students [21]. However, in each country, it is usual that only a few university education institutions or research centers offer such a possibility, being regularly far from potential candidates. How to attract them? Which initiatives can be formulated to make this opportunity equitable? We can appreciate quantum information's importance as a discipline in different countries in many educative initiatives implemented in several levels of education. For instance, some experiences introducing the teaching of quantum optics have been reported in secondary education [22], together with more theoretical approaches teaching Dirac notation [23]. In high school, an experience teaching quantum computation has been reported [24], just in the preamble of higher education. Interestingly, such experiences also include technical education regarding Photonics [25].

Higher Education has many examples of educational initiatives in quantum information and Photonics. Creation of complete educative modules or courses has several implementation examples [26,27], or at least its inclusion in other courses [28]. Photonics initiatives are an essential applied area of education, with centers created for the discipline [29–32]. All those efforts are directed towards developing leadership in quantum technologies [33].

2.3. Research Digital Transformation Accelerated by the COVID-19 Pandemic

The COVID-19 pandemic turned our education systems upside down. Overnight, educational activity stopped, and it had to be quickly and effectively reinstituted through the most viable and affordable option, which society managed to provide. Following the health emergency, there was the educational emergency and the use of the Internet in teaching, research, and collaboration [34]. Internet use expanded in the 1990s, and during the pandemic, the Internet was the unifying element of the educational emergency, the best channel for learning through this crisis. It underwent a creative development never seen before, an irreversible boost to online education that had taken decades to gestate [35].

Scientific research has evolved from an exclusive professional area for groups of researchers working at distant locations on their initiatives to finally moving into a well-connected, broadened human activity. Based on the concept of digital transformation [36] applied to research development, Figure 3 presents how groups of researchers worked in the last century (gray) using traditional communication channels based on printed journals, in-site research stays, and exclusive workshops with limited invitations. With the advent of the Internet, journals came online, speeding up the rate of publications and scientific dissemination (orange). It boosted research by dramatically improving the old online abstract databases common in the 1980s. In the 21st century, when video calls became common, other effective channels boosted collaboration, reduced travel expenses, and optimized joint research work [37] (orange). It included the interaction between researchers and students [38]. It was the scenario barely present during the advent of the COVID-19 pandemic, a function of the open-mindedness of researchers' groups for those practices [39]. Still, some could remain scientifically isolated. Several resources were developed before the lockdown, but the boom in their usage occurred during the health confinement. Many scientific conferences were developed online, thus ensuring scientific dissemination and collaboration. To solve the problem of no access to physical laboratories, at least in a limited way, some remote access was implemented, in most cases, following a strictly agreed agenda. Sometimes, novel Internet-based applications were created to manage and design experiments in a previous stage of presential experimentation. Those well-characterized tools easing scientific collaboration are marked in green as Internet-based products used for that purpose.

Such was the case in our research and teaching area with Optics studio [40], a collaborative virtual-reality software providing all previous stages to the optics and photonics experiments, as experiment design, mounting, specialized optical elements purchase, for the simulation of each experiment. Together with other Internet-based collaborative applications to share documents, writing, simulations development, and easy communication (Zoom or Teams, for instance), most research groups continued not only working but also learning how to do research differently and with improved efficiency, thus migrating to the digital research transformation [36].

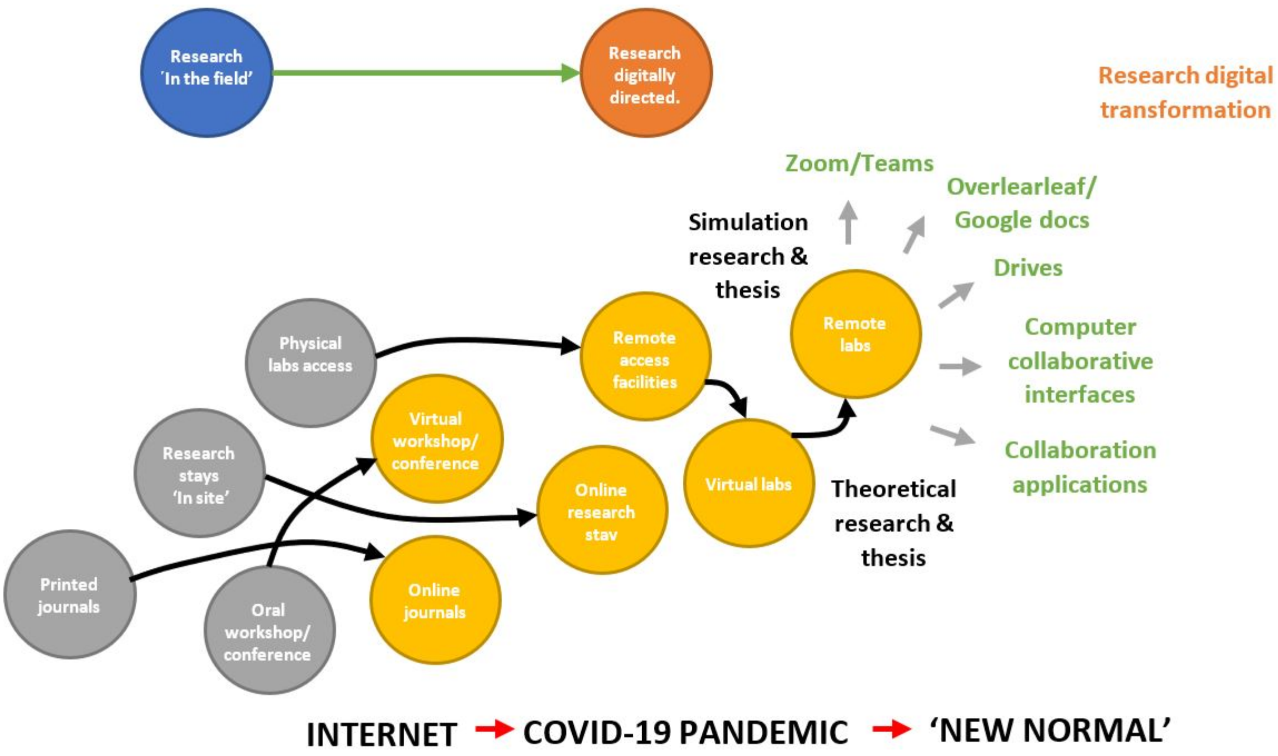


Figure 3. Evolution of research activities from face-to-face to digitally conducted. The COVID-19 pandemic boosted the transition by integrating lots of resources and conditions.

The COVID-19 pandemic, beyond the dramatic health crisis, put at stake many of the ecosystems in human activities, primarily face-to-face interactions. It was the case for office work and commerce, which quickly reacted through collaboration and remote interaction on the Internet consistently developed over the past decades for these purposes [41,42]. Those who did not move timely on such technologies ended up suffocating quickly. Education, in most of its areas, was another inexorable victim of the pandemic [43]. After decades of debate and resistance to experimenting with online or hybrid education [44], instead promoting face-to-face education as the unique or primary model, the indispensable activity for the human being (presential learning) became suspended overnight and had to turn to the viable alternatives already developed for electronic commerce [45]. In the end, Education decisively turned to the direction resisted for years: massive Internet use [46]. Even today, during the "New Normal," not all actors worldwide have embraced the experience, continuing to resist using the Internet for online or blended education, instead of capitalizing on the experience and achieving educational goals [47,48].

3. Research Objectives, Materials and Methods

This section considers the main research questions that emerged in the current stage of our educative initiative 12 years after its beginning. Then, proper objectives were established for concrete research tasks and the materials and methods used to collect information and data for the analysis.

3.1. Research Questions and Research Objectives

Despite several punctual effectivity analyses performed throughout the history of our program, particularly to evaluate collaboration through learning analytics [49] and recounting the actions and outcomes during the COVID-19 lockdown [50], no global analysis considered its 12 years of operation and evolution entirely. A general, but still genuine, education-related research question was stated in the Introduction. In terms of our interests, it should be clarified in some different interest components. Thus, our first research question is centered on the global evolution of the educative initiative during its first 12 years of operation as a function of educative elements, human resources, digital and experimental innovation, and proper research outcomes. Such a question should be extended further, asking how the development of research products becomes assessed in terms of involvement, collaboration, and quality, several aspects of interest in research education. The last issue (quality) is crucial because it is how research is measured. Finally, because of effective Internet use in our initiative, another concern is assessing its relevance in the program's evolution and outcomes. The analysis of the research products should also ask about the real impact of digital transformation in the educative initiative on the students' inclusion and their research production. The research objectives should be stated in those three inquiry terms. Thus, the research objectives were aligned, delimited, and established as follows:

(1) To perform a chronological evolution inventory and assess the educative elements, contents, technological resources, innovation, digital evolution, and outcomes for our quantum information education program over the last 12 years.
(2) To develop a global analysis of the research outcomes and their evolution in a classical research assessment. This mainly refers to scientific products and human resources developed through the 12 years of deployment, considering students' inclusion, research collaboration, scientific product quality, and learning innovation.
(3) To assess a possible differential impact introduced by the digital transformation on the educative initiative, as it was gradually included through the 12 years of evolution.

All were pursued under the global educative initiative performed by our research group, thus covering three main aspects, initiative inventory of actions and outcomes, research assessment for education-based scientific production, and digital transition assessment boosted by the Internet to facilitate blended learning.

3.2. Materials and Methods Statement

Several analyses were developed for this research, particularly for the two last research objectives centered on research indicators. Although a statistical inference analysis was not viable due to the number of students involved, an alternative approach based on a diagrammatic analysis [51] coming from data analytics let us know, visualize, and understand the correlations of interest and their intensity through the entire process. Specific descriptive statistics were then inferred and analyzed from those reports regarding some classical indicators in research management.

To fulfill the first research objective, we depicted chronological events in an orderly timeline, extracting information from our operation registers (students, programs, products, and their academic level), together with other essential dates for obtaining grants, introducing innovations, international conferences being organized, and research collaborations. Primary information was reported without limitation from the author registers. The chronological inventory fulfilled the scope of the first research objective. Syllabus registers were extracted from Tangle [52] for each learning experience throughout the history (workshops, research stays, and minors). Detailed information from learning analytics from Tangle was reported in [49]. For this report and its interest in the digital transition, the research products analysis was performed using diagrammatic analysis.

For the second objective, scientific research production was analyzed by gathering metadata information. Thus, the second part of the analysis involved proper graphs in analyzing the correlations of interest regarding research collaboration, year of publication, indexation, authors, etc. In fact, in data analysis, graph analytics is an emerging tool for data science, widely valuable for representing, understanding, and analyzing complex relationships between several linked variables or entities; graphs are a kind of mathematical structure to comprise related information in several processes [51]. Those data were crossed to obtain comprehensible plots reporting valuable descriptive statistical information, such as relative production, index of impact per author, and so on. Those analyses revealed an evident transformation in the rate, quality, and complexity of research collaborations when the initiative entered a digital transition.

3.3. Data Collection

Most of the chronological events data (workshops, research stays, minor) were provided by the historical registers of the author almost without limitation regarding the entire research group who collaborated through the educative initiative, research elements, and innovations. The first objective precisely aimed to gather the information to be reported in this work, thus providing a comprehensive chronological vision through time (in terms of educative spaces, evolution, research products, innovations, students involved, and awards) and additionally obtaining a public report of it. The only unreported limited information corresponded to conference participation and non-indexed proceedings appearing as minor events in the current analysis. Nevertheless, that information was previously reported [49,50].

Data related to scientific publications were limited to the author as the group and initiative founder, thus measuring and reflecting a representative impact per researcher in the group. In addition, despite other multiple research products being developed as posters, non-indexed proceedings, and conference participations, the report of scientific products was limited to Scopus publications to have a well-known quality measurement. Thus, data were obtained directly from the author registers, but they also could be obtained from any data source of the article's compilation (Scopus, ORCID, or Google Scholar; another reason just to consider articles indexed in Scopus). Each publication included metadata from those sources (year of publication, authors, impact factor, JCR Scimago quartile, etc.). Those data are synthesized below for current research purposes.

The following two sections deal with the analysis regarding the first research objective (Section 4) for clear discussion and presentation. Then, the two last objectives are covered in Section 5.

4. Quantum Information Education: A Twelve Year Chronological Follow-Up of an Educative Initiative in a Mexican University

During the COVID-19 lockdown, scientific and academic research had a more established history in using digital technologies than education; nevertheless, ambivalence was also perceived [53]. Research required, in many cases, access to specialized laboratories; this was solved through controlled access, laboratory automation, and remote computer services via the Internet. Nevertheless, research was intimately linked to education through the academic degrees of graduate students and the motivation of new generations of students waiting to experience the field of scientific research [54]. For many research groups, the pandemic accelerated digital scientific collaboration worldwide, reforming science, technology, and innovation. It forced the digital transformation of research education and scientific collaboration [55]. If this experience and the value of the Internet in research are not capitalized upon, the pace of collaboration without distance restrictions will grind to a halt. It would threaten the future again, with other possible worldwide contingencies coming [56].

To address the first research objective, we describe the different educative elements or spaces developed in the initiative, briefly depicting their evolution, motivation, and contents. Of particular interest to prepare for further research objectives, this text reports the gradual digital transformation supported by the Internet. It is also the story of creative technological resources introduced to improve the program, allowing it to include many more students. The COVID-19 pandemic resulted in the Internet being treasured as a channel of scientific dissemination, communication, and collaboration [57]. Thus, this report also analyzes the remarkable and vital impact of the Internet on the growth and expansion of the current initiative [58].

4.1. A Program for the Attraction and Education of Human Resources for Quantum Information Research

For a research group, the attraction of students is essential. They are part of our academic life, becoming valuable collaborators within the mandatory mission of our university. In an educational environment, where most students think about their professional future as entrepreneurs or employees, it is not easy to show the value of research activity. Most students do not seek research, despite planning graduate studies for their next future. The groups' activities should be directed toward research. Our research group was very young, departing in 2008, but student attraction was always one of the first goals.

This subsection depicts each learning activity developed within the initiative to establish a better understanding and language for the analysis in the following sections. They are also chronologically presented in Figure 4 with information obtained from the enrolment registers.

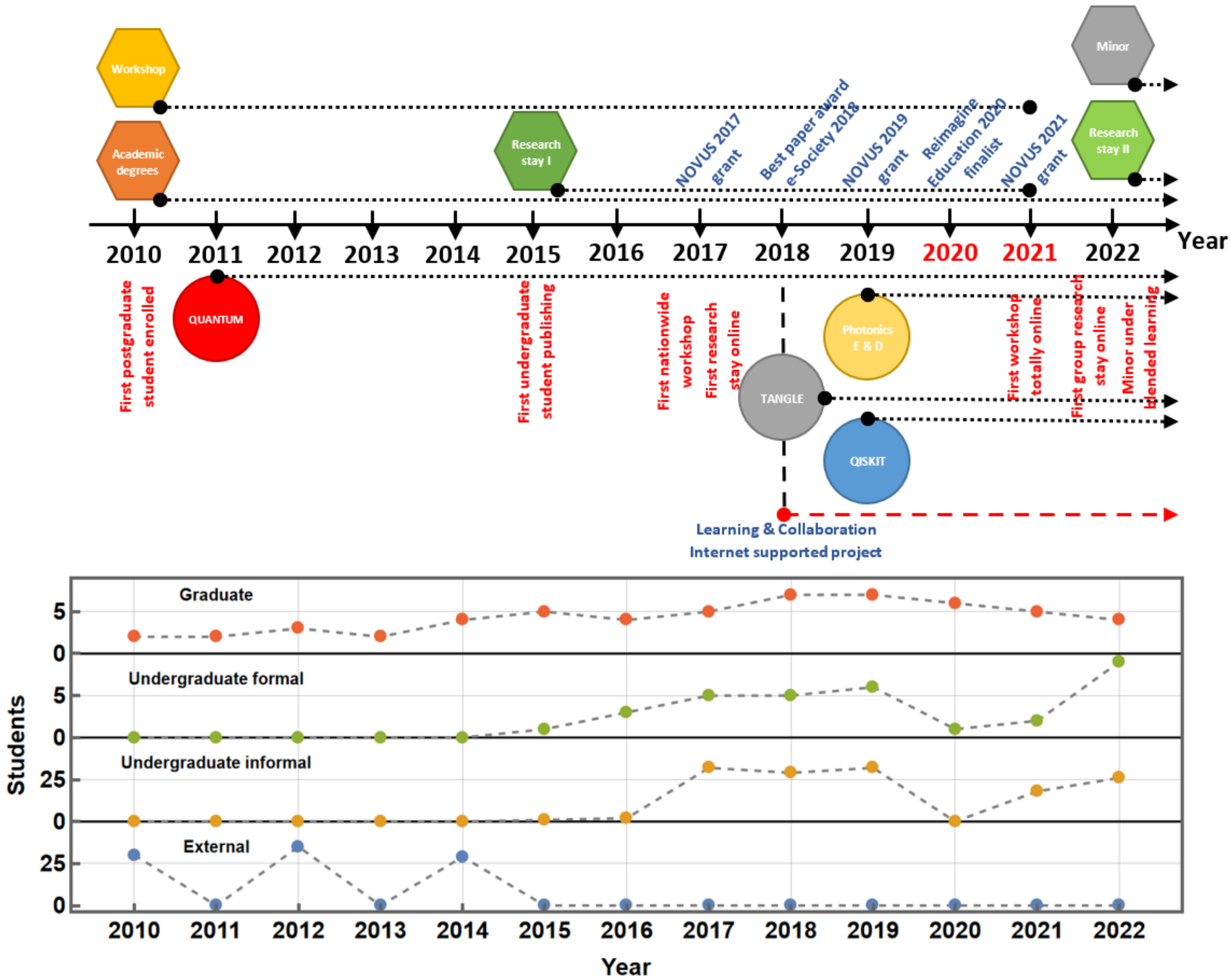


Figure 4. Didactic elements (upper timeline) ordered as they were implemented: workshop, research stays, and minor. In red are some important events, and in blue are some grants received through the follow-up period. Below are some innovative aspects introduced: QUANTUM, Tangle, QISKIT, and Photonics experiments. The lowest plot shows the number of students by their type.

4.1.1. Graduate Programs and Undergraduate Students' Attraction

The inclusion of graduate students in the master's or doctorate degrees occurred mainly for students participating in research stays or organized national workshops, although not exclusively. Many students were enrolled in master's and doctoral studies in Engineering Science, Computer Science, or Nanotechnology graduate programs. Students have been received since 2011 to those programs contributing to research projects associated with our research group, with nine researchers mentoring students. The topics involved in those theses ranged from quantum algorithms, quantum cryptography, quantum communication, and quantum applications in chemistry and biology to more theoretical topics.

It is mandatory to publish at least one original research article in Q1/Q2 journals as ranked by JCR Scimago to obtain a master's degree (two years) and at least two to obtain a doctorate (four years). Those projects sometimes involve undergraduate students publishing as collaborators, resulting in fast learning and immersion for undergraduate students. Notably, regarding distance digital transformation, during 2020–2021, two master's degree students and one doctoral student finished timely and completed their degrees; they were mentored by Mexican and foreign researchers. Those students published eight scientific research articles in that period.

4.1.2. Activities for Undergraduate Students to Increase Their Engagement

The following activities are presented chronologically as they were implemented as a function of the group initiatives.

4.1.3. Local Workshops for External and Internal Undergraduate Students

In 2010, our research group began teaching annual workshops and national schools for students, introducing them to quantum information and processing principles. The yearly experience was repeated until 2016. Most students came from the surrounding metropolitan region; only 8–10% were students coming from other states of Mexico. Most were undergraduate students; the recruitment percentage for graduate studies was low, around 3%.

4.1.4. Nationwide Workshops for Internal Undergraduate Students

National workshops on quantum information and processing began to be offered in 2017 for internal students at our university from all campuses. In 2017, Tangle [52,59], our online educative suite was developed, so the workshop experience was extended to two weeks, one as a blended learning experience [49]. Around 160 students participated in those workshops in the full periods between 2017 and 2021. Five percent of them participated in a further research stay. The experience was repeated through 2021. This last time was entirely in an online format due to the COVID-19 lockdown, which began in 2020 [60].

4.1.5. Tec20 Research Stays (Type I)

Research stays were formal activities granting credits in each student's academic program. By taking four specialized courses in one year along with their remaining courses, students aimed to learn a scientific topic in-depth, thus developing skills for research. Those stays were offered flexibly between the sixth and eighth semesters of each academic program. Most students were locals, so the stay was practically always developed as a face-to-face activity in Physics, Electronics, Chemistry, Mechatronics, Nanotechnology Engineering, and Computer Science programs. Initially, it was not mandatory to publish original research, but this practice was pursued during our last four generations. Only one student from another campus developed the stay through remote sessions with Zoom and Tangle [52]. Notably, the total number of scientific research articles he published was eight. Afterward, he became a collaborator and introduced QISKIT in other sections of the initiative [61]. Such an experience served during the two years of the COVID-19 pandemic as a reference to working successfully with other students under that teaching scheme.

4.1.6. Tec21 Research Stays (Type II)

In the new Tec Educational Model [62], implemented in 2019 (called Tec21), the research stay changed its operative scheme for 2022. It corresponds to one semester of total immersion (it is the only academic activity and takes place during the seventh semester). In this version, the publication of at least one article became mandatory. Such an achievement allows students to obtain some credits toward an associated scientific master's degree if they choose to belong to one of the graduate-associated programs. For this quantum information research stay, there is an affinity between the stay and students' possible undergraduate programs in Electronic Engineering, Physics, Nanotechnology, and Computer Science. In 2022, the first Tec21 generation had this experience; nine students were received. The experience was offered nationwide through a remote modality with 66% of the students from other Tec campuses.

4.1.7. Minor in Photonics and Quantum Systems

The minors within the 2019 plans were established as a total immersion activity (the Tec21 research stay was another alternative). In the minor, each chosen area corresponds to one of the national research groups within the institution. Thus, our research group offered a minor in Photonics and quantum applications. It is offered to students in the Physics and Nanotechnology programs. The experience consisted of five modules and the parallel development of an applied project. In 2022, this experience was offered for the first time because only seventh-semester students can be enrolled (similar to the Tec21 research stays).

4.2. Typical Contents Considered in the Different Educative Elements

Quantum information content should be appropriately adapted for the intended audience. For example, based on a survey, [63] reported different approaches for similar initiatives to teach quantum mechanics through several education levels. Quantum information processing should follow proper, independent development because each educative element (workshop, research stay, and minor) has a mixture of interests and previous learning experiences from students from several undergraduate programs. In [64], a series of considerations to establish those contents were established as a function of students' backgrounds. For our work, because most students arrive from well-identified science (physics, chemistry) and engineering (electronics, computer sciences, nanotechnology, chemical, and mechatronics) programs, the approach is based on a mathematical presentation, followed by a set of applied topics in quantum information.

Table 1 shows the overall syllabus considered for research stays and the minor. Big topics appear in the first column, and the contents are detailed in the second. The third column reports the main links to the computational applications linked with each topic, following the nomenclature (1) QUANTUM, (2) QISKIT, and (3) Photonics experiments and demonstrations (Photonics E&D). With around 50–60 hours of teaching in each space (research stay and the minor), the applications should support those topics. (The research stay still had around 30 more hours to assess the work toward an original research publication project). Despite the available time, which is profoundly different from the workshop (considering their two-week extension), the plan is based on similar topics. We covered only the topics marked with an asterisk in the second column for the workshop.

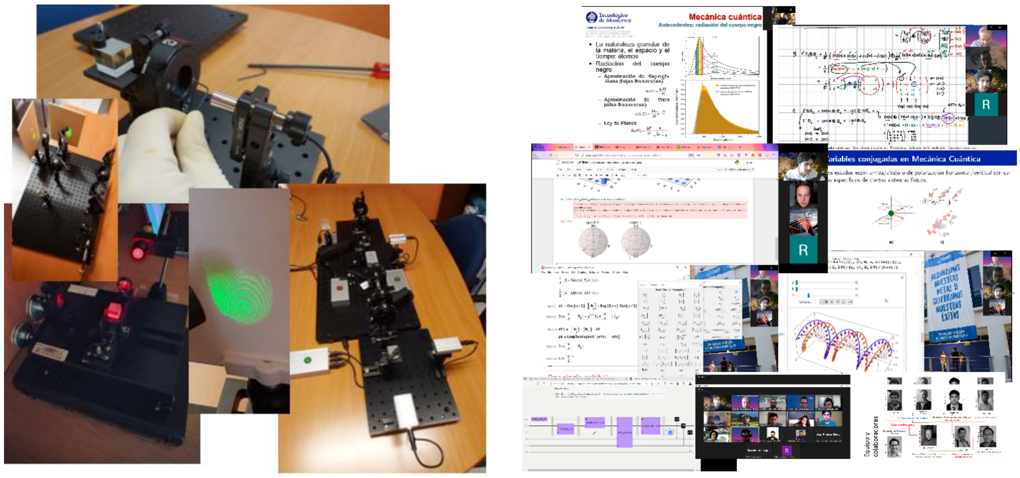
Based on Table 1, Table 2 provides a more detailed reference to the topics in each computer application or experimental practice. All those contents were sought to be covered in a harmonic chain with the theoretical contents. Figure 5a shows some images of the Photonics experiments and demonstrations included in the 2021 blended learning workshop, the research stay, and the minor during 2022, all delivered online. They included mounting two types of interferometers (Michelson and Mach-Zehnder), the demonstration of BB84 cryptography protocol, the Bomb tester experiment, and the quantum eraser experiment. Those experiments also included a previous explanation of different optical elements and concepts, such as polarizers, beam-splitters, polarization rotators, laser pumps, parametric down-conversion crystals, optical alignment, etc.

Table 1. Central contents for quantum information course included in the research stay and minor with the computer simulations and experiments included in QUANTUM (1), QISKIT (2), and Photonics experiments and demonstrations (3).

Theoretical Contents Developed in the Formal Courses (Research Stay and Minor)		
Unit Name	**Topics Description**	**Integration**
Introduction	∗ Brief history of quantum mechanics and notable experiments	3
	∗ Stern–Gerlach experiment and physical conjugate variables	1, 3
Dirac notation and basic definitions	∗ quantum states, kets, Hilbert spaces, dual space, bras, and inner product	1, 2
	∗ State decays, associated probabilities and quantum fidelity	1
	∗ Outer product and operators: Dirac and matrix representations	1
	∗ Unitary, Hermitian, Normal, and Projective operators	1
	∗ Projective and weak measurements, measurement operators and probabilities	1, 2
	– Operator functions, Schrödinger equation and evolution operator	1
	∗ Qubits, Bloch representation and the $SU(2)$ group	1, 2
	∗ Pauli operators, commutators, anti-commutators, and properties	1
Composed systems	∗ Tensor products, states and operators of composed systems	1
	∗ Entanglement, Schmidt coefficients, Bell states, and entanglement measures	1
	– Quantum mechanics in postulates	-
Quantum circuits	∗ quantum states evolution as a circuit	1, 2
	∗ Not, CNot, Hadamard, controlled and other gates	1, 2
	∗ Direct and inverse Bell circuits	1, 2
	∗ Teleportation algorithm for single and composed qubits	1, 2
	∗ BB84 protocol	3
	– Deutsch–Josza problem	1
	– Grover algorithm	1, 2
	– Quantum Fourier transform	1
Mixed states	– Pure and mixed states concept, physical interpretation of a mixture	1
	– Density operator and matrix, populations and coherences	1
	– Trace, partial trace, and partial transpose	1
	– Definitions for mixed states: probability, measurement, expected values, and evolution	1
	– Bloch ball and Bloch representation of mixed states	1
Quantum communication	– Quantum channels, Kraus operators and Pauli channels	1
	– Syndromes and quantum error correction	1

Table 2. Practices commonly developed using the computer-based applications (QUANTUM, QISKIT) and photonics experiments included in the courses (Research stay and Minor).

Contents of Computer-Based Applications And Experimental Innovations Sections		
(1) QUANTUM	**(2) QISKIT**	**(3) Photonics E&D/Optics Studio**
States, operators and measurements	Quantum and classical registers	Polarization and Stern–Gerlach effects
Bell circuit (direct and inverse)	States initialization with operations	Quartz polarization beam splitters
Qubit rotations and measurements	Defining composed gates	Interferometers arrangements and mirrors
Teleportation circuit	Bell, Teleportation and Grover circuits	Polarization rotators
Deutsch-Jozsa algorithm	Quantum simulations and Ising model	Bomb tester experiment
Grover algorithm	Adiabatic quantum computation	Quantum eraser experiment
Quantum Fourier Transform	Protein folding and chemical potentials	BB84 cryptography protocol



(a) **(b)**

Figure 5. (**a**) Images of Photonics experiments and demonstrations as they were broadcasted during the blended learning experiences in 2021 and 2022. (**b**) Similar integration of QUANTUM, QISKIT, Optics studio, and electronic notes enriching the blended learning experience.

4.3. Full-Blended Learning Approach during the COVID-19 Lockdown: An Effective Approach Attaining Planned Research and Educative Goals

All the previous initiatives reported were implemented over time (see Figure 4), improving and adapting the contents to the research projects to involve the students. They all were stated to support research culture [50]. Figure 4 shows them from 2010 to 2022. Starting from the face-to-face workshops with classical methods to enrolled graduate students, particularly interesting is the development of QUANTUM [65], an add-on developed with Mathematica software for ease of student learning. This add-on was widely used by over 60 institutions in about 20 other countries.

The official establishment of research stays with credits boosted the arrival of undergraduate students and the collaboration with graduate students pursuing masters or doctoral degrees. The stays and the workshops went nationwide for our students and involved them in the yearly institutional initiative. Since 2017, by an initiative of the research group, some research stays using simulations began being developed online with students on other campuses using Zoom. The creation of Tangle, an Internet-based learning suite to concentrate all quantum information teaching efforts by the group, led to developing those experiences combining, fitting, and sharing contents [60].

Thus, when the lockdown arrived in 2020, our group had a proven strategy to teach all those previously mentioned students. Several theses, conference participations, and journal publications were developed successfully during the period [50]. Other learning initiatives supported by the Internet were then included. In 2019, the use of QISKIT, an IBM programming interface [61] to interact with real quantum computers, began to be taught. Additionally, some photonics experiments introduced during the 2019 workshop were improved and broadcasted by combining a multi-camera setting and the lenses of mobile devices. All those initiatives gained visibility, thus garnering some educational innovation funds for their development, allowing more technology and experiment materials to be implemented. Other recognition came with the best paper prize in an international conference (e-Society 2018) and the selection of that initiative to be included in the shortlisted projects in Reimagine Education 2020 contest.

Figure 5b illustrates the use of Zoom broadcasting the three educative elements offered in a blended learning format. They included QUANTUM, QISKIT, Optics studio, and the development of students' structured learning notes managed as an integration of several tools. The demography of the follow-up is shown in the lowest panel in Figure 4, obtained from the enrolment registers. It depicts the number of students in several well-characterized groups through the implementation history. The number of graduate students remained stable, while formal undergraduate students increased through the lockdown. Many published original research and scientific articles. The number of informal students also stabilized through the yearly workshops and migrated to the minor in quantum applications. The reduction in external students resulted from the newly opened official spaces.

5. Results Evaluation Based on Research Products, Collaboration, Quality, and Demography: A Transition Boosted by the Internet

This section assesses the two last research objectives. The analysis mainly focused on the research products and their inherent involvement and collaboration network. It encompasses the chronological evolution and also the impact of digital evolution.

5.1. Chronological Development of Research Products and Educative Innovation Besides the Digital Transformation of the Initiative

Pairing the development presented in Figure 3 (mainly based on the concept of digital transformation [36], Figure 6 shows the elements in that trend for quantum information education in our research group. Information was obtained from the historical registers of the author. The nationwide broadcasting of workshops, research stays, the minor, and researchers' collaborations are depicted there, as well as the two international conferences on the main campus of our university in 2015 and 2021. Those conferences are organized every two years with other national partner research institutions (IPN and CINVESTAV). The last conference in 2021 was entirely virtual.

Figure 6 also refers to the previously depicted innovations using Internet-supported applications (QUANTUM, QISKIT, Optics studio) and the students included in research networks, such as ResearchGate, Scopus, Google Scholar, and ArXiv, among others. For collaborative writing, the use of Overleaf was promoted. It exploits many Internet possibilities to enrich the research learning experience, collaboration, and outcomes dissemination. The impact of the main technological and experimental innovations was assessed under a recent model [66]. It is presented below in the last plot of this section.

The leading international collaborations in research are also reported in Figure 6, involving both primary researchers and students. First, our research group has been closely connected to other Mexican institutions since its origination. Further collaborations were developed with universities in Colombia, the United States, Canada, Poland, France, and Israel (the most recent collaboration with one of our former students currently in Denmark is not yet reported in the figure). The lowest panel in Figure 6 reports the number of scientific products published in Q1/Q2 or Q3/Q4 journals, or at least in Scopus-indexed conference proceedings. Information was obtained by crossing the data reported in Table 3 and the enrolment metadata of each student. Different developers generated and led these, including external non-credit-granted students, graduate students, undergraduate students in research stays, and researchers. Such information is reported below in Table 3. Note, particularly, the increase in publications by the two central groups (graduates and undergraduates in the research stay) favored by the initiative and Internet use. Thus, Table 3 comprises the information of 69 scientific research articles distributed in two columns. Each contains the article name, area (1, Physics/Math; 2, Communication; 3, Computation; 4, Other applications), the researchers involved, the students involved, the type of article (1, Scopus indexed conference; 2, Q3/Q4 JCR Scimago quartiles; Q1/Q2 JCR Scimago quartiles), and the year of publication. That information could be obtained from the author's Scopus profile and is mainly used in further analyses.

5.2. Relational Collaboration between Researchers and Students as a Function of the Research Products

The analysis of collaborative relations in research was approached by introducing a graph [60] based on those links and adding metadata of each research product and participant. In that approach, the participation of students becomes appropriately identified within the research ecosystem of the group, denoting, in addition, all crossed collaborations and the quality of publications.

Directly obtained from Table 3, Figure 7 exhibits a graph reporting the complex relations within the group during 2010–2022 around the original research publishing. Each product is labeled as Ax, with x a progressive number for the publications. Researchers collaborating are labeled as Ry, R1 being the author, regarding only the publications within the group where he was part of the authors. Finally, Ez labels each involved student.

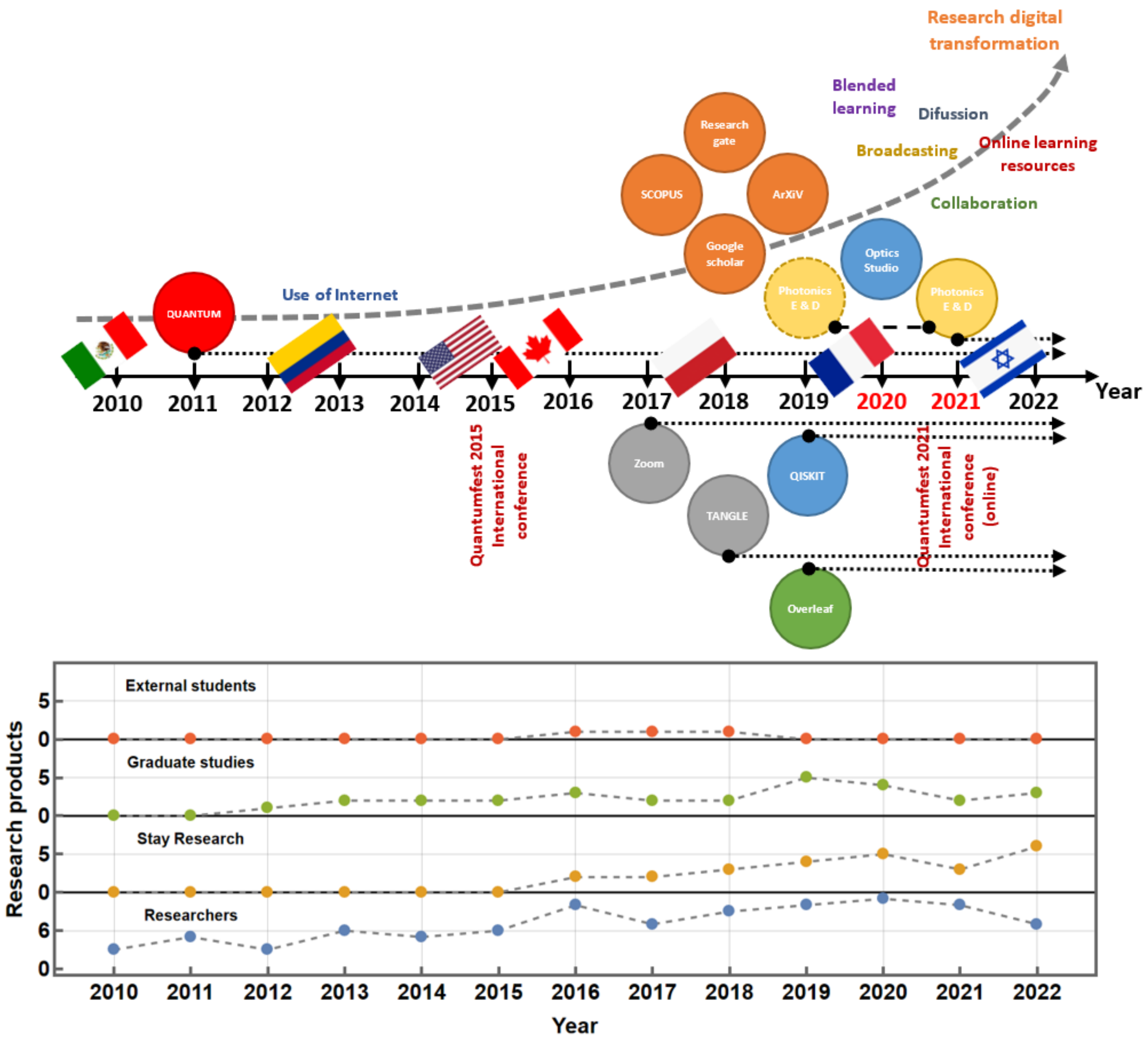


Figure 6. Timeline depicting the digital evolution of the entire educative initiative, the international conferences organized, educative grants and rewards obtained, international collaborations, and innovations added to the initial strategy. Research products are reported at the bottom.

Undergraduate students have become the most favored. While students in the minor were not forced to publish, the group experience managing research stays improved learning and involvement in a concrete research problem. Sometimes a good research problem is an associated topic a graduate student develops as part of his master's or doctoral degree. Graduate students had a more modest growth (see Figure 4), potentially increasing with the last undergraduate generation from the 2022 research stay. Figure 4 shows a clear correlation between the year digital implementation began and its sustenance during the COVID-19 pandemic. It is also apparent in Figure 6.

Table 3. List of Scopus-indexed scientific articles published by the current author in collaboration with other researchers and/or students.

Article	Area	Researchers	Students	Type	Year	Article	Area	Researchers	Students	Type	Year
A1	1	R1	-	2	2010	A36	2	R1,R2,R8,R9,R10	-	3	2019
A2	2	R1	-	1	2010	A37	1	R1,R2,R7	-	3	2019
A3	1	R1	-	3	2011	A38	1	R1	-	2	2019
A4	1	R1	-	3	2011	A39	2	R1	-	2	2019
A5	1	R1	-	3	2013	A40	1	R1,R2,R3	-	1	2019
A6	1	R1	-	1	2014	A41	4	R1	E3	2	2019
A7	1	R1	-	1	2014	A42	1	R1	-	1	2019
A8	3	R1	-	1	2014	A43	2	R1,R2,R8,R9,R10	-	1	2019
A9	1	R1	-	3	2015	A44	2	R1,R2,R8,R9,R10	-	1	2020
A10	1	R1	-	2	2015	A45	2	R1	E4	2	2019
A11	1	R1	-	3	2015	A46	4	R1	E3	2	2019
A12	1	R1	-	3	2015	A47	1	R1	-	2	2020
A13	1	R1,R4,R6	-	2	2016	A48	2	R1	E4	2	2020
A14	3	R1,R5	-	2	2016	A49	4	R1	E5	2	2020
A15	1	R1	-	2	2016	A50	4	R1	E3	2	2020
A16	1	R1	-	1	2016	A51	1	R1,R2	-	3	2020
A17	2	R1,R4,R6,R11	E15	1	2016	A52	4	R1	E3,E5	2	2020
A18	1	R1	-	3	2017	A53	4	R1	E3,E5	1	2020
A19	1	R1	-	3	2017	A54	2	R1	E4	1	2020
A20	3	R1	-	2	2017	A55	2	R1,R2,R8,R9,R10	-	1	2021
A21	2	R1	E1	2	2017	A56	2	R1	E5	1	2020
A22	2	R1	-	1	2017	A57	4	R1	E3,E5	2	2021
A23	2	R1	E1	1	2017	A58	2	R1	E4	2	2021
A24	1	R1	E2	2	2017	A59	1	R1,R2,R3	-	1	2021
A25	1	R1	-	3	2018	A60	2	R1	E4	2	2021
A26	1	R1,R2	-	3	2018	A61	4	R1	E3	3	2022
A27	1	R1	-	3	2018	A62	2	R1	-	1	2022
A28	2	R1	E2	2	2018	A63	1	R1	-	1	2022
A29	1	R1	-	2	2018	A64	2	R1	E4	2	2021
A30	1	R1	-	1	2018	A65	4	R1	E3	2	2021
A31	1	R1,R2	-	1	2018	A66	4	R1	E5	2	2021
A32	1	R1	-	1	2018	A67	3	R1	E6,E7	2	2022
A33	2	R1	-	1	2018	A68	3	R1	E8,E9,E10	2	2022
A34	1	R1	-	1	2019	A69	3	R1	E11,E12,E13,E14	2	2022
A35	2	R1	-	3	2019	-	-	-	-	-	-

The graph considers the several types of articles (type or level of journal), researchers (internal or external to the research group of the author), and students (undergraduate or graduate) as the nodes, being colored in agreement with the label definitions on the symbology chart on the left. In addition, the edges relating each researcher or student with a specific research product appear colored as a function of other characteristics of each group (nationality of the researchers in solid lines and original undergraduate area of students in dashed lines), also included in the symbology on the left. This graph exhibits the complex relations involved in each publication work. Note several behaviors of the students. Some publish a single work, others publish several, and some interact with other students. Among them are undergraduate students working, supporting, and learning with graduate students toward an academic degree. Note that the vast diversity of undergraduate areas included in the group on the part of the graph farthest to the right, the most recent undergraduate students participating in the 2022 research stay (the Tec21 generation).

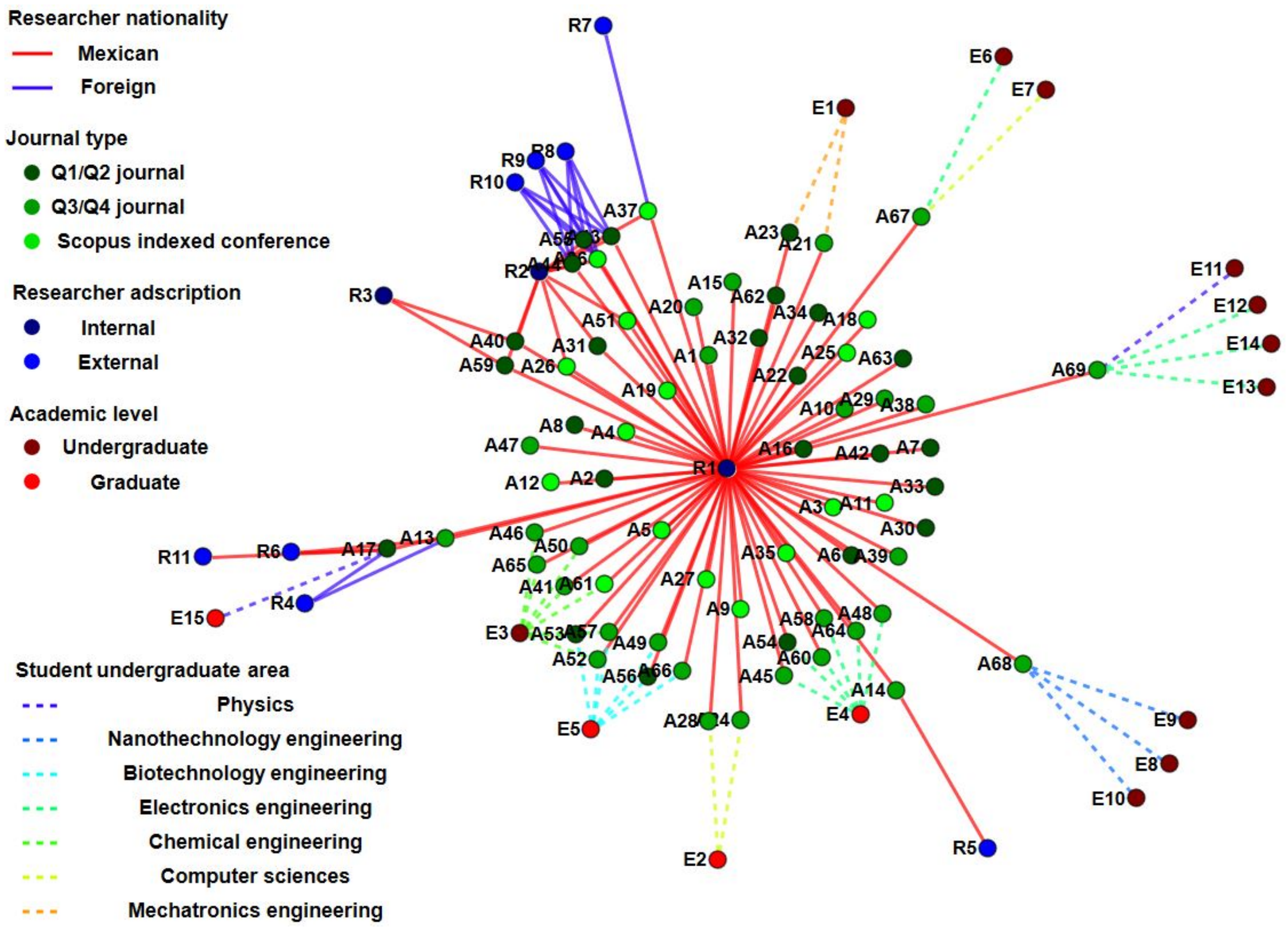


Figure 7. Relational graph exhibiting each research product A*x*, with the students involved E*z*, together with researchers R*y*. Nodes and edges are colored, referring to additional information for those elements in agreement with the symbology on the left.

As a summary for the last graph, Figure 8, being processed from data of Table 3, reports each student involved with the researcher R1. The vertical axis reports the number of products for each student. The dot color sets the average journal type in agreement with the color bar scale at the top. Finally, a pair of vertical lines below each dot reports each student's academic level (left) and the undergraduate area (right). The students most to the right (E6–E14) with only one product correspond to those in the newest version of research stays (Tec21). This analysis lets us notice the big picture of the research products and their collaborative relations within the group, but we also require a chronological analysis. It is shown in the following subsection.

5.3. A Yearly Analysis of Research Collaboration Involving Students as a Function of the Research Products

The incidence of products by year provides us with a proper analysis of the evolution of the entire initiative. Definitively, some institutional initiatives attracted students. Nevertheless, the beginning of the digital transition open to all students nationwide finally improved their participation and involvement in the scientific products generation using a fast and effective training program.

Obtained from data of Table 3, Figure 9 shows a different view of the journal publications. In this case, each scientific product was related to its year of publication (appearing as a node with the year as a label) and the involved students (following the same nomenclature in Figure 7). Some graphs are isolated (those for the initial years) because they did not include students or because their participation was punctual (as in the initial years). Interestingly, the graphs converge with the use of the Internet to broadcast the experiences, and then they became chained through time because the Internet facilitated sharing and included several partners in the projects. It is a fascinating fact showing the effectiveness of those technologies in maintaining cohesion in a group of students. Some of them were maintained for extended periods through their continuity towards graduate studies or participation in different projects after continuing in other groups. In this graph, the edges corresponding to each scientific article were colored in agreement with the main classification area shown in the symbology on the left.

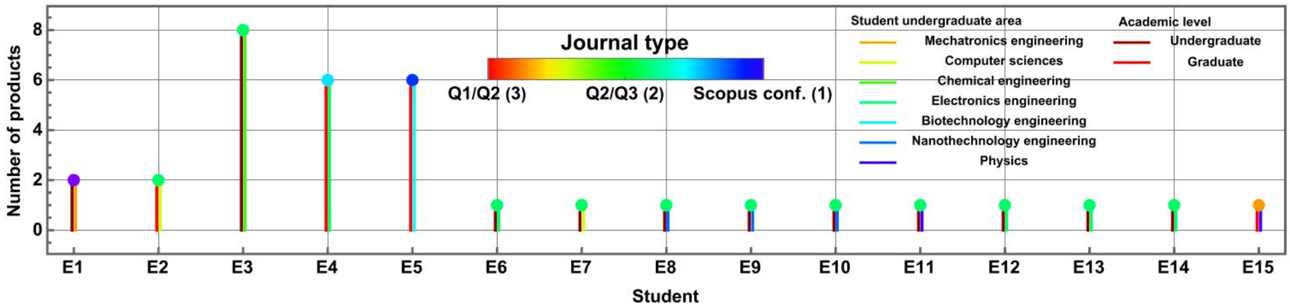


Figure 8. Number of scientific products for students produced/advised by the author (R1). The plot also reports the average journal type (dot color in agreement with the color bar scale), the undergraduate area (left vertical line), and the academic level (right vertical line).

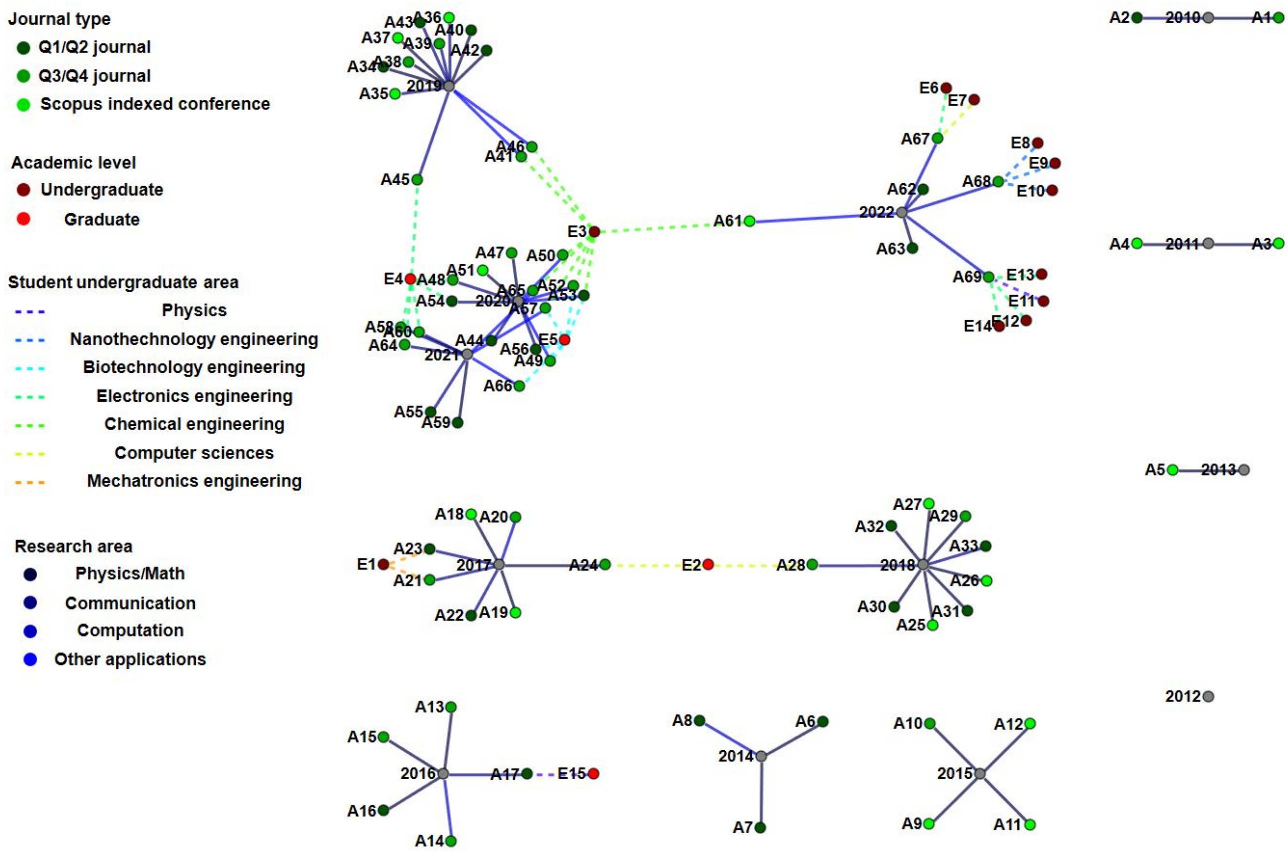


Figure 9. Another view of the relations between research products and students by year. Disjointed graphs show the increase in continuous collaboration among students and their involvement in research in the last years.

5.4. Chronological Evolution of Quality, Impact, and Involvement of the Research Products

Finally, an analysis based on the evolution of research products was performed, taken from the two last graphs in Figures 7 and 9. Thus, Figure 10 (processed from data of Table 3) shows the averaged participation fraction of students in the publication work of each year. (Such a fraction is calculated as the number of students divided by the total of authors, then averaged by year.) It is shown by the dashed grey line and reported on the left vertical axis. Each dot is also colored in agreement with the average type of journal as stated in the color bar at the top regarding the order Q1/Q2, Q3/Q4, and Scopus indexed proceedings, thus giving $3, 2, 1$ points as weight, respectively, to obtain an averaged color. Despite being below that in 2014, it is also certain that more students were included, moving the global level of publication in the Q3/Q4 range. In the same plot, the black line reports a different yearly indicator (a simplification to that recently published in [66]) calculated as the average score of the journal level for the publications during the year times the average fraction of publications by author,

$$I_{\text{year}}^{impact/author} = \left(\frac{1}{NP_{\text{year}}} \sum_{x_{\text{year}}} JT_{x_{\text{year}}} \right) \cdot \left(\frac{1}{NP_{\text{year}}} \sum_{x_{\text{year}}} \frac{1}{NA_{x_{\text{year}}}} \right) \quad (1)$$

there, NP_{year} is the total of articles for the year, $JT_{x_{\text{year}}} \in \{1, 2, 3\}$ is the journal type weight (see the color bar in Figure 10), and $NA_{x_{\text{year}}}$ is the number of people authoring each article Ax in the year. Such an indicator is lowered by the quality of the journal and the number of collaborators. Thus, the peak in 2014 refers to publications performed by few researchers and high quality. The lowering from 2015 to 2022 reflects more collaborations, including students in some publications, and the increase in the Q3/Q4 journals.

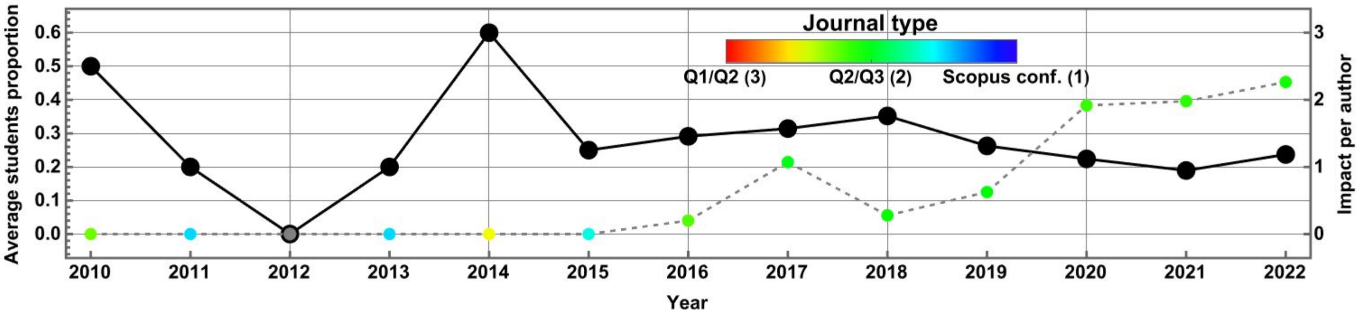


Figure 10. Timeline plot reporting the average student proportion (dotted line) participating in the research products by year. Colored dots report the averaged journal type using a weight (see color scale). The black line reports on the right scale the impact per author index.

6. Discussion

The original educative plan within the research group was to attract graduate students into the graduate programs associated with us, commonly undergraduate students, but sometimes graduate students still not performing advanced studies. Despite the beginning initiative being relatively widespread and welcoming, with tens of students yearly, not all students were ready to continue their advanced studies. Thus, the attraction effectiveness became limited. Then, the initiative moved on to groups of captive students in the institution in the next-to-last semester before their graduation. The figure of research stay already existed in those years. First, it was a medium to reach potential students (still considering that just two or three became enrolled yearly). The students' attraction was a pyramidal process starting from the tens of students to effectively reaching just a few, as could be perceived from the previous analysis. This section revises our outcomes by adding contextual comments from the author to review the fulfillment of each research objective.

6.1. Some Additional Comments about the Evolution through the Twelve Years Inventory

First, students in research stays had a relatively large permanence in our group, thus learning quantum information, communication, and processing. Nonetheless, after graduation, most of those students sought admission opportunities overseas or in more theoretically oriented educational institutions. They did not develop original research because the initial goal was only to attract them to graduate studies. Nevertheless, such a goal became foreseeable in time. Interestingly, that engagement helped keep them in masters studies with us. When the workshop audience changed from a general open invitation into a mandatory enrolment, students from different academic programs arrived, such as chemical engineering, chemistry, nanotechnology, and mechatronics.

It began a new kind of relationship because, with at least one publication resulting from the stay experience, they felt more invited to extend the stay for a couple of years to attain additional publishing goals, together with deep theoretical learning and deep learning in a computer simulation. They valued both aspects to begin doctoral studies overseas. For some years, this was the most typical behavior of our involved students. This work has analyzed a group of students associated with the author regarding publication works, which began around 2016 for undergraduate students in the research stay experience. However, the real boost began in 2017 using the Internet for a blended learning experience, including students from other campuses.

Such digital improvements allowed extending the initiative's impact on a larger population throughout the country, multiplying the number of students thanks to broadcasting tools provided by the Internet. Despite those punctual contacts beginning with few students, during the COVID-19 lockdown, it was a natural medium to continue research with researchers and students (graduate and undergraduate). Thus, during the "New Normal," we attracted students through a sustained blended learning experience in the last workshop organized. We then met with new initiatives within our institution for the Tec21 educational model regarding research stays and the option for minors. Thus, in 2022, the minor was a learning opportunity for students enrolled, and for the research group, it was possible to be identified as an option for advanced studies. For students in the research stay (Type II), the scientific research development and publishing were mandatory, leading to generating original work currently under consideration by several journals.

In the previous analysis, the first objective required a comprehensive chronological view of the complete road developed in 12 years in quantum information education, such as the evolution of educative spaces, the number of students through time, grants, rewards, and scientific production. The syllabus presented in Table 1 and its complement in Table 2, showing the technology and experimental innovations introduced, show a continuously improved set of contents to maintain an adequate teaching and learning roadmap for the publishing goals and immersion within the research group. The experimental component should be improved more professionally, as in the minor, accompanied by other colleagues in the photonics terrain. Today, students with experimental interests benefit from associating with experimental researchers in our extended research group, Photonics and Quantum Systems.

6.2. A Research Assessment for Our Global Initiative in Terms of Scientific Products and Human Resources Development

The scientific products (as related to students as authors or co-authors in the second research objective) have shown significant development (see Figures 7–9), indicating an evident ecosystem of research involving students, particularly since the inclusion of digital resources and the blended learning approach. In that sense, the COVID-19 pandemic was highly positive to reinforce and definitively set those practices in the global initiative.

Despite the yearly workshop migrating professionally to the minor, the three spaces worked with the blended approach (workshop 2021, research stay 2022, and the minor 2022). In total, 34 scientific articles were written and published by the 15 students associated with the author of the current research, with a level ranging from the Q2/Q3 journals. This is not trivial, considering that most of these students developed the research in just five effective months (one semester), which included their basic learning.

As previously commented, in this work, the variable participation in scientific conferences and the generation of non-indexed proceedings were avoided. Nevertheless, it is essential to mention that those activities have a meaningful function in the entire development of each student. In fact, students were encouraged to present partial outcomes in those conferences—with variable participation—because they boosted productivity by fulfilling partial goals, finally landing on Q1/Q2 or Q3/Q4 research products. A previous discussion about this was included in [49,50].

Complementarily, including more students from several distant campuses and the increasing number of undergraduate disciplines involved in the program deepened the impact, as the research production analysis has shown.

6.3. The Decisive Use of the Internet and Its Resources to Migrate the Initiative into a Blended Learning and Collaborative Approach

Finally, to discuss the fulfillment of our third objective, we highlight a clear impact of the digital transition in terms of practices and blended resources (Tangle, QISKIT, Optics studio, Zoom, etc.), as seen in Figure 6. Moreover, Figure 9 clearly shows the increase in the involvement of students in the publishing task starting in 2017, when digital resources began to be developed and included.

As an ending note for this third objective, we compared some students' feedback from the exit surveys evaluating each learning activity. Our institution applies such surveys in all courses or activities. Each question is evaluated on a 0 (worst) to 10 (best) scale. Information was obtained from the institutional registers for those feedback surveys. Thus, Figure 11 provides two yearly evaluations coming from the exit surveys: (a) the general assessment of the activity (dots) and (b) the students' evaluation of the accompaniment or support provided by the professor (circles). Activities are identified by colors: (1) Workshop (blue); (2) Research stay (green), both types; and the minor (red). Arrows mark the plus/minus one standard deviation range in each application. Some years are missing because activities could not be applied.

One interesting fact about the students' assessments is that evaluations improved over time. Note that some years and activities had a perfect evaluation of 10. Interestingly, the accompaniment always became better evaluated than the global assessment of the learning activity, corresponding to an overall evaluation (contents, management, value, and quality). Additionally, notably during the COVID-19 pandemic (2021 workshop) and the "New Normal" (2022 research stay and minor), both evaluations sustained high scores despite their online format. In particular, note that the evaluation for the accompaniment was perfect for the workshop and the research stay, an outstanding and unexpected outcome for the professor. It implied the student recognition of the educational value of the activities and the accompaniment achieved by the professor through the digital channels where activities were delivered. Notably, the author should remark on the importance of this evaluation for the research stay because it differed from the other two, in extension and its goal, and the pressure to publish original research.

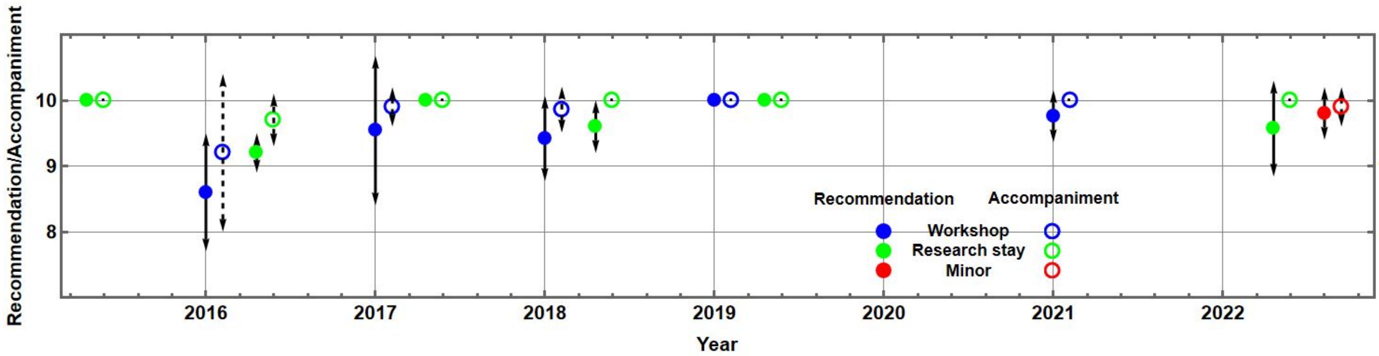


Figure 11. Timeline plot reporting the general student assessment of each activity (dots) and the evaluation of the support/accompaniment by the professor (circles). Arrows mark the range of plus/minus one standard deviation. Activities are shown in different colors: Workshop (blue), Research Stay (green), and Minor (red).

7. Conclusions

Despite our short memory, people born before 1990 can realize how the Internet has sped up our world in just three decades. Moreover, comparing our life between the 1980s and the 2020s dramatically shows how a global pandemic can harm our lives, as it did in the past century during the 1918 flu pandemic. This is true for worldwide human health and particularly for education and research.

Thus, regarding investments in light of the COVID-19 pandemic, the Internet has become one of the best bets for human beings. Nevertheless, we had lots of things to learn during the lockdown. Have we really learned something? For instance, recently, one of the author's research colleagues announced the doctoral seminar of one of his students in a face-to-face session. For the author, living in a distant place, it will be impossible to attend. During the pandemic, such practices moved to online sessions, but we have quickly fallen back on our old traditions.

In contrast, even before the COVID-19 pandemic, the Optical Society of America maintained a close relationship with all their associates, promoting face-to-face but also specializing in hybrid conferences. It continued during the lockdown, of course. Now, those practices widen the scope of their scientific dissemination. Thus, in 2021, it changed its name to OPTICA because it extended its frontiers, becoming a global scientific community today.

7.1. First Research Objective: A Final Conclusive Summary from The Twelve Years Follow-Up

The extensive road followed in quantum information education by our group, as depicted in Section 4, clearly had an inflection point while the COVID-19 pandemic boosted digital transformation. For example, the author needed to provide electronic whiteboard markers and Zoom to broadcast the class for collaboration after the push promoted by one of our former research stay students in 2017, who insisted on becoming involved in our research activities from a city 876 km away from us. If the COVID-19 pandemic had never occurred, the author probably would have continued his old practices of admitting local students. Thus, during the "New Normal," neither the 2021 workshop nor the 2022 research stay and minor would have had a nationwide scope, thus limiting the valuable learning horizon of some students and their original publications.

7.2. Second Research Objective: An Increasing Number of Crossing Collaborations and Speed-Up in the Scientific Production

As observed from Figures 7 and 9, the number of collaborations increased, starting with the first blended learning experience. Collaboration automatically connected students with several research interests among several campuses. The COVID-19 lockdown imposed an unavoidable agenda and practice, forcing the inclusion of alternative and improved resources. Finally, all that knowledge and experience were leveraged by moving all learning experiences into a blended scenario during the "New Normal". As Figure 11 shows, students recognized the effort.

A particular interest and attention should be put on the blended learning experience during the 2022 research stay. The noteworthy aspects are that (a) it was the only academic activity for those students during the semester, they became satisfied with the goals reached during the last semester in the university; and (b) in less than six months, those students met the challenge to learn the theoretical basis of quantum information and communication and then develop original research using computer simulation in a specific topic in those areas. This blended experience brought together distance-learning students in two countries (Mexico and the United States), five different states (Jalisco, Nuevo Leon, Estado de Mexico, Mexico City, and Illinois), and five undergraduate areas (Physics, Electronics, Nanotechnology, Computer Science, and Robotics).

The Internet has broken the frontiers imposed by distance, and education has become more inclusive, particularly required by the emerging research area.

7.3. Third Research Objective: The Use of the Internet to Improve Learning and Extend Inclusivity in the Program

The 2022 research stay was delivered blended and was the largest generation of undergraduate collaborators ever seen by the author (just the local students came in face-to-face contact, but I continually pushed them to broadcast their work to their partners). They developed works related to Quantum Machine Learning, Quantum Natural Language, Teleportation, Quantum Cryptography, and Quantum Communication and experienced rich learning. The graph in Figure 9 notably exhibits the presence of this initiative for quantum information learning and research, boosted by the continuously improving Internet. The capital conversion of all crises and threats to humankind crises is part of our human spirit. The lessons learned and appropriated from the COVID-19 pandemic effectively improved the education and research realm, enriching centuries of previous developments in those terrains.

7.4. Research Limitations, Future Work, and Final Remarks

The current 12-year experience has shown almost complete evolution regarding undergraduate and graduate students in research education centered on quantum information. This work did not present the conference participation, despite its recognition as a boosting activity to fulfill the research goals. Further analysis could be consulted in the literature [49,50]. It should be considered that the experience ultimately becomes limited to some students at the top of the pyramidal research structure, who finally produce original research in the area. The follow-up for students in the generic activities (workshops) is not included, but it could be considered for future work. Despite many of those students not performing research inside the research group, a considerable fraction go on to graduate studies and conduct research in alternative or related areas. Another limitation is that the research reported is firmly based on theoretical aspects and simulation approaches and is limited to the experimental domain. Further research should consider experimental-based research performed with the advice and collaboration of other researchers. Another limitation could be that just the student collaboration under the direct supervision of the author was included as an instance (despite another research report including a more extensive analysis with several researchers in the group [50], despite still being limited to the COVID-19 lockdown period).

A final remark should be stated from the research outcomes. In the past, research activity was offered to students close to the learning area. Before being organized by academic departments or faculties, research was usually not open to all interested students, or worse, those activities had a limited scope because of the requisites. In the modern conception of research, the multidisciplinary approach facilitates inclusion. However, still, inclusion requires supporting tools such as QUANTUM to scaffold students' comprehension of the mathematical aspects. An engaging tool such as QISKIT promotes interest in quantum circuits interacting with actual quantum computers. Those computer-based tools used collaboratively through the Internet have promoted distant student interactions, experimental education through specialized tools (such as Optics studio), and inclusion of students in distant locations who would have difficulty locating close to the principal researcher's location.

In any case, the dominion of teaching experience based on a blended approach should change our minds about the scope of research education and its advantages in teaching coverage, effective collaboration, valuable inclusion, and learning enrichment. By proving different approaches and their outcomes, other than the traditional and unique face-to-face approach, we can probably attain better or complementary ways to improve education, thus closing the gap between the present and future in science and technology.

Funding: The author acknowledges the financial support of the Novus 2021 Grant with ID N21-214.

Institutional Review Board Statement: Ethical review and approval were waived for this study due to the fact that no individual information is included.

Informed Consent Statement: Patient consent was waived due to any individual information is included.

Data Availability Statement: The raw data supporting this research will be made available by the author, without undue reservation.

Acknowledgments: The author acknowledges the technical and financial support of Writing Lab, Institute for the Future of Education, Tecnologico de Monterrey, Mexico, in the production of this work. This work is dedicated to the memory of Esperanza Zepeda-Trujillo, who passed away on 3 April 2023. She always believed in the continuous effort into Education, a spirit maintained for humankind during the COVID-19 lockdown. My warmest recognition to my Ph.D. advisor, Bogdan Mielnik, who always exhibited profound scientific generosity, extended to tens of graduate students in Poland and Mexico. The author acknowledges all students participating in the 2021 Quantum Information national workshop during "Semana I", and those students enrolled in the 2022 research stay in Quantum Information and Processing, together with those participating in the Quantum Information and Communication module within the Photonics and quantum systems minor, for their effort and enthusiasm. A recognition for Alan Anaya-Morales, a former student in the Quantum Information and Processing research stay, currently at the Technical University of Denmark, who first believed in and boosted the blended learning version of this educative initiative.

Conflicts of Interest: The authors declare no conflicts of interest.

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