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Framework for understanding quantum computing use cases from a multidisciplinary perspective and future research directions

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ABSTRACT

Recently, there has been increasing awareness of the tremendous opportunities inherent in quantum computing (QC). Specifically, the speed and efficiency of QC will significantly impact the Internet of Things, cryptography, finance, and marketing. Accordingly, there has been increased QC research funding from national and regional governments and private firms. However, critical concerns regarding legal, political, and business-related policies germane to QC adoption exist. A few relevant studies are currently available, and those few focus heavily on the technical side of QC. Thus, this study offers a multidisciplinary review of QC, drawing on the expertize of scholars from a wide range of disciplines whose insights coalesce into a framework that simplifies the understanding of QC. This study offers a timely contribution to both practitioners and academia, as it explores use cases in business, addresses fundamental legal and political issues undermining QC's adoption, identify possible areas of market disruption, and highlights several research gaps critical to advancing knowledge within the field, including definition of 52 Research Questions that are critical for forecasting, planning, and strategically positioning QC for accelerated diffusion.

1. Introduction and background

Quantum computing (QC) originates in and utilizes the principles of quantum mechanics in performing computations (Hassija et al., 2020). Quantum computers can handle information at speeds exponentially higher than classical computers (Bova et al., 2021). Rapid technological changes underlying the limitations of classical computers have heightened interest in QC in recent years, which is underscored by the volume of investments made by different countries in recent years. According to industry reports, global investment in QC has reached a threshold of 25 billion USD, with China, USA, Germany, France, and Canada leading this phenomenon

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(Qureca, 2021). Recently also, the US President announced two presidential directives and signed the executive orders on advancing QC (The White House, 2022). In addition to these national-level commitments, significant privately led milestones have been achieved, especially by big technology companies, accelerating the use of QC (MacQuarrie et al., 2020; Casati, 2021; Lele, 2021). To this end, it is projected that increasing industrialization, swift technological changes, and extensive collaborations will accelerate the pace and diffusion of QC to social and business applications sooner rather than later (Sharma, 2014; LeBlanc, 2021).

As an emerging and highly technical domain, most existing studies concentrate significantly on the technical aspects of QC (Lubasch et al., 2020; Cerezo et al., 2021), with some explorations into social and business uses (Rahaman & Islam, 2015; Orus et al., 2019; Hassija et al., 2020). The literature on the social and business uses of QC falls into two main categories: *opportunities* and *challenges*. Within these opportunities, QC would fundamentally transform the financial industry, particularly in credit sorting, arbitrage, stock values, and portfolio management (Rahaman & Islam, 2015; Orus et al., 2019; Hassija et al., 2020). QC would also impact the marketing discipline in terms of an efficient and target-driven recommender system (Ferrari Dacrema et al., 2021) and advertisements with high conversion rates (Mo et al., 2021). Moreover, QC would be critically useful in democratic systems and electioneering processes, including e-government areas, such as secure e-voting. However, despite potential massive opportunities and use cases, scholars echo that the high cost of integrating QC into everyday life (Gill et al., 2020) and attendant security presents significant challenges (Smith, 2020). In addition to potential international security concerns (Lindsay, 2018; Der Derian & Wendt, 2020), transitioning to QC would still require significant research to cushion the attendant security challenges (Smith, 2020).

Prior studies on this topic are subject to two major limitations. First, there is no coherent framework on the business, legal, and policy perspectives of QC from an interdisciplinary perspective. Experts have warned that QC would have a fundamental effect on every aspect of our lives (Forbes, 2019), and a framework from an interdisciplinary perspective is critical to understanding QC's potential impacts on society. This is vital to enhancing strategic planning and management among all relevant stakeholders. Second, prior studies from non-technical fields lacked an explicit future research agenda, which could be the springboard for expanding QC as an emerging area of inquiry from a non-technical perspective. Based on the above limitations, the purpose of this study is to provide a framework for the business, legal, and policy perspectives of QC and a solid future research agenda (in the form of research questions), which would be crucial for future research. A unique feature of this study is that contributors were drawn from business, QC, political science, and law to offer different insights into the research objectives. The article is structured as follows: Section 2 presents the methodology of literature review; Section 3 offers interdisciplinary perspectives on QC; Section 4 outlines an agenda for future

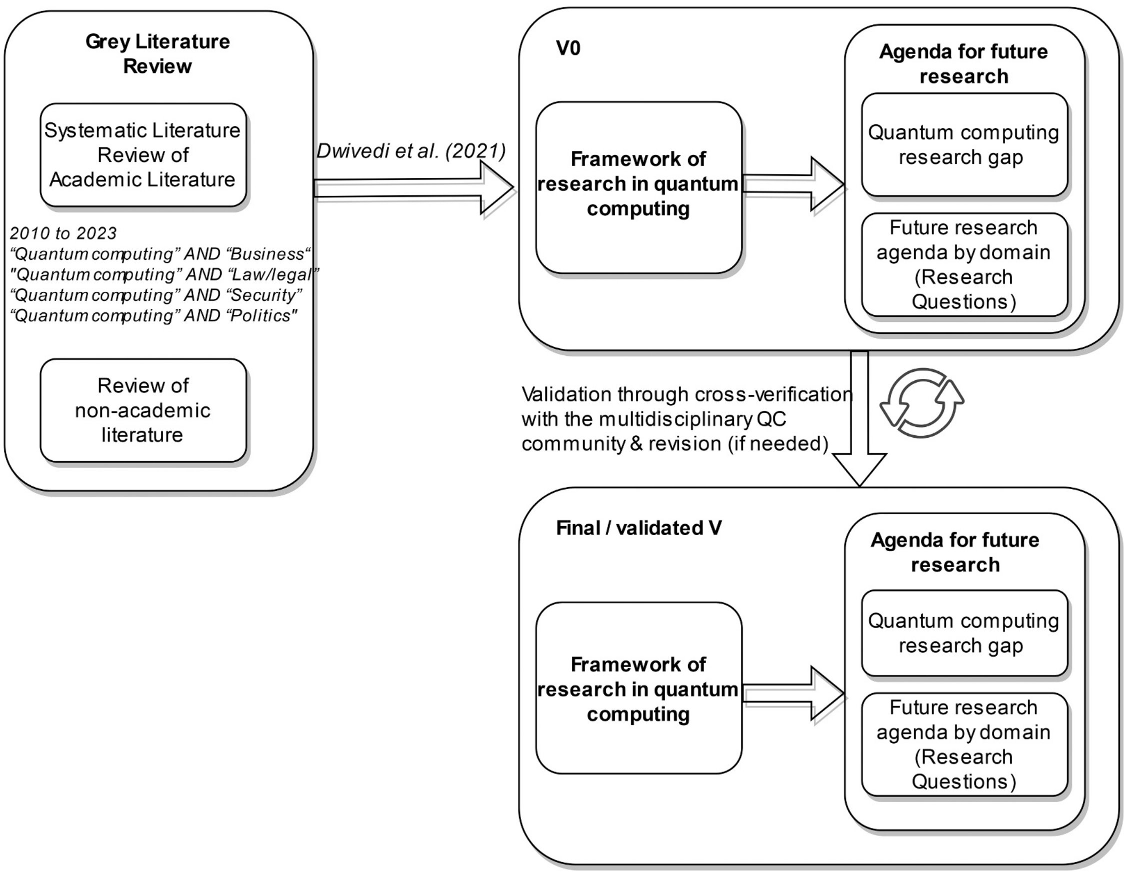

Fig. 1. Research methodology.

research; and Section 5 presents the conclusion.

2. Methodology

Given the current state of the research in this area, a gray literature review was found to be appropriate to extract sufficient insights. Thus, an extensive review of the literature addressing QC from a multidisciplinary perspective was done by querying Scopus - considered the largest indexer of global research content that includes titles from more than 7000 publishers worldwide; as such, Scopus delivers the broadest coverage of any interdisciplinary abstract and citation database, covering 240 disciplines (Nishanthi et al., 2023). Using a timeline of 10 years (2010–2023), the following search queries were used: *"Quantum computing" AND "Business"*; *"Quantum computing" AND "Law/legal"*; *"Quantum computing" AND "Security"*; and *"Quantum computing" AND "Politics."* The search yielded total of 2477 publications. We followed Snyder (2019)'s recommended abstract speed-reading and majority of the articles were dropped as they did not fit into the research objectives. On further examination, we arrived at 29 articles including conference papers. The 29 publications were chosen because they fit the inclusion criteria, which were about the business and social use cases of QC, and exclusion criteria that were about studies dealing on QC's technical specifications. Considering the importance of the topic, we supplemented the academic literature with news articles and other anecdotal materials that were found to be relevant. Put together, as argued by Bidra and Huynh-Ba (2011), the final publications for our analyses were subjectively decided based on their relevance to the study objectives.

Considering the nature of the study, we decided that triangulation of findings and validation in the form of their discussion within the community seems to be the most relevant method to be used. To this end, the findings were presented at QWorld Quantum Science Days 2023, an annual international scientific conference organized by QWorld Association - a global network of individuals, groups, and communities collaborating on education and implementation of quantum technologies and research activities. The event which held between May 29 – 31, 2023 was attended by more than 100 members of community representing both academia, research and practice. We received useful feedback, including ideas which shaped the integrated framework (Fig. 4). In Fig. 1 below, we present the diagrammatic representation of the research methodology.

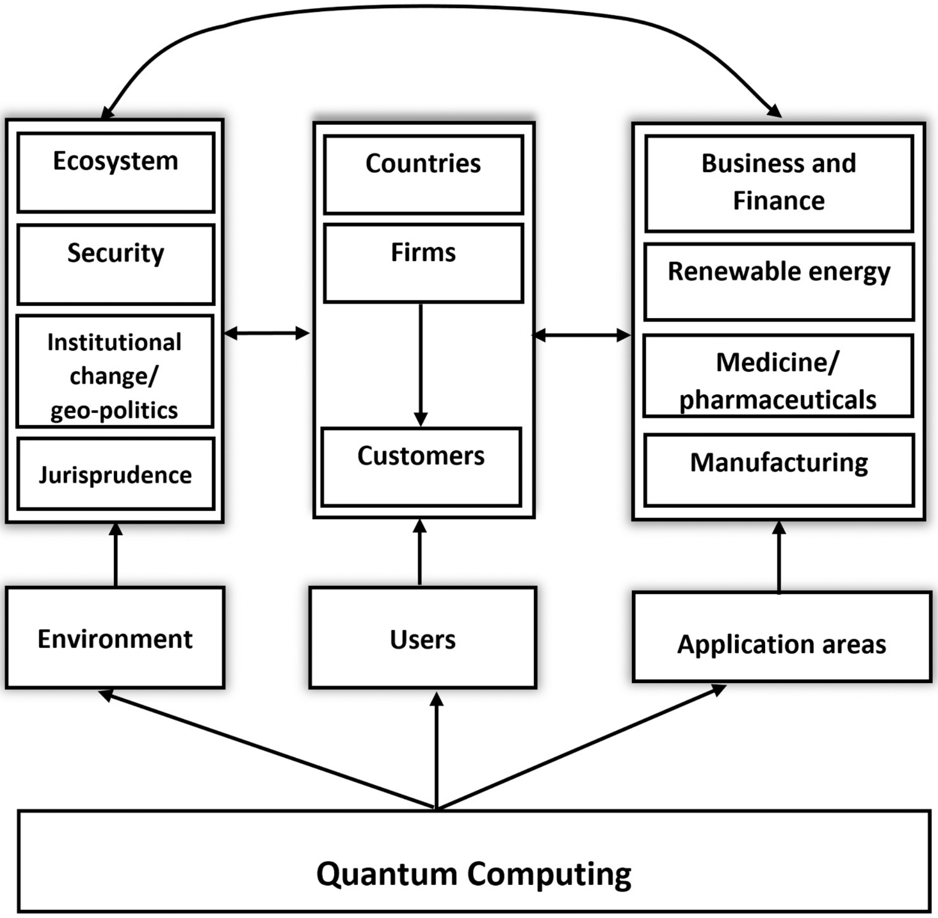

Fig. 2. Classification of QC.

3. Results and discussion

In this study we present a multidisciplinary review of quantum computing that, drawing on the expertize and experience of scholars from a wide range of disciplines, aims to simplify the understanding of QCs, identify possible areas of market disruption, and offer empirically based recommendations that are critical for forecasting, planning, and strategically positioning QCs for accelerated diffusion. In more detail, based on Dwivedi et al. (2021), we considered three perspectives of QC that are (1) **environment**, (2) **users** and (3) **application areas** (Fig. 2), for which we identified six research subareas, which we explored with further elaboration on the most popular topics and application areas that are expected to be covered in the future, as well as those that are overlooked in the current literature, but are considered very important for both academia and practice, including the abovementioned various fields and actors (business, government, society). 52 research questions were defined for six identified research subareas, namely, (1) **adoption** (9RQs in total), (2) **security** (13RQs), (3) **politics and the economy** (8RQs), (4) **financial services** (7RQs), (5) **marketing, services and data privacy** (6RQs), and (6) **management and wellbeing** (9RQs).

3.1. Environment

Quantum technology is changing the institution of the market and the fundamental structures of marketplaces (e.g., the architecture of the digital technology-oriented Internet). It is changing the agendas of the players (e.g., political programs regarding investment projects or global bodies, such as the Internet Assigned Numbers Authority [IANA]) and triggering an overall institutional change. The environment surrounding QC adoption includes (1) ***ecosystem***, (2) ***security*** (3) ***institutional change / geopolitics***, (4) ***jurisprudence***.

3.1.1. Ecosystem

As the race to develop quantum computers intensifies, interests are generally devoted to technical compositions and infrastructural backbone (Möttönen & Vartiainen, 2006; Pekola et al., 2010; Rahaman & Islam, 2015). The growth of QC has, to date, been hindered by diverse factors. Prominent among these is the limited number of realized qubits and the necessary overhead for error correction, which makes use cases challenging to scale to business domains. Even though recent research has proven many industrial applications, an ecosystem approach is critical for increasing the adoption of QC technology. Bayerstadler et al. (2021) argued that through cloud computing, access to hardware is possible, though scale and costs limit industrialization activities. Different terminologies have been used to describe how an ecosystem approach can accelerate the use of QC in social and business domains. Leading this ecosystem approach is the German government's Quantum Technology and Application Consortium (QUTAC), comprising 10 members of different industries drawn from pharmaceutical, production, automotive manufacturing, chemical, insurance, and technology.

Leymann et al. (2019) echoed the community-driven approach to the acceleration of QC by proposing the Quantum Software Platform, which proposes that specialists can harness stored algorithms by cleaning and unifying them and storing them in a quantum algorithm repository. Developers can access algorithms that have passed through quality assurance and execute them on QC. For end users who do not find algorithms that match their needs, they can send requests to the community, which will provide solutions. In this case, software companies can create and offer quantum programs that match specific customers' requests. The QC market is also expected to be shaped by a large number of stakeholders who represent different areas that are not purely technology-related. QC is an emerging field with the potential to fundamentally change computing and build smarter machines (Dilmegani, 2021). Perhaps one of the most widely known real-world examples is "*Sycamore*"—a 54-qubit processor produced by *Google*, which they describe as "*the first in a series of ever more powerful quantum processors*" (Arute et al., 2019).

3.1.2. Security

Different studies have addressed security concerns regarding QC. Khan and La Torre (2021) stated that quantum information technology is rapidly becoming commercialized, with the pharmaceutical, fintech, and gaming industries as core beneficiaries. Security breaches in these industries would have adverse consequences for the economy. Their study argued that while the diffusion of QC is a concern for public key encryption schemes, the randomness functionality in quantum objects can be used to defend hacking attempts. Using securitization theory, Smith (2020) echoed attendant security concerns, especially cryptographic decryption, but also argued that most of these concerns are natural, particularly with an unfamiliar technology. Smith (2020) further adds that the security challenges posed by QC would also be solved by the same. The study further analyzed the perceptions of QC in the national security community. For instance, the initial reaction of the United States Army and the National Security Agency (NSA) some decades ago was not a serious security concern, but recently, the US has been among the countries leading QC research (Hoofnagle & Garfinkel, 2022). The European Union (EU) and China have also made significant investments in QC projects.

With the Internet of Things (IoT) gaining momentum, there are also security concerns that QC could break its encryption with attendant fatal consequences (Althobaiti & Dohler, 2020). Quantum computers' abilities can also pose dangers to society. Among other things, they are an efficient tool for breaking common encryption measures (Mailloux et al., 2016, p. 43). In particular, asymmetric encryption methods can be compromised due to their public key components. However, certain measures are being developed to protect data in the future (Mailloux et al., 2016, p. 45). Central examples are *quantum cryptography*, which makes use of quantum mechanics, and *post-quantum cryptography*, which uses improved algorithms that are also executable on classical computers. However, there is still a lack of clear, standardized measures to protect data, even after quantum computers are in use.

Similarly, within the domain of the Internet of Vehicles (IoV), Gupta et al. (2022) proposed an identity-based two-party authenticated key agreement protocol to defend against possible quantum attacks. The study concluded that QC offers significant potential to provide security on the IoV. Gill et al. (2020) literature review classified cryptography challenges into four categories: (1) performance and cost, (2) hardware, (3) security attacks, and (4) design. In terms of performance and cost challenges, one of the issues identified was the need to reduce the use of expensive materials, such as dark fibers. For hardware, they suggested that hardware able to communicate millions of qubits at a faster rate is required. In terms of security attacks, they highlighted possible challenges, such as a detector-blinding attack, an efficiency-mismatch attack, and an eavesdropping attack, among other issues. Finally, to overcome design challenges, they suggested that a high key rate is required to conduct frequent updates to avoid attacks.

3.1.3. Institutional change and geopolitics

The development of machines and tools takes place within a framework shaped by human interactions with each other and with things. Intelligent technologies develop around these and form technological structures (Kornwachs & Stephan, 2009). In earlier work in political science, even very different technical installations, such as railway tracks, telephone lines and the infrastructure of air transport, were understood as large-scale mechanical installations that produce institutional change in the broadest sense (Mayntz & Hughes, 1988). According to Steiner and Grzymek, technology has a direct impact on the world we live in; values flow into technology, and technologies are thus "*the very realization of values*" (Steiner & Grzymek, 2020). Similarly, quantum computing can be seen as another technological advancement that affects our society and our values. Quantum computers have the potential to perform complex calculations faster and more efficiently than conventional computers.

Things change as technological development becomes entangled with political power. The "*age of digital geopolitics"* described by Bendiek et al. (2019) has seen the emergence of several trends of change that affect and are affected by policy, causing concrete action and the policy fields themselves to change. The policy perspective on QC is linked to the perspective of strategy and the concrete actions associated with it, which can be interpreted in terms of strategy (Wene, 2018; Kong et al., 2022; Christiansen et al., 2023). The terms *"research funding,"* "*economic development,*" *"technology development,"* and "*technology competition*" cannot accurately describe the strategic power component in terms of political strategic investments in the development of high-tech goods, which has increasingly gained space under the conditions of digitalization and regarding international relations. China's perspective on technological sovereignty as a form of political power is evident through various factors, including the Chinese quantum-based satellite *Micius*. The satellite *Micius* was developed through collaboration with European quantum expert Anton Zeilinger and other European researchers situated in Heidelberg. According to Gabriel and Schmelcher (2018), China has a number programs to push QC development: (1) the ongoing initiative to establish a quantum communication network between major Chinese cities since 2016; (2) the strategic alignment of Chinese technology policy with initiatives like the Silk Road; (3) China 1000-heads program concept; and (4) China's involvement in shaping technical standards.

QC is a central part of the Chinese power strategy, yet other countries emphasize technological supremacy as a sign of power in the international arena and the word of quantum supremacy, as well as quantum race have been heard by most industrialized countries who have developed digital strategies that put technological sovereignty and supremacy at the front. This is the case for Europe, as Thierry Breton, EU Commissioner for the internal European Market has justified the new policy "REGULATION (EU) 2019/452″ as a result of a technological war between China and USA (Breton, 2020). And in April 2022 the Quantum Computing Cybersecurity Preparedness Act (H.R. 7535) was introduced into the House of Representatives by US Congressman Ro Khana, member of the democratic party (Congress of the USA, 2022).

Leadership in technology is central to world domination in the age of the knowledge economy and technopolitics. Thus, according to (Mainzer 2020, p. 236) the key question in the global contest of QC, quantum technology, and AI is whether a technocracy with (e.g., Chinese) state capitalism and Confucian ethics will prevail over Western market economics and democracy, in which quantum technology and AI systems are understood as a service of individual liberties. To answer the question, *how QC will impact the International Relations sphere*, we need to identify and evaluate the fundamentals of the web of interactions in which this technology is embedded as it is developed and used.

3.1.4. QC-era jurisprudence

Interestingly, as with other emerging technologies, the legal system needed to accommodate QC's diffusion is still nascent. Many countries are racing to implement legal provisions to deal with unanticipated issues triggered by emerging technologies. Scholars are already beginning to explore emerging legal issues in the QC era. For instance, Atik and Jeutner (2021) provided a classification of legal fields imminent to the QC era. These include optimization problems, burden of proof, and machine learning. In addressing optimization problems, their study raised a number of issues. For instance, *are users going to suffer irreparable injuries? Are adequate remedies in place to cushion these injuries? Are there quantitative measurements of harm? Are public interests protected?*

It is important to keep in mind in the background that transitive and digital technologies - and this of course includes post-digital technologies like the quantum computer or the quantum internet - can change normative orders (Kettemann, 2020; CloudGeeni, 2021).

Furthermore, the decryption of conventional security systems by quantum technology poses a challenge to current standards for the protection of informational self-determination and personal data. In particular, it must be determined whether previous legislative acts, such as the General Data Protection Regulation (GDPR), can cope with post-quantum cryptography despite their fundamental technology neutrality, or whether serious gaps in the scope of protection arise for private and public communications (Lurtz, 2020). Although the principles of the GDPR may remain applicable to new technologies, a mere transfer seems questionable (Roßnagel, 2020). This can be seen, among other things, in the fact that for personal data (and only for such data is the GDPR applicable), it must be determined whether the data can be (re)personalized regarding the available means, whereby future developments must also be considered and, consequently, the development of quantum computers must be considered (Erbguth, 2019).

There is also the question of uniform regulation of quantum technology at regional levels. For instance, the European Union (EU) Commission has promoted research on future technologies, such as quantum research (EU-Commission COM, 2020). At the same time, concerns about constitutional principles, such as the protection of personal data, which is protected by Article 8 of the EU Charter of Fundamental Rights, are growing. Should states have the technical capability to decrypt any encrypted message, which could massively impact freedom of expression (Atkinson, 2020)? Due to the potential dangers to freedom of expression, regulatory options at the national, international, and European levels should be considered comparable to the EU Commission's Digital Markets Act (DMA) (EU-Commission COM, 2020).

3.2. Users

Our framework also highlights the centrality of the users, which include ***countries*** and ***national governments*** , as well as ***firms*** that deploy QC for their operations and efficient customer services. According to Prescient and Strategic Intelligence (Prescient and Strategic Intelligence, 2020), the QC market thrives because of growing investments by governments and private companies, with the number of investors growing in the last few years. National governments will benefit significantly from mainstreaming QC into the economy due to its transformational impact on national security and defense (Der Derian & Wendt, 2020), manufacturing and production (Bayerstadler et al., 2021), and cryptography (Dilmegani, 2021).

3.2.1. Individual user factors

It remains to be seen to what extent the use of quantum computers will become widespread in society. Contemporary Technology Acceptance Models such as the Unified Theory of Acceptance and Use of Technology (UTAUT), Innovation Diffusion Theory (IDT), Theory of Planned Behavior (TBP), Theory of reasoned action (TRA), Theory of Planned Behavior. (TPB), can provide clues to this. According to the Technology Acceptance Model (TAM), the key factors for spreading a new technology in society are *perceived usefulness* and *perceived ease of use* (Jockisch, 2009, 237). Anecdotal reports highlight that QC technologies are embedded in consumer electronics (e.g., television, laptops, and personal computers) in the form of quantum dots (Luo et al., 2018). Although these technologies are being adopted slowly, they will steadily become mainstream in the coming years. Based on the perceived usefulness and perceived ease of use results, *usage intention* is then translated into *usage behavior*. Therefore, the spread of QC is likely to depend heavily on how consumers perceive this technology. These individual user factors can be examined more closely for their relevance to QC.

3.2.2. Society-wide adoption

It is currently unclear when quantum computers will be available for general use by the public and how strong the range of their benefits will be for private individuals. This will influence their future spread in the industry and private sectors and should be monitored accordingly. Rather specialized tasks for quantum computers excel in terms of perceived benefit (Ernst et al., 2020, p. 137); thus, use by the general population might be limited. Whether this is indeed the case, and whether the spread and establishment of quantum computers in society will remain inhibited until they demonstrate broader utility and comfort of use remain to be seen. Society's high (positive) expectations for QC (Ernst et al., 2020) could act as a catalyst in this regard. Due to the strong social component of this topic, a significant deviation from previous model conceptions is also conceivable. In the realm of future research, studies can examine how the advent of QC will affect society and the impacts that are already occurring. How this spread changes when a hybrid form of classical algorithms and quantum mechanisms (Preskill, 2018) is utilized should also be examined. In addition to watching the development of QC, the development of measures for data protection in times of quantum computers should be monitored, and standardization measures in this area should be advanced to enable widespread use.

3.2.3. Governmental interests

Quantum technology is changing the institution of the market and the fundamental structures of marketplaces (e.g., the architecture of the digital technology-oriented Internet) (Gill, 2021). It is also changing the agendas of the players (e.g., political programs regarding investment projects or global bodies, such as the IANA) and triggering an overall institutional change (Der Derian & Wendt, 2020). Quantum technology is "deep tech" and substantively linked to the fields of nanotechnology, supercomputing, and photonics. Trustworthy communication in the state and administration is a basic prerequisite for a stable democracy and the security of citizens. Thus, the construction of a quantum communication infrastructure means building an attack-proof critical infrastructure. Governmental adoption takes different forms. For instance, since 2019, on the initiative of the German Federal Ministry of Education and Research, the German Aerospace Center, the Fraunhofer Gesellschaft, and the Max Planck Society have been building a quantum network pilot for tap-proof and tamper-proof data transmission, exclusively for initial use by federal authorities (Fraunhofer, 2019). However, quantum communication is currently not considered efficient. A commercial network is still in the early stages of planning, and this is a problem in a global competitive environment whose success matrix is primarily innovation, for example, especially for innovative medium-sized companies. For governments, ministries, and public authorities, the use of digital technology is now a basic requirement for efficient functioning. Quantum evolution can also trigger a revolution in the field of agriculture, such as in the production of fertilizers. Thus, quantum research impacts not only research-intensive industries but also industries that are weak in research, and it can potentially function as a revolutionary tool. Overall, the standardization of QC is still in its infancy.

3.3. Application areas

Our literature search uncovered several areas that are likely to be impacted by QC (see a summary of these domains in Table 1). We analyzed the dominant themes (see Fig. 3) and found that **business and finance** (35 %) was most prevalent. Specific domains of how QC will impact business include *bank arbitrage*, *insurance*, *advertisement* and *recommender systems*. Aljaafari (2023) states that QC will revolutionize the e-commerce sector, which is primarily driven by complex algorithms to determine pricing, recommendation, enabling it to process large amount of data. Next to business/finance is **law/ legal** (23 %), **pharmaceuticals and medicine** (16 %), **national security** (10 %), **manufacturing** (10 %) and others (6 %), which includes **renewable energy**. A detailed discussion of these domains is presented in the subsequent sections.

3.3.1. Business and finance

Within the business domain, marketers are constantly faced with the challenge of achieving a high conversion rate with online advertisements. Fan et al. (2020) performed an experiment, in which they adopted a digital annealer, which is a quantum inspired "ising" computer, to estimate the online advertisement conversion rate. They found that the proposed method increased accuracy from 0.176 to 0.326 at a faster speed. The experiment also shortened the period of advertisement with a higher degree of accuracy compared to traditional methods. Similarly, QC can also be used in recommender systems to simplify the challenges of displaying relevant recommendations to the target audience. Ferrari Dacrema et al. (2021) employed a quantum annealer in carrousel selection, which proved that QC can simplify carrousel selection challenges on many movie-on-demand and music streaming services. The application of QC to ease the challenges of recommender systems was echoed in another experimental study (Nembrini et al., 2021), where selections made with collaborative-driven quantum feature selection (CQFS) resulted in better diversity and accuracy compared to the recommender system used with other methods.

Extant studies have revealed that QC has transformational effects on the financial services sector. Egger et al. (2020) presented a quantum algorithm to estimate credit risk in comparison with what has been obtained from Monte Carlo simulations in classical computers. They found that the quantum algorithm precisely estimates credit risk scoring better than Monte Carlo and does so at a faster speed. Similarly, in estimating credit portfolio risk measurement, Kaneko et al. (2021) applied a combination of quantum amplitude estimation (QAE) and pseudorandom numbers and found that they could use a parallel computation of separable terms and achieve faster results. The implications of this operation are that financial institutions can leverage QC to efficiently manage credit portfolios with different customer categories.

3.3.2. Renewable energy

Another prospective area of application that was recently presented (Giani & Eldredge, 2021) belongs to disruptive technologies—renewable energy. The authors stated that the adoption and scale-up of renewable resources in the next few decades will introduce many new challenges to the electrical grid due to the need to control many more distributed resources and to account for the variability of weather-dependent generation flows. Therefore, they identified places where QC is likely to contribute to renewable

Table 1
Highlights of domains that could be impacted by quantum computing.

Study	Domains that could be impacted by quantum computers (QCs)
Rahaman and Islam (2015)	• QCs will solve combinatoric problems, particularly those that are difficult for humans and classical computers. • QCs will significantly impact cryptography and cybersecurity issues. • QCs will simplify banks' arbitrage and credit sorting derivatives, which pose significant challenges to the current operational mechanisms of banks.
Hassija et al. (2020)	• QCs will solve problems related to combinatoric optimization, linear algebra, differential equations, and factorization. • The landscape will be transformed by QCs in specific areas, such as machine learning, cybersecurity, and performing unstructured searches. They will also impact the financial industry by using market simulation to predict stock values. • QCs pose a threat to cryptosystems.
Orus et al. (2019)	• The financial industry is constantly faced with complex decisions, such as the determination of assets to be placed in optimum portfolios due to market dynamics, the determination of opportunities in different assets, and the estimation of risks and returns of a portfolio. • QCs can be used to perform optimization models, machine learning, and Monte Carlo-based methods to solve these problems.
Cusumano (2018)	• Three countries are identified as being at the forefront of QCs: the US leads with about 800, and Japan and China are following closely behind. • QCs will solve many challenges in cryptography, cybersecurity, optimization, and simulation. • Challenges in building QCs center on the technicalities involved.
MacQuarrie et al. (2020)	• Many countries support various studies in quantum computing. The National Science Fund in the USA leads this initiative, recruiting graduate students to research in this novel field. • This study identified two approaches used in the development of QCs. (1) The full-stack approach, as used by *IBM*, is a model, in which the company produces and controls the entire value chain. • Conversely, *Amazon* and *Microsoft* have launched (2) structural open innovation; they open partnerships for start-ups for the development of hardware and software to be supported by their cloud services.
Lindsay (2018)	• Although QCs pose international security threats, technological developments have been made to mitigate these risks.
Venegas-Gomez (2020)	• With the ecosystem approach from *Amazon* and *Microsoft*, many start-ups are joining the race to develop hardware and software for QCs. • Regional and international regulatory guidelines for the development of QCs are clearly lacking.

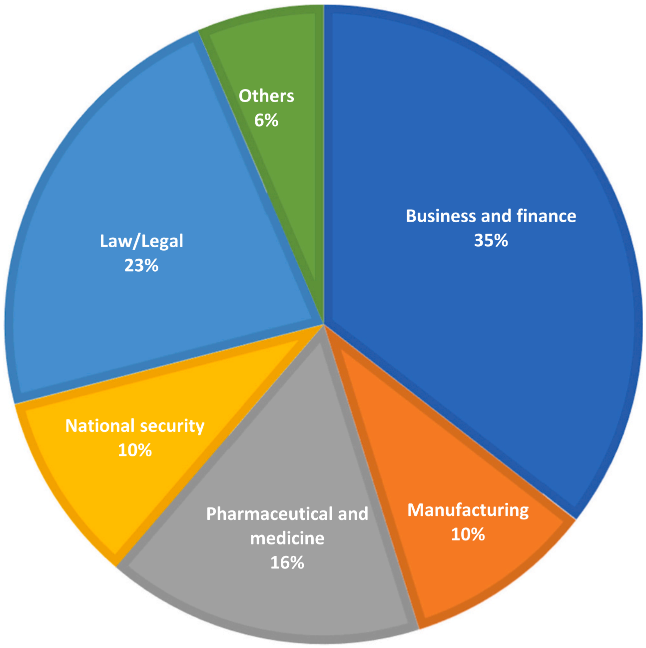

Fig. 3. Dominant themes of potential impact of QC.

energy: simulation, scheduling, dispatch, and reliability analyses. The relevant problems have the common theme that there are potential future issues concerning the scalability of current approaches that QC may address. This diversity makes QC even more desirable. According to Arute et al. (2019), QC would be helpful in designing new materials, such as lightweight batteries for cars and airplanes, new catalysts that can produce fertilizer more efficiently (a process that today produces over 2% of the world's carbon emissions), and more effective medicines.

3.3.3. *Medicine and pharmaceuticals*

Quantum computers' ability to focus on the existence of both 1 and 0 simultaneously could provide immense power to the machine and allow it to successfully map molecules, which could potentially open new opportunities for pharmaceutical research. Some of the critical problems that could be solved via QC are improving the nitrogen-fixation process for creating ammonia-based fertilizer, creating a room-temperature superconductor, removing carbon dioxide for a better climate, and creating solid-state batteries. This was explained by the ability of QC to develop vaccines and drugs several dozen times faster than with other techniques. This cannot be proven today, given that achieving the required computational capabilities requires years of in-depth engineering and scientific work, but this opinion is shared by many QC scientists and practitioners (Arute et al., 2019; McKinsey Digital, 2020). On the other hand, Thomasian and Adashi (2021) stress the effect of QC adoption on medical records. They argued that continuous research must be made to provide quantum-safe cryptography necessary to safeguard health security.

3.3.4. *Manufacturing*

Automakers could use QC during vehicle design to produce various improvements, including those related to minimizing drag and improving efficiency (Luckow et al., 2021). They could also use QC to perform advanced simulations in areas such as vehicle crash behavior and cabin soundproofing or to "train" the algorithms used in the development of autonomous driving software (Burkacky et al., 2020; McKinsey Digital, 2020). Considering QC's potential to reduce computing times from several weeks to a few seconds, Original Equipment Manufacturers (OEMs) could potentially ensure car-to-car communications in almost real time. Shared-mobility players can use QC to optimize vehicle routing, thereby improving fleet efficiency and availability. Another critical use involves helping mobility providers simulate complex economic scenarios that allow them to predict how demand will vary by geography (Burkacky et al., 2020).

4. Agenda for future research

In line with our research design, this study explored emerging themes from extant studies on QC (Fig. 4). We acknowledge that we could not include some studies because they were more technical and therefore significantly outside the scope of our study. We believe that QC would see wider adoption in a few years, with increasing research attention. While we provide an outline and an integrative framework of QC (see Fig. 3) we have also elaborated on these areas in Table 2a,b.

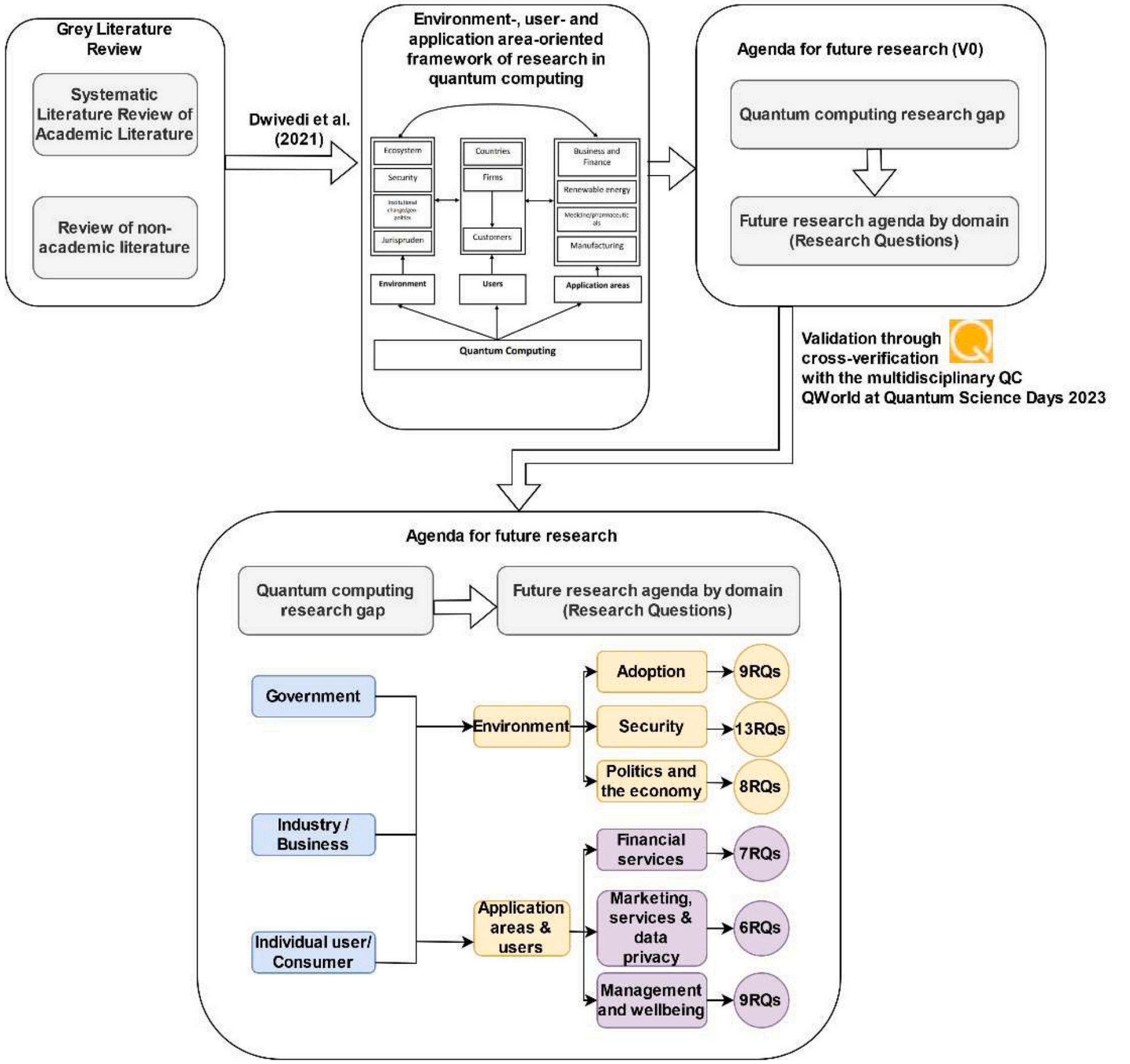

Fig. 4. Integrative framework of QC.

4.1. Environment

QC has not experienced increased adoption, despite the attention it has received in recent years. Many factors are responsible for this, some of which were explored in the preceding sections. However, there are critical areas that merit attention in future studies, which are summarized in Table 2a.

4.2. Application areas and users

As an emerging area, it is unclear how QC could impact different industries and service types. However, the literature is unanimous that there will be fundamental shifts in service types, especially within the financial services industry. The following research questions are worth considering in future research explorations within the QC domain. These questions are limited to non-technical fields because they have received scant attention in the literature (Table 2b).

5. Limitations and conclusion

The study is not without some limitations. The first limitation is that data collection was done only on Scopus database. While it is

Table 2a
Future research agenda.

Theme	Research questions on quantum computers (QCs)
Adoption	1. (a) What are the likely barriers to the adoption of quantum computers? (b) What roles would memetic, normative, and coercive factors play in the national adoption of QCs? 2. (a) Would QCs extend technology to emerging economies? (b) Would QCs create new opportunities for the emergence of new firms in emerging markets? 3. Would QCs widen or close the gap between rich and poor nations? 4. (a) What benefits do industrialized nations have over poor nations in QC adoption? (b) How can poor nations overcome these disadvantages to accelerate its adoption? 5. What are the likely adverse effects for poor nations that participate in QC diffusion in the early stages? 6. What impact would QCs have on democracy, voting, and elections, especially in poor nations?
Security	1. (a) What specific regional and national threats are likely to be seen in the widespread use of QCs? (b) What countermeasures are available to defend against these threats? 2. (a) What specific regional and national sectors are more exposed to these threats? (b) How extensive would the damage be when adequate precautions are not taken to counter these threats? 3. What are the likely potential risks to individuals in the QC era? 4. Would new firms that specialize in QC anti-threats, as with current antivirus and related firms, emerge and offer a different range of services to protect firms and consumers from threats? 5. (a) What specific challenges are cryptography and aligned industries likely to face? (b) Would QCs be a threat to, for instance, the blockchain and cryptocurrency space? 6. How secure would the metaverse be in the face of ubiquitous adoption? 7. (a) What threats to financial industries (e.g., banks, insurance, arbitrage, etc.) are likely? (b) How severe would these attacks be to individuals, firms, and the nation? 8. (a) Are there likely challenges posed by the integration of artificial intelligence, machine learning, and QCs? (b) How would these integrations affect the individual and the state?
Politics and the economy	1. (a) What would the future of work in the quantum computing era look like? (b) Would QCs take jobs away or create more jobs? 2. What new opportunities do quantum computing software platforms and cloud services offer to job creation? 3. What would the micro, meso, and macro effects of diffused QCs be on the economy? 4. Would QCs aid or deter money laundering activities? 5. (a) How are QCs likely to change or challenge existing tax administration? Would QCs aid or deter tax compliance, evasion, and reporting? 6. Would QCs widen or narrow social inequalities?

Table 2b
Future research agenda.

Theme	Research questions on quantum computing (QC)
Financial services	1. What opportunities does QC bring to the financial industry? 2. (a) How would QC aid in the design of flexible and resilient service networks that provide favorable outcomes for all participants and their communities? (b) What does QC contribute to achieving this objective? 3. (a) How does QC contribute to the future of large infrastructure centers, such as bank branch networks? (b) Could QC speed up the mobilization of financial services' delivery to build social resilience? 4. How does QC affect the co-creation of value in a digitally empowered financial services environment? 5. How will QC change the existing customer-driven financial service delivery channels of online banking and mobile banking? 6. How can QC lower the barriers to accessing digital financial services among certain customer segments (e.g., disadvantaged consumers and marginalized groups)? 7. How can QC affect the delivery of financial services? What products (such as stock prediction) are most influenced by QC?
Management and wellbeing	1. Would QC redefine organizational leadership? 2. What new skills are needed in the QC era? 3. How would QC affect the mode of work? Would QC accelerate and institutionalize the remote work mode? 4. How would QC impact employee productivity and well-being? 5. How would QC impact customer proactivity and well-being?
Marketing, services, and data privacy	1. (a) What new QC-driven service types are likely? (b) From an ethical perspective, how acceptable would it be to offer different services and prices to different customers? 2. How can customers be convinced to view themselves as active receivers and participants of services instead of passive recipients of services (as they currently do)? 3. (a) Will QC increase service personalization? (b) Should there be ethical or legal limits to the amount of personalization offered in the service industries? (c) Do we need new rules and ethical guidelines that limit the amount of (personal) data collected and used? 4. (a) How much information are customers willing to provide to get better (e.g., faster) service? (b) What is the privacy and immediacy tradeoff in the QC era? 5. How much intrusion will we accept from platforms in terms of how personal information is used? 6. What role would QC play in accelerating the diffusion of emerging technologies, such as augmented reality, virtual reality, cloud-based services, artificial intelligence, etc.?

considered the most comprehensive overview of the world's research findings, and we believe that the results covering other databases would be generally the same since we were interested in the aggregated results and determination of the patterns, it can be still worthwhile to consider conducting this analysis covering more databases. Second, the feedback we collected from the QWorld community was collected in an unstructured way, which, while indicating a general acceptance of the proposed framework and an agenda for future research, could have provided fewer specific details, as it would be if a more structured approach to feedback collection would be used although we believe that, data triangulation is a valid approach that has proven to be able to increase the trustworthiness and validity of the results.

In spite of the above limitations, we believe that the current study makes a substantial addition to research. Recent scientific breakthroughs have made the emergence of dozens of small-scale quantum computers possible, implying that scaling and wider adoption are imminent. Therefore, identifying possible areas of market disruption and offering empirically based recommendations are critical for forecasting, planning, and strategically positioning prior to QC's emergence. Recently a call for a framework from an interdisciplinary perspective has been made to help an understanding the potential impact of QC on society, which is vital to improve strategic planning and management by governments and other stakeholders. This study took this call and provided a preliminary version of a framework for understanding the social, economic and political use cases of QC and a solid future research agenda, including definition of 52 Research Questions that will be critical for the adoption of QC. The insights offered by various contributors from diverse disciplines - business, information systems, QC, political science, and law, which have been then validated through the discussing the findings with the QC community - offer a broad-based view of the potential of QC to different aspects of our technological, economic, and social lives.

Declaration of Competing Interest

"None".

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