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# Quantum computing: current and potential applications in digital agriculture

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**Abstract** – Quantum computers use the properties of quantum physics to perform information storage and processing operations. The operation of these computers involves concepts such as entanglement and superposition, which endow them with a great processing power that even surpasses that of the most powerful current supercomputers, while consuming significantly lower amounts of energy. The different studies analyzed in this review article suggest that quantum computing will have a deep impact in areas such as finance, logistics, transportation, space and automotive technology, materials science, energy, pharmaceutical and healthcare industry, cybersecurity, and agriculture. In digital agriculture, several applications that could be executed more efficiently in quantum computers for data processing and understanding of biological processes were identified and exemplified. These applications are grouped here into the following four areas: bioinformatics, remote sensing, climate modeling, and smart farming. This article also explores the strategic importance of mastering quantum computing, highlights some advantages in relation to classical computing, and presents a mapping of the services already available, enabling institutions to undertake strategic planning for the incorporation of quantum computing into their development processes. Finally, the challenges for the implementation of quantum computing are highlighted, along with some ongoing initiatives aimed at furthering research at the forefront of knowledge in this area applied to digital agriculture.

**Index terms**: agriculture 5.0, biotechnology, computer science, geotechnology, precision agriculture, rural development.

## Computação quântica: aplicações atuais e potenciais na agricultura digital

**Resumo** – Os computadores quânticos usam as propriedades da física quântica para realizar operações de armazenamento e processamento de informações. A operação desses computadores envolve conceitos como emaranhamento e superposição, que os dotam de grande poder de processamento que supera até mesmo o dos mais poderosos supercomputadores atuais, consumindo quantidades significativamente menores de energia. Os diferentes estudos analisados neste artigo de revisão sugerem que a computação quântica terá impacto profundo em áreas como finanças, logística, transporte, tecnologia espacial e automotiva, ciência dos materiais, energia, indústria farmacêutica e de saúde, segurança cibernética e agricultura. Na agricultura digital, foram identificadas e exemplificadas várias aplicações que poderiam ser executadas de forma mais eficiente em computadores quânticos para processamento de dados e compreensão de processos biológicos. Essas aplicações são agrupadas aqui nas quatro seguintes áreas: bioinformática, sensoriamento remoto, modelagem climática e agricultura inteligente. Este artigo também explora a importância estratégica do domínio da computação quântica, destaca algumas vantagens em relação à computação clássica e apresenta um mapeamento dos serviços já disponíveis, o que permitirá que instituições empreendam um planejamento estratégico para incorporar a computação quântica em seus processos de desenvolvimento. Por fim, são destacados os desafios para a implementação da computação quântica, juntamente com algumas iniciativas em andamento que visam aprofundar a pesquisa na vanguarda do conhecimento nesta área aplicada à agricultura digital.

**Termos para indexação**: agricultura 5.0, biotecnologia, ciência da computação, geotecnologia, agricultura de precisão, desenvolvimento rural.

## Introduction

This article discusses current and potential applications of quantum computing within the paradigm of digital agriculture, understood here as the application of digital technologies to the links of agricultural production chains, based on the concept of Agriculture 4.0, which refers to the use of disruptive technologies in food production (Massruhá et al., 2023), including precision agriculture, robotics, machine learning, artificial intelligence, blockchain, as well as biotechnology, genetic engineering, and nanotechnology.

The evolution of digital agriculture towards Agriculture 5.0, guided by a more intensive application of sophisticated technologies to enhance productivity, sustainability, and profitability in the sector is highlighted in the literature. Polymeni et al. (2023) concluded that artificial intelligence and robotics, with the adoption of autonomous robots, will be important tools in cases of reduced operational labor in the agricultural sector. In this context, the authors emphasize that quantum technologies emerge as promising alternatives for building future networks capable of providing very high data transmission rates and with a significantly improved security.

Feynman (1982) proposed the initial foundations of quantum computing, pointing out that, with classical computers, which represent physical processes through numerical algorithms based on differential equations, an approximate view of the real world is obtained, while computers using quantum mechanics would be capable of emulating conditions analogous to those of nature. Therefore, in general terms, quantum computers are machines that use the properties of quantum physics to store data and perform computational operations (Lu, 2024).

To simulate any quantum system, including the real world, quantum computing involves a distinct paradigm from the Turing machine (Turing, 1937), which is currently materialized in personal computers, computers embedded in vehicles, and mobile devices. That approach has the potential to enable a better understanding of the natural world and of various biological processes subject to a multitude of variables, as well as to facilitate the development of new technologies and applications.

Quantum computing tools are already being adopted in several economic sectors, including: finance, logistics, transportation, space and automotive technology, materials science, energy, pharmaceutical and healthcare industry, cybersecurity, and agriculture (Naveh, 2022). Among the main technological fields of application, the following have been identified: modeling, simulation and optimization of systems, machine learning, and storage and processing of large volumes of data (Polymeni et al., 2023).

The objective of this work is to present the principles of quantum computing and the applications of this technology in the field of digital agriculture. A literature review was conducted to cover these concepts and present the potential applications of quantum computing to solve problems in the agricultural domain.

This article is structured into six sections, presenting: 1. this introduction to the topic; 2. the main concepts related to quantum computing, outlining its foundational principles; 3. a comparison between the paradigms of quantum and classical computing; 4. the main application markets, along with a survey of currently existing quantum computing services; 5. applications and advantages of quantum computing in the context of digital agriculture, considering technological axes and related scientific fields of agriculture; and 6. concluding remarks.

## Quantum computing: history and key concepts

The term quantum computing was initially proposed by Feynman (1982), gaining a greater prominence through the studies of Manin (2000), who questioned whether classical computers would be capable of simulating processes of quantum physics.

The postulates of quantum physics sparked strangeness and discussions in the early 20th century. To illustrate the probabilistic nature of the theory, physicist Erwin Schrödinger proposed a thought experiment (Ezratty, 2021), in which a cat is enclosed in a sealed box. Inside this box, there is a Geiger counter associated with a mechanism that releases poison if any radiation from a radium atom also present in the box is detected. If radiation has already been detected, it can be concluded that the cat is dead, but if not, it may still be alive. Therefore, from the perspective of the experiment, the cat is simultaneously alive and dead. The state of the system only collapses to one of these two possibilities when the observer opens the box to know the answer. This experiment exemplifies the probabilistic aspect and issue of the superposition of two opposite states simultaneously.

The superposition, measurement, and entanglement principles of quantum mechanics endow quantum computers with the so-called quantum advantage (Table 1): the ability to solve problems that are beyond the reach of classical computers. In 2029, Google announced, in Nature (Arute et al., 2019), that its 53 qubits Sycamore quantum processor solved in 200 s a problem that would take a state-of-the-art classical computer 10,000 years to complete. In fact, many quantum computing algorithms are much more efficient in terms of complexity than their classical counterparts, as will be further commented.

## Comparison between quantum and classical computing

The simplest quantum computers are quantum annealers, such as those manufactured by D-Wave (Burnaby, Canada), followed by the noisy intermediate-scale quantum (NISQ) computers (Preskill, 2018) and fault-tolerant universal quantum computers. The capabilities of these computers vary: while the D-Wave annealing computer has 5,000 qubits, for example, the latest IBM NISQ computer, released in December 2023, has only 1,000 (Castelvecchi, 2023).

One of the greatest challenges in building a fault-tolerant universal quantum computer is controlling the unwanted interactions between its qubits and the environment, as the superposition state collapses in the presence of noise (Ezratty, 2021). This is one of the reasons why such computers are constructed with a high degree of isolation and temperatures close to absolute zero, while classical computers operate at room temperature or in rooms with common cooling (Ezratty, 2021). However, the differences between these two types of computers go beyond the issue

**Table 1.** Fundamental concepts in quantum computing.

| Concept | Description |
|---|---|
| Superposition of states in a quantum system | While in a classical computational system, a bit stored in memory can be in state “0” or “1”, in quantum systems, the state can be “0” and “1” simultaneously, in a superposed manner. The fact that quantum systems can be in more than one state at the same time led to the concept of quantum information, expressed in qubits, and to the development of quantum computers, which process these units of information. The principle of superposition is one of the factors that provide parallelism to a quantum computer (Manin, 2000; Casati & Benenti, 2005). |
| Measurement | The state of a quantum system is only known when a measurement is taken, a characteristic associated with the collapse of the system to a particular state that occurs at the time of this measurement. In the case of the cited cat experiment, the measurement occurs when the box is opened, when the cat will be in one of two states (either dead or alive) and no longer in a state of superposition. |
| Quantum entanglement | Another property of quantum physics used by quantum computers is quantum entanglement (Horodecki et al., 2009). Qubits can be entangled in such a way that a change in one of them has implications for the entire set even if they are separated and placed in distant locations from each other. That is, if an entangled particle is measured, the effect of this measurement will be felt instantaneously by its counterpart, even if it is in another part of the universe. This effect has generated different interpretations and discussions over the past decades. Turner (2022), for example, noted that physicist Albert Einstein once classified entanglement as a ghostly activity, since nothing, not even information, could travel faster than light. Quantum entanglement is fundamental for the parallelism of quantum computers because, from a certain number of entangled qubits, the necessary condition for the development of more complex computational algorithms is achieved (Arute et al., 2019). The relevance of the entanglement effect is evident with the awarding of the 2022 Nobel Prize in Physics to physicists Alain Aspect, John F. Clauser, and Anton Zeilinger for their studies on the topic. |

of temperature and noise, manifesting primarily in their operation in terms of parallelism, measurement effect, entanglement, superposition, and information representation (Figure 1).

Because of the requirements for isolation and low temperatures of quantum computers, the vast majority of institutions with the necessary resources to develop, acquire, or operate such equipment are large corporations, such as IBM, Google, Intel, Microsoft, and the University of Science and Technology of China (Brooks, 2024). Despite their complex construction and operation, these computers are attracting attention due to the potential practical quantum advantage of quantum computing: solving problems of practical interest that are not tractable by traditional supercomputers in areas such as simulation and modeling of different processes (Daley et al., 2023), which requires quantum algorithms.

## Quantum algorithms

To perform processing on quantum computers, a specific class of algorithms needs to be developed, known as quantum algorithms. Even before the development of the first quantum computer, Shor (1997) proposed a quantum algorithm to efficiently solve the problem of factoring large prime numbers, i.e., find the prime factors of a given positive odd integer. Such a problem is extremely difficult to solve on classical computers and provides the basis upon which the cryptographic systems developed in recent decades and used to date are built, such as the RSA system used in banking operations and secure Internet communications (Rivest et al., 1978). According to Casati & Benenti (2005), a quantum algorithm that efficiently solves the prime factorization problem, implemented on a large-scale quantum computer, would break this widely used cryptographic system.

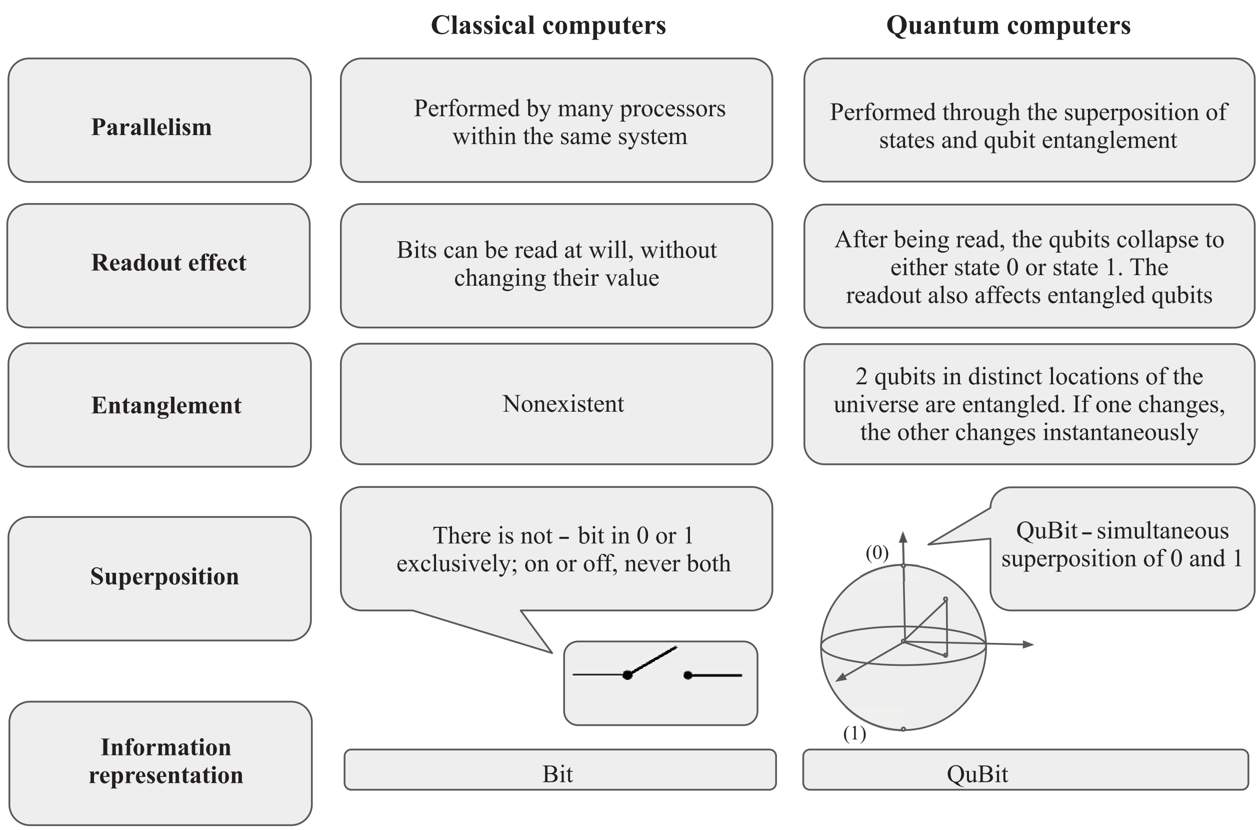


**Figure 1.** Main differences between classical and quantum computers.

In terms of computational complexity, the execution of some algorithms widely used in digital agriculture is much more efficient through quantum computers. For example, in their quantum versions, the complexities of the K-means algorithm, the principal component analysis, and of the convolutional neural networks are reduced from O(kN) to O(log kN), O(N) to O(log N), and O(N) to O(log N), respectively, whereas those of the Bayesian networks, Boltzmann machines, and reinforcement learning are reduced from O(N) to O(√N). In addition to providing an efficient method for storing information, quantum mechanics also facilitates information search. Currently, for example, to find a phone number in a list containing N randomly stored numbers would require O(N) queries to a database; however, Grover (1997) proposed an algorithm that uses state superposition to reduce query time to O(√N).

## Application markets and survey of existing quantum computing services

Among the main countries investing in research related to quantum computing, China stands out as the world leader, with a planned government investment of US$15 billion (Naveh, 2022). The European Union follows with US$7.2 billion, with Germany, France, the Netherlands, and Sweden as its largest investors; the goal is for Europe to have its first quantum computer by 2025 (European Commission, 2021), paving the way for full quantum capacity by 2030. France announced, in 2021, that the country would spend €1.8 billion to launch a new quantum computing platform (Future Today Institute, 2022), aiming to be one of the world leaders in the development of research and applications of this technology in different areas of knowledge.

In addition to government programs and large companies, some startups have also managed to raise funds for the construction of quantum equipment. The Canadian company D-Wave announced, as early as 2007, that it had built a fully functional 16-qubit computer and, recently, a 5,000-qubit device (Armasu, 2019a, 2019b). The Jülich Research Center in Germany acquired one of these computers and set up a special facility to house it, intending to optimize target interactions for the development of new drugs, for supplying chain management, and for radiation planning for cancer treatment (Jülich Forschungszentrum, 2023).

According to the Boston Consulting Group, capital investment in quantum computing continues to rise (Langione et al., 2022). The combined investments from 2020 and 2021 totaled $2.15 billion, an amount greater than the combined total of the preceding ten years. The majority of the investment is allocated to quantum hardware, but investments in software have grown by approximately 80% compared to the previous decade.

An example of massive investment is the partnership formed in 2022 between the Cleveland Clinic and IBM for the installation of Quantum System One, involving resources in the order of $500 million over the next ten years (IBM Newsroom, 2022). The focus will be on emerging pathogens and virus-related diseases, aiming to shorten critical research in treatments and vaccines.

Since quantum computers are expensive structures, some companies and collaborative initiatives have launched cloud services for testing algorithms or even getting familiar with this new form of computing. In 2017, IBM launched its quantum computing cloud service (Tilley, 2017). In 2018, a partnership between the Chinese Academy of Sciences and Alibaba enabled the launch of the Alibaba Quantum Laboratory (AQL), offering an 11-qubit quantum simulation service (Peng, 2018). In 2021, Microsoft announced the release of the Quantum Azure platform for developers (Microsoft, 2022). All these services encourage users, especially researchers, to run algorithms on quantum computers and conduct preliminary experiments, which allows of identifying bottlenecks, optimizing user experience and favoring the development of a new generation of processors. Some of the cloud services already available for testing and proof of concept in quantum computing are described in Table 2.

There is also a significant number of open-source software developed for quantum computing, as pointed out by Fingerhuth et al. (2018). This indicates that, in addition to governments and private companies, the market has also been moving to create an ecosystem around the quantum theme.

In this sense, some universities have already started offering courses in Quantum Engineering. For example, Saarland University in Germany initiated its undergraduate course in 2019, the University of New

South Wales in Australia began its master's program in 2021, and Virginia Tech in the USA began offering a specialization course in 2022 (Chen, 2023). In the case of the University of New South Wales, the motivation for creating the course came from a prediction that, by 2045, 19,400 professionals would be needed in the area, while PhD programs would only be graduating a maximum of 5,000 students (Chen, 2023).

## Quantum computing in digital agriculture

Studies are showing that quantum computing will have a profound impact on areas such as finance, logistics, transportation, space and automotive technology, materials science, energy, agriculture, pharmaceuticals and healthcare, and cybersecurity (Naveh, 2022). In agriculture, Maraveas et al. (2024) highlighted that the parallelism and computational speed of quantum systems will empower farmers with insights and recommendations to maximize yield, while minimizing environmental impact on agricultural production. Quantum systems have advantages over classical computing and can improve the precision of monitoring agricultural and livestock activities.

The impact of quantum computing should extend beyond cryptography, as quantum computing enables new advancements in artificial intelligence, which can subsequently be applied in various other fields of knowledge, including the sciences studying biological processes. According to the National Security Commission on Artificial Intelligence (2021), advances in artificial intelligence are positioning biotechnology as one of the most economically competitive sectors.

These applications of quantum computing can be categorized into the following transversal axes, which will be further detailed: I. modeling, simulation, and optimization of systems; II. machine learning; and III. data processing and storage.

## I. Modeling, simulation, and optimization of systems

In the field of modeling and simulation, there is great interest in quantum computing for modeling complex chemical structures, particularly in applications in the materials and pharmaceutical industries (Cao et al., 2019), which explains why many argue that this area will see the earliest impacts of quantum computing (Emerging Disruptive Technology Assessment Symposium, 2022). In 2017, IBM scientists made the cover of the journal Nature (Kandala et al., 2017) by simulating beryllium hydride ($BeH_2$), a material used as rocket fuel, through a 7-qubit NISQ quantum computer. In this simulation, the researchers were able to measure the lowest energy state of $BeH_2$, which is crucial for understanding chemical reactions, opening the door to more complex simulations. Although this particular molecule could have been simulated and verified on a classical computer, this would not have been possible for more complex molecules.

Regarding system optimization, several problems that are currently solved suboptimally in classical

**Table 2.** Quantum computing providers and services.

| Provider | Service description |
|---|---|
| Alibaba | The Alibaba Quantum Cloud Development Platform is an open-source development kit in the Python language designed for simulating quantum algorithms and quantum computers (Peng, 2018; Alibaba Quantum Laboratory, 2022). |
| IBM Quantum Lab | The Qiskit Platform, developed in open source mode, also uses Python as its base programming language. The code can be run on a simulator installed locally or on a real quantum computer via the IBM Quantum Lab (Open-source…, 2022). |
| Google | The Cirq platform from Google is an open-source platform designed for noisy intermediate-scale quantum computers. The fact that Google has a quantum artificial intelligence team reinforces the significant benefits for the field of artificial intelligence derived from the use of quantum computers (Ho & Bacon, 2018; Google, 2022). |
| Microsoft | The Azure Quantum platform is an initiative by Microsoft to provide a cloud-based quantum computing service. The quantum hardware providers are independent of Microsoft itself, and registered users receive $500 in credit to use with each of these providers. Among the providers are: Quantinuum, IonQ, Rigetti, Pasqal, and Quantum Circuits (Microsoft, 2022). |
| Amazon | Amazon provides cloud quantum computing services using hardware developed by various manufacturers such as QuEra, D-Wave, IonQ, Rigetti, Xanadu, and OQC. Current prices are $0.30 for a quantum circuit or starting from $0.00019 per execution, depending on the chosen hardware among the mentioned manufacturers (Amazon, 2022). |

computers could have their exact solution using a quantum computer. Among these, the very common problem in the logistics and supply chain area, known as the “traveling salesman problem”, stands out. In it, the best route is sought by passing through all points with the shortest possible path, which is restricted to a not very large number of points in classical computing. Another similar problem that could be optimized by quantum computers is flight planning by airlines, which could perform daily planning for thousands of passengers flying to hundreds of destinations on a specific day, reducing travel time, air traffic congestion, and fuel costs (Gil et al., 2018).

## II. Machine learning

A hybrid computing approach, where both conventional computing and NISQ quantum computers are used, could result in a considerable progress when compared with the use of conventional computers alone (Cao et al., 2018). This hybrid form is employed in variational quantum eigensolvers (VQEs) to predict the properties of the electronic structure of small molecules. According to Cao et al. (2019), the developments involving VQEs may favor the commercial utility of quantum devices much earlier than expected.

Beyond the algorithmic complexity mentioned earlier, machine-learning computational methods appear to have much to gain from the use of quantum computers. In an article published in the journal Nature, Huang et al. (2022) used Google’s Sycamore computer to predict properties of physical systems, perform quantum principal component analysis, and learn approximate models of physical systems, showing that the number of experiments required to train the quantum system is four orders of magnitude lower than that needed for conventional computers. This efficiency has led to the proposition that the combination of quantum computing with machine learning would elevate computer-based learning systems to a new level of evolution (Dunjko, 2022).

## III. Data processing and storage

One advantage of quantum computers is their greater efficiency to store and process large volumes of data when compared with conventional computers. For example, to be stored, the three billion base pairs of the human genome require 1.5 gigabytes on a conventional computer, but only approximately 34 qubits of a quantum computer (Outeiral et al., 2021). According to the same authors, doubling the number of qubits to 68 provides enough space to store the genomes of the entire human population.

Another advantage is that quantum computers have a direct impact on statistical methods and machine learning, which are applied in different areas. In computational biology, for example, supervised learning techniques have been widely used to predict how well a ligand will bind to a protein, whereas, in the biomedical field, the increase in speed related to some classes of algorithms and to information storage and retrieval stands out (Outeiral et al., 2021). In addition to its use for the simulation of chemistry, as in the abovementioned case of $BeH_2$, quantum computing can also assist in the early stages of the drug discovery process (Zinner et al., 2021) and can be used to simulate how new synthetic proteins will fold in the body, supporting new protein-based therapies (Future Today Institute, 2022).

These three axes are closely interconnected with regard to biotechnology, as it interfaces with modeling and simulation, as well as with machine learning. Next, the axes will be transversely dispersed in the overall landscape of quantum-computing applications in digital agriculture.

# Fields of application in digital agriculture

In the context of digital agriculture involving different biological processes, the potential areas for quantum computing applications, along with the algorithms and/or methodologies used in their execution, can be found in the fields of: I. bioinformatics, II. remote sensing, III. climate modeling, and IV. smart farming (Figure 2).

## I. Bioinformatics

Quantum computers have a great potential in the early drug discovery process. On two NISQ computers (one from IBM and another from Quantinuum), Kirsopp et al. (2022) tested a variational quantum eigensolver, which uses both classical and quantum computers to quantify protein-ligand interactions. The authors observed mathematical proof of the potential of existing quantum algorithms in speeding eigenvalue calculations and linear system resolution for simulation and optimization, aiding in drug-receptor interaction processes and protein folding, which can be predicted with a greater accuracy than in classical systems. This capability has sparked interest from the pharmaceutical industry, i.e., 17 of the 21 largest corporations in the sector reported ongoing activity in quantum computing, including Roche, Pfizer, Merck & Co, AstraZeneca, and GSK (Zinner et al., 2021). The Canadian startup Menten AI is combining protein design, machine learning, and quantum computing to develop new therapeutic molecules in record time (Zinner et al., 2021). The quantification of protein-ligand interactions is important in agriculture for analyzing the structural information between a receptor (target protein) and a ligand (agrochemical). Neshich et al. (2015) applied this in silico analysis in the search for a chemical compound to control the pathogenicity of the *Xilella fastidiosa* bacterium, which causes damages to citrus crops.

## II. Remote sensing

Research and applications in the use of remote sensing images with different resolutions (spatial, spectral, temporal, and radiometric) have evolved greatly in recent years, contributing to the mapping and monitoring of land use and land cover at local, regional, national, and global scales. Some of the initiatives in which quantum computing is applied in remote sensing include the use of the D-Wave 2000Q quantum annealer for training digital classifiers in multispectral images via support vector machine, a method based on machine learning (Cavallaro et al., 2020). This type of method can exponentially amplify the volume of data to be analyzed, with a shorter digital image processing time and a higher accuracy. These aspects favor the agro-environmental monitoring of large territorial extensions by better separating land use and land cover classes. Another recent application involves the processing and digital classification of agricultural crops using hyperspectral images obtained with D-Wave QA (Cavallaro et al., 2020). Otgonbaatar

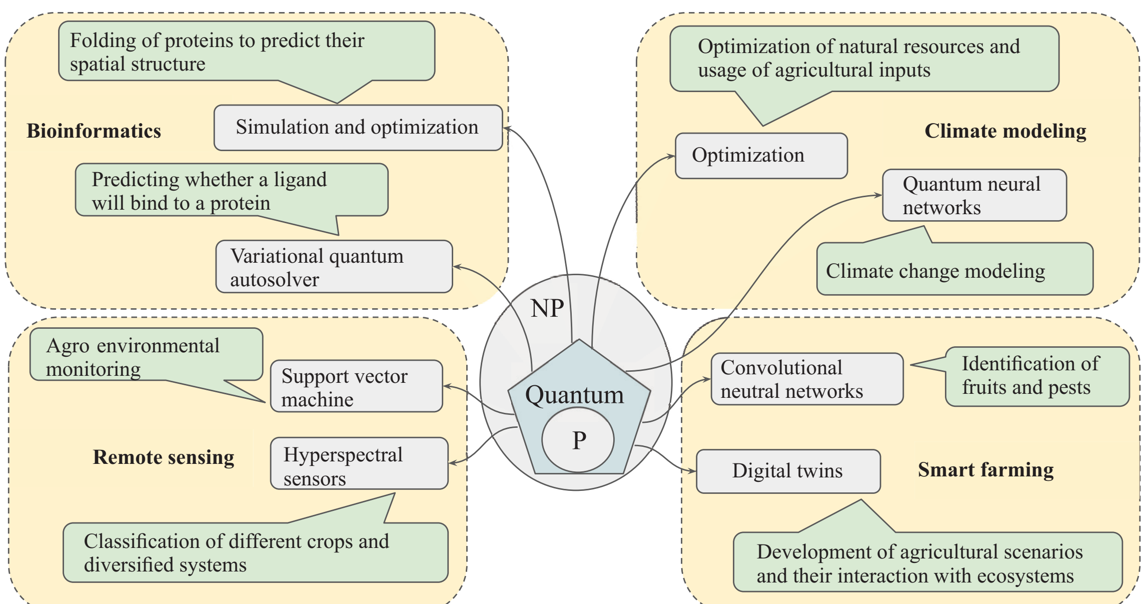


**Figure 2.** Synthesis of quantum computing applications in digital agriculture. In the center are polynomial time (P) problems, which are solved by classical computers. Quantum computers are suitable for problems with complexity levels between P and nondeterministic polynomial time (NP), whose computational algorithms are indicated by arrows. At the outermost level, some examples of applications in agriculture are given in the previously mentioned areas of bioinformatics, remote sensing, climate modeling, and smart farming.


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& Datcu (2021) developed a method based on a quantum boost classifier to classify a dataset from the airborne visible infrared imaging spectrometer sensor, which made it possible to eliminate noise and enhance the understanding of the spectral profile behavior of dozens of spectral bands, increasing the accuracy of the classification of different agricultural targets such as soybean, corn, wheat, alfalfa, and pastures. These and other quantum computing-based processes also have the potential for the digital classification of more complex agricultural production systems, such as agroforestry systems and integrated crop-livestock-forest systems.

## III. Climate modeling

Several challenges involving biological processes from soil-plant-climate interactions and climate adaptation could benefit from quantum computing, such as the detection of anthropogenic changes, generation of precipitation time series, prediction of flowering dates, and analysis of ecosystem models. The formulations for these problems using the simulated annealing technique could be efficiently solved with existing D-Wave computers that operate natively in annealing mode (Berger et al., 2021). It is also worth highlighting the investments of agro-multinationals, such as Badische Anilin & Sodafabrik (BASF), a world leader in the chemical field, which recently announced a partnership with Pasqal, a French startup specialized in quantum computing applications in climate (Vigliarolo, 2022; How & Cheah, 2023; Pasqal, 2024). Although BASF already uses meteorological models to generate growth simulations for different agricultural crops and to support input management, this interorganizational articulation aims to improve climate modeling based on quantum computing, in order to maximize the use of natural resources and inputs in agricultural production through system optimization techniques. Information on factors such as solar radiation, humidity, and topography is combined in complex nonlinear differential equations, which are processed more efficiently by implementing quantum neural networks on Pasqal's neutral atom quantum processors. The cited companies also emphasize that the used algorithms can model climatic patterns at multiple spatial and temporal scales, predicting short- and long-term local and global events, generating innovative, faster, and more accurate solutions for climate change modeling.

## IV. Smart farming

Within the scope of smart farming, quantum computing processing can contribute to various applications, such as balancing the supply and demand of different crops on adjacent farms (Ou et al., 2022). The technology can also contribute to the conception of quantum digital twins, used to solve modeling and simulation problems and to understand the aspects of a system, allowing to answer questions and provide insights about the real system, such as the planet Earth (European Space Agency, 2021), or about the impacts of food systems on ecosystems (Amir et al., 2022). The twin dedicated to food systems is of particular interest in elaborating agricultural scenarios and their interaction with ecosystems, as models can be run for a particular crop, considering water availability and irrigation systems (Maraveas et al., 2024). Via quantum principal component analysis, this method can also be applied to animal welfare, helping to discover which variables are determinant for animal thermal comfort (Maraveas et al., 2024). Other techniques accelerated by quantum computing, such as convolutional neural networks, can be used to identify fruits and diseases in images from different sensors, whereas Bayesian networks may be used to model and evaluate ecosystem integrity in rural areas (Outeiral et al., 2021). Furthermore, systems of linear equations serve as the basis for determining a least-cost ration for animals, while reinforcement learning is used to simulate and control different plant development parameters in growth chambers at research institutions (Harrow et al., 2009).

It should be noted that, with the advent of quantum computing, the processes conducted in current scientific experiments do not necessarily need to change substantially. In other words, the method used to acquire field data would not necessarily be modified, but quantum computing would alter the scale of problems that can be solved and how modeling is performed in this system, significantly improving the response time of rural producers to possible management interventions, involving planting, cultural practices, and/or harvesting of a particular crop. For example, quantum processing would make it possible to process 100,000 interactions obtained in the field (soil, plant, and climate) in the same amount of time it would take to process 10,000 possible data interactions on a traditional computer.

In this early stage of quantum computing development, the direct users primarily involve companies and institutions capable of dealing with the complexity, training, and skills required for the construction of this system. Therefore, it is not expected that farmers will be direct users, but that their interface with a quantum system will be through a portal or API developed by companies qualified for such purposes.

## Trends and opportunities of quantum computing

As the research and development of quantum computing applications advance, the scientific and industrial community is beginning to formulate frameworks to address the risks and opportunities involved, ethical considerations to pursue, and expectations regarding the impacts this technology will have on society. The World Economic Forum (2022) proposes a governance framework to guide stakeholders from different areas in which quantum computing can be applied, including government, industry, academia, civil society, as well as investors and policymakers. This governance framework has predefined themes as its central unit, each with a set of principles supported by fundamental values to guide the actions to be taken by the stakeholders to steer the development of this technology, considering its goals, opportunities, and risks. The proposed themes include: the transformative capacity of quantum computing, access to hardware infrastructure, open innovation, raising awareness and engagement, workforce development and training, cybersecurity, privacy, sustainability, and standardization. Among the values listed are: transparency, common good, accessibility, equity, inclusion, responsibility, and non-maleficence.

According to Purohit et al. (2024), organizations will need to assess their level of maturity in quantum computing development to gain a competitive advantage and ensure they are ready to profit from the applications of this technology. For this evaluation, the authors propose quantum technology readiness levels, ranging from level 1 (development and research of the basic principles of quantum phenomena) to 9 (development of practical applications for the real world), inspired by technology readiness levels, a method used to measure the maturity of a technology by determining its level of development, testing, and integration. Additionally, to measure the maturity of the quantum technology market, the authors also propose quantum commercial readiness levels, ranging from level 1 (ideation phase showing that a quantum technology offers a viable solution to an identified market problem) to 5 (the technology is ready for commercialization at scale).

In Brazil, the challenges for the implementation of quantum computing are being mapped, and important initiatives are already underway. However, it is essential to deepen research at the frontier of knowledge through studies seeking solutions based on quantum computing applied in digital agriculture and other areas of interest. In this regard, the National Research and Education Network, the Ministry of Science, Technology, and Innovation (MCTI), and Softex organized the online event “Brazil Quantum Computing Challenge” (Os desafios..., 2021), in November 2022, to discuss the challenges of quantum computing in the country. Another initiative in Brazil was the launch of the MCTI-Softex Network of Quantum Technologies by MCTI, to be coordinated by the manufacturing and technology integrated campus of Senai (Senai Cimatec, 2022), with the aim of fostering the Brazilian ecosystem of quantum computing, integrating government actions with research centers and startups, while preparing the country for this technology.

On May 17, 2023, Embrapa and Senai Cimatec launched the Mixed Digital Research and Innovation Unit in Tropical Agriculture (Galinari, 2023). This initiative will involve the use of new sensors, quantum technologies, automation, and robotics in areas such as artificial intelligence, precision agriculture, Internet of Things, photonics, and traceability. The goal is to increasingly position Brazil at the forefront of agricultural research. In 2024, the São Paulo Research Foundation (Fapesp, 2024) launched a research program to promote the progress of quantum technologies, boost the development of startups, attract global investment, and bring talent to the state of São Paulo.

Other actions that can leverage the development of this technological field in digital agriculture in the country include: establishing partnerships between public and private companies, startups, government, and academia to form a quantum computing ecosystem; providing funding opportunities through funding institutions for projects in this area; training professionals and students in the use of this technology; providing access to available quantum computing services; and establishing policies for the development and use of quantum technologies and applications.

## Concluding remarks

This work centers on quantum computing, presenting its potential and the current available services, particularly in the context of digital agriculture. Because of their properties, quantum computers allow of considerable gains in both the computational ability and time required to solve difficult problems when compared with classical computers.

The advances in quantum computing can assist in capturing the complex relationships existing in natural systems, considering both biotic and abiotic factors, which allows of solving the mathematical equations that model these systems, taking into account agro-environmental implications, while optimizing the use of natural resources in a more sustainable manner. The obtained results could support decision-making in rural areas more efficiently, involving biological processes with some degree of uncertainty, such as soil-plant-climate interactions modeled through systems transposed to quantum computers.

Despite the promising potential of the applications involving quantum technology, their development remains a challenge for modeling biological processes in agriculture, which typically face a wide range of variables throughout the day, week, month, or year, depending on the aimed production (plant or animal). Therefore, the evolution of these applications in different productive sectors and at the 1:1 scale (plot, field, or paddock) requires continuous computational development and personnel training for scientific and technological advancement.

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