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A comprehensive cost mapping of digital technologies in greenhouses

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ABSTRACT

Conventional greenhouse producers face significant challenges in integrating advanced Industry 4.0 technologies into their production processes. One of the main obstacles is the lack of clarity regarding the components of technological costs. This article develops a cost mapping for the implementation of such technologies in the context of greenhouses. The mapping distinguishes between capital expenditures (CAPEX) and operational expenditures (OPEX), categorizing the key technological components and their financial implications. Based on the general findings from the literature review, several cost areas can be identified and classified as follows: hardware acquisition, installation and retrofitting, integration and customization, software and services, operational and maintenance costs. This cost structure will serve as a basis for future economic models and cost-benefit analysis (CBA), promoting strategic decision-making and a more informed and precise selection of digital technologies.

1. Introduction

The social, economic, and environmental challenges driven by increased energy consumption and the need for food autonomy highlight the need for substantial efforts to optimize energy efficiency and boost agricultural production capacity throughout the year [37]. This is particularly important for countries with very short favorable climate seasons and a short growing season, which restrict production and increase dependency on imports, with the level of dependency varying by product type [38]. In the case of Canada, a significant portion of the fruit and vegetable supply relies on imports, thereby leaving the country vulnerable in the event of any disruption to global trade that would be detrimental to maintaining local supply capability [9].

Greenhouses and CEA (Controlled Environment Agriculture) systems lately represent a promising way to reduce such dependence. However, their high energy consumption suggests that maintaining an optimal microclimate in colder regions entails a significant energy cost [51]. In Quebec, energy consumption in greenhouses operated by small and medium-sized producers largely depends on sources such as natural gas, propane, and fossil fuels, significantly contributing to greenhouse gas (GHG) emissions [15,56]. The major factors of energy use are the heating/cooling and ventilation systems, along with artificial lighting [11]. Electrification of the agricultural sector therefore creates an opportunity for better sustainability and competitiveness, but at the same time raises important challenges, as high energy consumption during winter may overload the electrical grid and strain the distribution infrastructure [31].

Due to such challenges, mechanisms have been developed to increase the resilience of the agricultural sector through modern technological innovations. Among them are various financial programs for greenhouse producers, which were intended to make it easier to access digitization and modernization of the agricultural sector [37]. Through automation and intelligent control, these advanced technologies improve productive efficiency and enable real-time adjustments to energy resource consumption [58]. In this respect, the digital transformation of agricultural, driven by Industry 4.0 technologies, is playing an important role in updating agricultural practices. Greenhouses are increasingly becoming high-tech, well-connected, and sustainable with the use of technologies such as the Internet of Things (IoT), cloud computing, Big Data, Artificial Intelligence (IA), Machine Learning (ML), and Advanced Systems of Automation. These are innovations that enable the complete management of agricultural processes by means of monitoring, regulation, and optimization operations remotely and in real time [4,30]. These advantages turn to benefits when the field practices improve on disease

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detection, irrigation management, fertilizer handling, the identification of crop maturity, marketing operations, supply chain management, and energy management [64].

However, the adoption of these technologies progresses unevenly and heterogeneously, complicating the search for solutions by producers that meet their needs, particularly since the horticultural market lacks mature and readily available technologies, especially in the field of automation [32]. This situation creates additional obstacles for farmers, particularly those managing small and medium-sized operations [76]. According to a study by CIRANO [61], the main obstacles to adopting modernization and digitalization strategies in Quebec's horticultural sector are the high costs of acquiring digital technologies, their rapid evolution, uncertainty about long-term profitability, fear of dependency on technology providers, and the need for specialized advice.

The economic viability of digital technologies has increasingly become one of the drivers of decision-making in their adoption, hence demanding a comprehensive cost-benefit analysis of the technologies to balance the costs of implementation against the potentially accruable economic benefits thereof [71,57]. However, such decisions in the absence of full information on the most economically viable solutions for their needs remain challenging for farmers. This lack of clarity causes indecision due to the possibility of making the wrong decisions that may later result in financial losses [24,25]. While the literature indicates that such technologies are likely to provide certain possible benefits, the fear of high initial capital costs, and relative uncertainty over long-term benefits remain among major concerns for many producers [60,39]. These are not the only limitations but also come from commercial, technical, and sectoral problems that complicate the choice of technologies which best fit each case [22]. On this matter, hesitation to adopt new technologies because of a lack of profitability analysis is not an exclusive problem of the agricultural sector, since this is a phenomenon shared with most industrial sectors [45]. In this context, there is a clear lack of economic viability analysis in general, highlighting the need for a deeper academic approach [58] to propose profitability studies for digital technologies in the industry [21].

The increasing complexity of digital technologies and automation has raised the proportion of indirect costs, reducing the effectiveness of traditional methods for evaluating the economic viability of digital technologies [54]. This challenge requires the development of more complete approaches to consider costs throughout the adoption cycle, meaning during all phases of a digitization project [54]. Without an appropriate structure, which groups these costs into certain categories, analyses are usually incomplete and difficult to extrapolate to other cases. This might illustrate the need for cost models that standardize the organization and classification of expenses, so these costs are easily comparable among different technologies. Consequently, the adoption of Industry 4.0 technologies requires a rethinking of cost management, planning, and budgeting [62].

This research represents a preliminary effort to identify and map cost elements related to the assessment and acquisition process of Industry 4.0 technologies for greenhouses to equip decision-makers with a tool that would enable them to perform not only direct costs identification but also accounting for indirect costs, which in many situations remain hidden from classical cost accounting. The research categorizes these components and, therefore, contributes to further studies. This also lays the foundation for improving the economic profitability models for technologies. Accordingly, the research seeks to answer the question: How can the different cost components related to the implementation of Industry 4.0 technologies in greenhouses be categorized? In this respect, a detailed mapping of the different costs involved in the adoption of these technologies is proposed. Such mapping comprises initial costs and technologies' operational costs, as well as the technical and operational challenges that arise from the integration of digital technologies. In doing so, all the above aspects will be integrated into the research to offer a wide perspective on the costs throughout the technology adoption cycle that might help reduce financial surprises and optimize Return on Investment (ROI) in the Industry 4.0 project for greenhouses.

The rest of the paper is divided into four sections: the first section presents a literature review on modernization and Industry 4.0 technologies, including economic aspects and cost elements; the second section introduces cost mapping into key categories. The third section discusses program results, and the last section presents the conclusions.

2. Literature review

The literature review was subdivided into several sections so that cost-related components of implementing Industry 4.0 technologies in greenhouses could be identified comprehensively. Section one compares the evolution of greenhouse modernization, identifying key Industry 4.0 technologies. The second section looks at the challenges that impede the adoption of the technologies. The third section focused on works dealing with the economic feasibility assessment of greenhouses. Section four then described studies that classify the costs concerning digital technologies, including examples from other industries to create a bigger picture of cost models relevant for digital agriculture.

The review was conducted using an exploratory search methodology in academic databases such as Scopus and Google Scholar, as well as through market reports and specialized publications. The selected key research terms included: Industry 4.0, Agriculture 4.0, greenhouse technologies, smart agriculture, modernization of greenhouses, cost models, cost structure, and cost-benefit analysis. These terms were selected with the purpose of covering both technical studies of technologies implemented within greenhouses, as well as economic analyses.

2.1. Greenhouses and industry 4.0

As a specific form of CEA, greenhouses provide the conditions for the proper development of plants throughout the year [53]. These facilities have undergone a remarkable transformation, evolving from simple protective structures to highly sophisticated agricultural systems [60,34]. The evolution of greenhouse agriculture reflects the impact of technology through industrial revolutions, moving from initial mechanization to today's advanced digitization, integrating automation and smart technologies for optimized year-round production [40].

Fig. 1 presents the chronology of greenhouses, from their very origin to the point where the adoption of new technologies turned this sector around completely over the centuries. The developments in this sector began to take a major turn in the 18th century with the introduction of heating systems with conduit ovens, followed later in the 19th century by steam, hot water systems, and hot air systems. The development of electric lighting in the 19th century paved the way for controlled experiments on the effects of light on plant growth. It facilitated the study of controlled ventilation and aeration starting in the 1930s. In the 1950s, humidification and evaporating cooling techniques were introduced. In the 1960s, significant progress was made with the beginning of using combustion gases as an additional source of carbon dioxide [53,14]. Since the 1970s, commercial greenhouses and climate control automation have been implemented, using computer studies to regulate radiation, ventilation, humidity, and temperature. From the end of the 1980s, smart greenhouse management began to emerge. This period would mark the use of sensors, software, and other systems that enable precision and accuracy concerning environmental condition management. [16]. By the late 1990s, robotic systems began to integrate into this field. In the early 2000s, greenhouses began the application of Wireless Sensor Networks (WSN), allowing environmental monitoring, early warning generation, and remote control [58]. The use of WSN in agriculture kept evolving to more IoT-compatible solutions, making use of more generic standards for communication [70]. Currently, the trend in greenhouses is marked by the use and incorporation of fourth industrial revolution technologies [12]. These technologies analyze large volumes

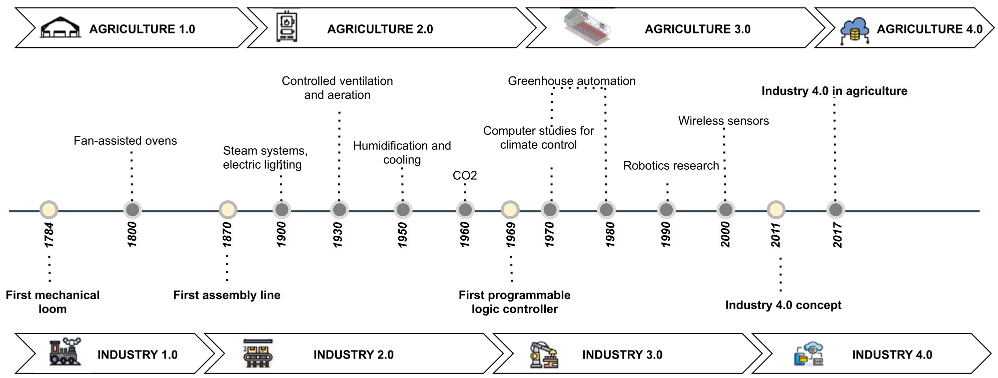

Fig. 1. Modernization and greenhouse agriculture, adapted from [40].

of data in real-time and make independent decisions, thus enhancing the efficiency and accuracy of decision-making in greenhouses [27].

A significant portion of academic research has focused on developing strategies to optimize the geometry, orientation, and materials of structures. Particular emphasis is placed on microclimate control, energy management, integration of renewable energies, as well as optimizing production schedules and the integrated operation of agricultural infrastructures [77,8]. Also, decision-making mechanisms have been subject to modernization, which in turn has resulted in increasing developments towards greenhouse automation. According to [48], the evolution of these technologies has evolved from human-to-human interaction, where traditional equipment requires manual supervision, to human-machine collaboration, whereby, through remote monitoring systems, operators can adjust variables by using intuitive interfaces. Finally, machine-to-machine collaboration takes control, with autonomous systems regulating climate and plant nutrition, learning from previous cycles to continuously optimize growing conditions.

The fourth industrial revolution is transforming all industries, including agriculture, where it is also known as Agriculture 4.0 [40]. The orchestration of such technologies configures a system that can coordinate and construct more effective, intelligent, and optimized solutions in various industrial and commercial fields [4]. These are applied to a few main aspects of this horticulture: automation of actuators, disease detection, irrigation and fertilizer management, crop maturity identification, as well as supply chain and marketing optimization [64]. Industry 4.0 has increasingly focused on underlining the technology's relevance for big volumes of data generation [24]. The volume necessitates IoT architectural solutions which proficiently handle data collection, processing, and analysis [17]. The IoT architecture presented in Fig. 2 describes an organizational scheme for smart agriculture where other technologies set up and communicate in a system. Special functions that ensure the coherent work of the entire system are separated and located in different layers. Each layer is responsible for certain aspects of IoT in agriculture, starting from data perception and its gathering to its analysis and application, which make integration and management of technology easier [52].

In an IoT system, the physical layer resolves the hardware components such as sensors and actuators in charge of detecting environmental conditions and physical actuators in the real system [4], whereas the communication layer acts as an intermediary between the physical devices and their capability for communication with other devices or systems. It provides the necessary connection through which data shall be transferred using various network and communication protocols [70,52]. The service layer is essential for processing and analyzing the received data. Here, IoT platforms, middleware, and advanced technologies such as Big Data, ML and AI process large volumes of data to generate actionable information and make strategic decisions based on these analyses [27]. The application layer provides the interfaces and functionalities with which users interact. These applications enable users to monitor the state of crops, manage resources intelligently, and make better and optimal decisions in key areas, such as control, logistics, as well as predicting for future problems [68]. In brief, this layered methodology integrates hardware with communication techniques and data analysis on an interdependent system and optimizes operation efficiency with the productivity of the greenhouse [52].

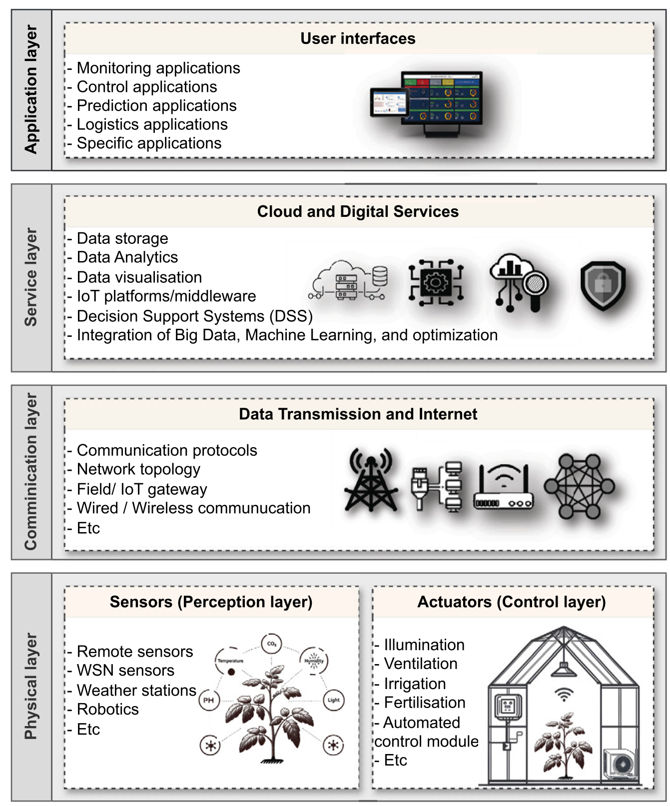

Fig. 2. Conceptual IoT architecture for Agriculture 4.0, adapted from [4].

2.2. Challenges in the adoption of digital technologies

The adoption of IoT solutions and data-driven systems in agriculture requires advanced infrastructures, such as specialized sensors, cloud-based analytics platforms, and robust communication networks [43,65]. These initial investments are typically capital-intensive and are often compounded by the need to integrate with existing infrastructures and the lack of standardization in communication protocols [7]. Although the physical infrastructure, such as sensors and irrigation devices, can be initially installed, a significant challenge is the integration of this network. In this regard, significant investments are required in software for platforms that enable data aggregation and analysis, as well as in custom integration services that facilitate the connection between these disparate devices [41]. Additionally, in rural areas, access to reliable electricity and the internet is not always guaranteed, which can undermine the effectiveness of smart systems that rely on constant data flow and real-time control [32].

Upgrading an existing greenhouse poses even greater challenges when it comes to modernizing its infrastructure. [28] highlight the complexity of integrating new technologies into traditional greenhouse structures without disrupting ongoing operations. In most cases, this requires a phased approach that balances the need for technological advancements with the practicalities of maintaining production. Key challenges in integration include ensuring interoperability between systems from different providers and legacy equipment, addressing data reliability issues caused by equipment failures and environmental factors, and developing scalable solutions to manage the large number of IoT devices expected to be deployed [22].

According to [1,35], the success of this implementation hinges on the standardization of data from all sensors and devices, which ensures seamless communication and accurate data interpretation. Standardization also allows developers to create a unified interface for managing the greenhouse, enabling real-time data transfer and synchronization. Furthermore, the integration of AI models into an operational control system adds another layer of complexity. As shown by [33] in their work on predicting climate conditions in greenhouses, deploying AI can be effective if, in addition to technical integration, it is grounded in a deep understanding of the agricultural context in which the technology is intended to operate.

Even though technologies like automation in greenhouses promise higher yields and more efficient resource management, the reality is that many small-scale farmers lack the financial resources and proper training to adopt these innovations without external support. Furthermore, regulatory challenges concerning data ownership between farmers and tech companies create uncertainty, which undermines producers' confidence in these solutions [61].

2.3. Economic viability in greenhouses

The economic viability of greenhouses is usually appraised by research studies focusing on the initial investment costs related to construction and equipment, in addition to operating costs like irrigation, energy, labor, and maintenance. These are also the factors deemed up to now to make it possible to assess the profitability of agricultural systems and their capability to enhance productive performance. For example, [6] evaluate the economic risks of investment in tomato production by assessing the impact of initial and operating costs (such as energy costs and labor costs) on the economic viability of the greenhouse. In a similar vein, [69] highlight the importance of energy costs when carrying out an economic feasibility analysis of Combined Cooling, Heating, and Power (CCHP) systems, considering installation costs and operation costs of energy consumption. Thereafter, [10] introduce uncertainty into the cost analysis and underline the fact that lack of accurate data, along with capital and operating costs, are the major challenges to profitability related to vertical farms. Regarding the techno-economic aspect, the work of [73] paid special attention to global optimization, duly relating the importance of the analysis of fixed and variable costs in relation to depreciation, agricultural inputs, and climate control systems in determining the viability of different greenhouse designs.

On the other hand, some recent research has evaluated the economic viability of the adoption of digital technologies in greenhouses. [55] presents a study on the economic feasibility of smart greenhouse technology using a Software Cost Estimation Model. For this, the variables of fixed costs are supposed to be the development of software modules and infrastructure needed to keep the operation of the greenhouse up and running. Meanwhile, [20] applies econometric models and Data Envelopment Analysis (DEA) to evaluate economic management in greenhouses. In this context, it estimates the magnitude of the effect of the integration of digital platforms on profitability, cost reduction, and technical efficiency improvement in greenhouses. [72] assessed the economic benefit of integrating digital technologies in greenhouses and plant factories through multi-objective optimization modeling. This work will retrofit technologies like sensors, robots, and automated systems, considering the reduction of cost to a minimum and profit maximization to ensure maximum ROI. It is also observed that these studies present general analyses on global economic benefits, such as increased operational efficiency or long-term cost reduction of the technologies; however, few provide a detailed breakdown of specific costs associated with implementing these technologies. The lack of detailed analysis makes it difficult to compare the implementation costs of specific technologies with the economic benefits they generate. As a rule, such technologies' costs are hidden in a variety of wide general production processes or lightly touched upon, without any deep analysis that would make their impact on profitability and return on investment in the processes assessable individually.

Among these economic analyses of agriculture, attempts, such as [57], model the relationship that exists between the costs of implementing IoT in agriculture in terms of hardware, maintenance, and services, and perceived benefits accruing to farmers and service providers. While the study indeed brought up a general framework for evaluating these technologies, the approach is very theoretical and does not provide any validation with real-world data.

2.4. Cost structures of digital technologies

Similar to manufacturing, cost structures in the greenhouse sector have dramatically changed with the smart technologies and Industry 4.0 advancements in automation, AI, and the use of IoT. Operational costs for greenhouses have traditionally been dominated by direct costs, including labor, energy, water, and raw materials like seeds and fertilizers, as was common in early manufacturing cost models. Indirect costs, on the other hand, have been apparently driven upwards by such inclusion of smart technologies once investment in advanced systems, employee training, and modernization of various facilities becomes obligatory [54]. Such a shift testifies to an emerging focus on efficiency and precision but at the same time refocusing financial priorities toward technological development and infrastructural development, a process that reshapes the cost dynamic of contemporary management [66].

Cost structures, including the adoption of modernization of greenhouses with integrated technologies that improve operational efficiency, have taken the center stage in the literature recently. Many studies have emphasized the evaluation of Total Cost of Ownership (TCO), this approach is widely applied across multiple sectors and technological areas due to its ability to analyze financial implications over time. In the agricultural field, a study [63] proposed a TCO framework for evaluating the costs of physical infrastructure and hardware in smart greenhouses, covering irrigation systems, environmental control, and sensors, along with operational and maintenance costs. However, this study did not specifically address the costs associated with digital technologies. In contrast, other works have applied the TCO model to areas like cloud computing, IoT networks, and data centers. For example, [74] examined cloud computing services by considering CAPEX and OPEX to reveal hidden costs and risks, which are particularly relevant for startups lacking internal IT infrastructure. Similarly, [29] calculated TCO for IoT networks by focusing on equipment, infrastructure, installation, and maintenance costs. Additionally, [42] provided a techno-economic framework for evaluating TCO in disaggregated data center infrastructures compared to traditional models. These studies highlight the expanding scope of TCO analysis, extending beyond traditional hardware to include digital and information technologies fundamental to modern greenhouse operations.

3. Methods

The literature review highlights the need for more detailed information regarding the implementation costs of Industry 4.0 technologies in greenhouses. While different attributes have been studied, detailed cost breakdowns by researchers would contribute to better economic analysis and aid in informed decision-making regarding the adoption of these technologies. Within this framework, the article raises the development of a mapping of the costs, a tool created for the identification, description, and analysis of the costs related to the adoption of digital technologies. The methodology is based on an interpretation of the information gathered from the literature review, considering the different approaches that represent the costs of digital technologies derived from implementation, operation, and challenges.

3.1. Theoretical foundations for cost mapping

Each of the tools that compose Industry 4.0 technology has certain roles to play at different phases of the process. Some technologies specialize in giving out certain keys or data with which other technologies are developed or optimized analytically. It is complicated to find the cost per technology in the general overview of Industry 4.0. Therefore, the mapping of the cost structure will be done through an integrated approach, considering technological solutions proposed and implications of their adoption from a technical and economic point of view. An attained holistic approach will be ensured through the TCO method, enabling the better visualization of CAPEX and OPEX.

Various functional elements and technical challenges identified in the literature were considered to propose categories that group the different cost elements. First, the layered structure of IoT was taken into account, which includes hardware (sensors and actuators), the communication layer, cloud service infrastructure, and applications that enable real-time decision-making [4,52]. These elements define the spectrum of costs, ranging from hardware acquisition to ongoing software services and data analysis. Each of the proposed categories addresses the technical and economic needs observed in studies on the implementation and challenges inherent to the adoption of technologies in Agriculture 4.0. Thus, categories were established, including: hardware of acquisition, installation and retrofitting, integration and customization, as well as software and services, operational, and maintenance.

The physical layer and the communication layer of an IoT architecture form the foundation for establishing an efficient network in a digitized agricultural environment. An IoT sensing device requires at least three elements: sensors, microcontrollers, and connectivity to send data [59]. In this context, this category focuses on identifying the initial expenditure on sensors, actuators, controllers, gateways, base station infrastructure, and other equipment necessary to automate and operate an agricultural system in smart greenhouses. The costs related to these elements are significant and represent one of the main challenges for farmers. On the other hand, the adaptation of these devices to the production system requires initial installations and potentially the modification of the existing environment for the new technologies. This may be the restructuring of the space, planning the correct number of devices, incorporating systems that would permit control of environmental variables. Therefore, this category presents the need for adaptation of already existing infrastructures and all the expenses concerning this process should be contemplated to enable the greenhouses to take advantage of technological innovations without further complications.

Integration and customization address the critical need to adapt technological solutions to fit the specific characteristics and needs of each greenhouse. It includes the integration of new systems with existing technology, which may require additional technical adjustments that demand specialized configurations. This, in the sense of IoT systems and digital platforms, often requires customization to very local conditions, such as crop characteristics or climate [41]. Additionally, the rigidity of applications is another technical challenge, which increases

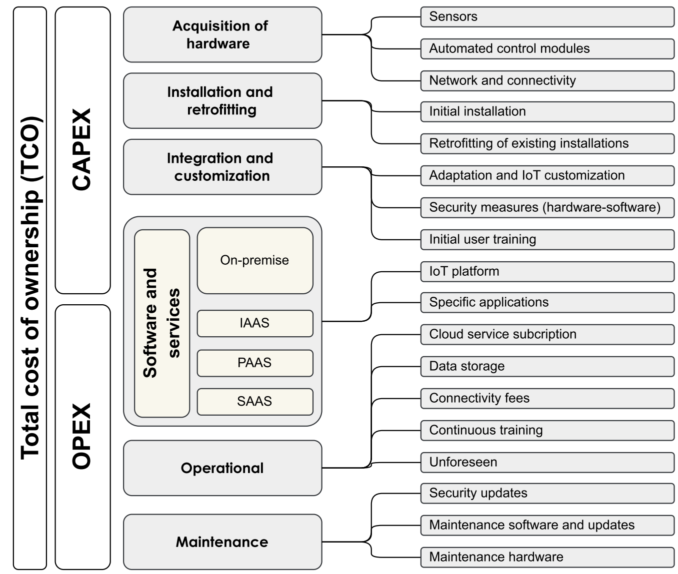

Fig. 3. Cost mapping in the Greenhouse Sector.

costs due to the adjustments and adaptations an application must undergo to be useful for a particular agricultural need. Additionally, it is necessary to implement comprehensive security measures from the outset, both in hardware and software, to protect against data breaches or technical failures. At the same time, personnel must be trained for the proper use of these technologies, which involves an initial expense in training and operational adaptation [65].

Service models in digital technologies have been proposed, such as On-Premise, IaaS (Infrastructure as a Service), PaaS (Platform as a Service), and SaaS (Software as a Service) [41,36]. Depending on the chosen model, management of local or cloud infrastructure may vary, as some layers of an IoT architecture can be managed internally or outsourced. This directly impacts how costs are distributed, allowing flexibility between initial investment, maintenance, and reliance on external providers, thereby enabling the selection of an expense structure according to the technological needs to be implemented in the process. The literature highlights that operating costs are key to managing technologies in smart greenhouses, including maintenance, data storage and processing management, and subscriptions to cloud services and connectivity fees [17]. Additionally, expenses related to ongoing training, software updates, and periodic repairs to keep the system running must be considered.

3.2. Cost mapping

To achieve a clear and consistent cost breakdown, we have integrated and categorized the main elements identified from literature. Accordingly, the Fig. 3 maps and categorizes such key elements, presenting a structured overview of the costs for adopting Industry 4.0 technologies in greenhouses. The diagram brings out the categories and systematizes them, making it easier then to discuss the different cost components and approaches that should be considered in the cost analysis.

3.2.1. Acquisition of hardware

Key hardware acquisition for smart greenhouses represents one of the main investments that undertake the adoption of Industry 4.0 technologies; among them, the basic components include IoT sensors the basis of data collection and some control modules, along with connectivity infrastructure for process automation. This is due to the fact that each of the previously mentioned elements affects cost groups deeply, essentially around CAPEX, the costs of which depend on factors such as the level of sophistication, number of devices to be deployed, multivariable control capacity, and ease of use, among others.

Sensors and control modules are directly related to their ability to collect and process data on variables primarily related to climate, soil, plants, and the environment [2]. The price range varies considerably depending on factors such as precision, durability, reliability, storage capacity, portability, coverage, data processing, connectivity, energy management, data acquisition, and control [19,26,13]. Sensors may be univariate, that is, measure one variable, or some may be multivariate, measuring different variables at one and the same time. The cost also varies according to the type of variable being measured. Sensors for simple variables like temperature are more affordable, while those measuring pH or multiple variables at the same time are more expensive due to their greater complexity. Additionally, more advanced sensors with connectivity features (e.g., Wi-Fi, Bluetooth) and edge computing capabilities tend to increase costs, and integrating them into a larger system often requires investment in gateways, platforms, and cloud services [18]. As they become more sophisticated, they can integrate internal programming logic to issue alerts and make automatic real-time adjustments [59].

On the other hand, control modules can be integrated with preexisting systems, such as HVAC (Heating, Ventilation, and Air Conditioning), irrigation, lighting, and CO2 generators. These modules are available on the market both for controlling individual systems and for managing multiple systems simultaneously and in a coordinated manner. They can be implemented in centralized approaches, where a single controller manages all operations, more economical but with a higher risk of critical failures, or in distributed approaches, which use multiple controllers to offer greater resilience and scalability, though at a higher cost [67]. There are a number of control approaches reported in the literature, specifically: fuzzy logic controllers, PID controllers, genetic algorithms, robust control, and Bayesian networks [3]. These control techniques are applied either remotely in the cloud or at a local level by means of control modules processing data collected by sensors. Microcontrollers or PLCs (Programmable Logic Controllers) make decisions based on the algorithms used, and relays or transistors act as intermediaries, sending signals to actuators that perform the physical actions [21].

Advances in IoT architectures have increased the diversity of communication protocols, with some of the most common being LoRaWAN, Zigbee, WiFi, Bluetooth, NB-IoT, among others [7]. However, in such choices, technical needs are not the only issue; appropriate protocols also need consideration with a view to costs. A series of issues, which include coverage, energy consumption, data rate, reliability, and interoperability between different standards and protocols, need to be considered with a view to the underlying costs of infrastructure, operation, and system maintenance [21,24]. Strategies using local gateways, which filter and process data before sending it to the cloud, are being implemented to optimize bandwidth usage and reduce cloud processing costs. Moreover, the topology that best fits should be considered before the deployment of any network, along with selecting the proper mechanism: wired networks, more stable but with higher installation costs, or wireless networks, more economic and flexible though potentially with coverage limitations [23,67].

3.2.2. Installation and retrofitting

Installation and modernization are important processes that require a clear understanding of the producer's specific challenges and objectives. At this stage, a characterization is necessary to provide diagnostics of the facilities, equipment, and existing structural configurations. This will facilitate the planning of a better deployment strategy, the correct placement of sensors and controllers, and possibly structural modifications. These will help in the distribution of the systems responsible for the creation of a controlled environment, therefore addressing problems associated with the optimal placement of devices in terms of minimum interference and maximum operational efficiency. In initial installations, they are increasingly opting for plug-and-play technologies. These systems, despite their higher initial cost, have gained popularity due to their ease of integration and quick deployment. By reducing the need for specialized personnel and simplifying the installation process, they allow for a smoother and faster start-up. This makes them ideal for those looking to get up and running quickly without the long-term challenges of complex integration [47].

An initial installation often requires modernization of the facilities to take full advantage of the new technologies adopted. This modernization may involve integrating physical control systems, such as heating, ventilation, and lighting, to help manage key internal variables and optimize crop production. This approach, supported by studies such as [72], who propose viable retrofitting combinations to maximize return on investment, emphasizes the importance of balancing initial costs with long-term benefits. Similarly, research by [73] highlights the importance of evaluating different greenhouse designs based on their financial outcomes, considering the integration of heating systems, CO2 enrichment, misting systems, among others.

3.2.3. Integration and customization

Introducing new technologies into greenhouses is an especially important challenge when there is any integration with older technologies, directly related to cost issues. Compatibility costs have often related to hardware and software settings, while in many such cases, it involves even the replacement of the equipment, either due to its becoming obsolete or simply because of the high cost that their integration has made necessary. From this perspective, proposals have been made to achieve integral interoperability through middleware systems, which act as mediators for the communication and integration of data between the different technological platforms [70]. This would also require additional investment for middleware implementation in both technical infrastructures, such as servers and cloud storage, and also for specialized technical support, which would ensure the smooth operation, updating, and maintenance of such systems.

The customization of technologies in greenhouses addresses the need to adapt systems to the specific conditions of each operation, as there is no one-size-fits-all solution. However, this process incurs additional costs, both in hardware configuration and software development, since generic solutions do not meet all specific needs [41]. To mitigate this challenge, the Buy-and-Integrate approach has gained popularity, allowing companies to adopt preconfigured technologies that can then be adjusted to the specific requirements of each greenhouse. This reduces both costs and implementation time compared to full development from scratch [47].

Since most of these technologies also involve sophisticated interfaces, this further requires not only the training of staff on new methods and continuous technical support but also updates to infrastructural setups for operations to be seamlessly and effectively carried out. Besides, investments in data security and access control should not be viewed as an additional cost but rather as part of strategic investment within risk cost planning. Such investments hold the arsenal of safeguarding the operational infrastructure, maintaining information integrity, and making the greenhouse resilient against technological risks [22,1].

3.2.4. Software and services

Costs vary depending on the chosen service model (On-Premise, IaaS, PaaS, or SaaS) due to how management responsibilities are distributed between the company and the provider. In On-Premise, the greenhouse industry assumes everything, from infrastructure down to applications, which implies high CAPEX and OPEX costs because it has to purchase, maintain, and manage all local hardware and software. IaaS reduces CAPEX costs by renting the infrastructure that includes servers, storage, and networks. However, operation, maintenance, and development at the platform, application, and security level are still the responsibility of the enterprise. Meanwhile, PaaS is a ready-to-use platform for creating, deploying, and managing applications without taking any bother about infrastructure. Expenses include platform use, data storage, database queries, the number of users, and application development by the producer. With SaaS, everything falls under the provider's responsibility, as users pay only for the use of the applications, giving them access to fully managed software in return for a subscription, which means less technical flexibility but greater ease of use [74,36].

IThe implementation of IoT platforms has been widely explored in the literature, consistently highlighted as a key technological solution for industries that need connected systems [65]. These platforms make it easier to collect and monitor real-time data from IoT devices, enabling process optimization through predictive and prescriptive analysis [5]. A great example of this is the use of advanced techniques like Big Data and machine learning in smart agriculture, which has shown to significantly improve resource management and boost agricultural productivity [65].

3.2.5. Operational

The investment in smart technologies for greenhouses is not a one-time expense; it is ongoing. The costs of cloud service subscriptions are linked to access to these services, as providers typically charge periodic fees, either monthly or yearly, for using their platforms. These fees can vary depending on the service level, the processing and analysis capabilities required, and the type of subscription. Cloud data storage also generates costs based on the volume of data stored and how frequently it is accessed. Some providers offer free subscription packages, but with limited features and storage capacity [1]. Connectivity fees arise from transferring data between IoT devices and cloud servers, with charges generally based on the volume of data transmitted and bandwidth usage. Furthermore, unforeseen costs can emerge, making the operating budget unpredictable. This uncertainty requires an emergency reserve or the capacity to make rapid adjustments in response to external factors. These aspects must be carefully factored into financial planning and risk management when adopting smart technologies [62].

Investing in training programs for staff and bringing in experts, such as data scientists and specialists, is fundamental. These expenses are ongoing, as continuous education and skill development are necessary to stay aligned with the rapid pace of technological advancements. At the same time, it's important to maintain a thoughtful balance between automation and human expertise. While automated systems can handle many tasks efficiently, the judgment and adaptability that humans bring are invaluable. [75] emphasize this through the concept of human-in-the-loop, where human oversight plays a key role in enhancing both the accuracy and efficiency of AI-powered systems.

3.2.6. Maintenance

One of the main challenges for any maintenance is ensuring system reliability and minimizing downtime. This will require software updates, security, and hardware upgrades to maintain the system's effectiveness and security [65]. The article [72] estimates maintenance and replacement costs by calculating how many times these activities are required during the system's lifespan, considering both equipment replacement and the labor involved. Typically, data security specifications are integrated into a provider's standard services, but the areas of responsibility for implementing and maintaining those security measures largely depend on one of the following service model options: On-Premise, IaaS, PaaS, or SaaS.

4. Discussion

Cost mapping is a tool in structuring cost elements for adoption, from acquisition and installation to operation, of Industry 4.0 technologies in greenhouses. It underlines six main categories: hardware of acquisition, installation and retrofitting, integration and customization, software and services, operational and maintenance, which frame the costing context during the whole technological adoption process. This also highlights the necessity of considering direct costs, as well as indirect costs, that arise as the project progresses in an industrial workflow.

Breaking down costs by category and element provides a dynamic, flexible analytical framework, which may be adjusted for different contexts and technological adoption scenarios. In such detail, each economic component can be changed in accordance with the particular conditions of each greenhouse, including variability in existing infrastructure, production goals, available resources, and levels of desired digitalization, which result in significant differences in technological needs and, therefore, variations in projected costs. The structured approach of the cost mapping facilitates the comparison of scenarios and the consideration of technological alternatives, acting as a mechanism that can help organize cost data to carry out economic feasibility assessments across various technological options. Additionally, it allows for the visualization of a scalable adoption model, which favors the planning of controlled initial investments in basic technological components, with the possibility of progressively expanding toward more advanced systems, optimizing the investment as new production needs or continuous improvements in the system are identified.

The key findings will be presented in light of the financial, technical, and operational challenges brought about by the adoption of Industry 4.0 technologies in greenhouses. We will also mention limitations and indicate where further research is needed.

4.1. Real world data

Real-world information and analysis for the adoption of Industry 4.0 technologies in agriculture remain limited and challenging, as much of the literature lacks detailed quantitative data. This gap complicates thorough assessments and meaningful comparisons of costs, especially for small and medium-sized producers. According to [44], the absence of a standardized approach to the economic evaluation of digital technology adoption limits the comparability of results and restricts a full understanding of its financial impacts. Several studies highlight potential benefits without providing robust cost frameworks, leaving decision-makers without clear guidance on investment strategies. This underscores the necessity for standardization in cost evaluation, which has also been echoed in other sectors of smart agriculture [17,70].

Regional variability further complicates this picture, driven by differences in technology providers, local economic conditions, and labor costs. As noted in studies on IoT adoption [52], technology providers often offer varying pricing models, service levels, and infrastructure requirements, all of which contribute to the complexity of projecting reliable cost estimates. Economic conditions such as energy prices and labor costs, especially in regions where agriculture is highly dependent on external resources, add another layer of variability [24]. This variability requires a case-by-case assessment when considering investment alternatives, as emphasized in techno-economic studies for other high-tech sectors, such as vertical farming [78] and smart irrigation systems [60].

Moreover, different digital technologies, from IoT sensors to AI-driven automation, come with distinct cost structures, requiring specific technical expertise for installation and integration [41,67]. For greenhouse operators, the lack of standardized, comparable cost models leads to significant uncertainty in financial planning, which can hinder broader technology adoption. This heterogeneity, combined with evolving technologies, calls for a concerted effort by researchers and industry stakeholders to develop more unified frameworks for evaluating the economic viability of smart technologies in agriculture.

4.2. Changing costs in time

Other cardinal considerations concern the cost structure, which is dynamic over medium and long-term horizons. The price of hardware tends to decline with time as technology continues to improve with economies of scale [49]. At the same time, software costs can continue to rise as more features and updates are developed [46]. The hardware costs will fall in the medium term, but operators should budget for increased software licensing and subscription fees, plus continuing training and integration costs. In the longer run, maintenance costs could stabilize as systems become more reliable, though periodic upgrades and replacement of obsolete hardware will still be required. This dynamic cost landscape underlines that a dynamic approach in adopting budgets is necessary; financial flexibility should go hand in hand with altered conditions. [78] has shown that economies of scale in the construction of Plant Factories with Artificial Lighting can help reduce unit costs considerably with an increasing scale of production. This finding emphasizes the potential for substantial cost savings in hardware through scaling, reinforcing the importance of planning for both decreasing hardware costs and variable software and operational expenses.

4.3. The role of AI

In the next generation of greenhouses, the role of AI is going to reshape the cost structure significantly. These AI-driven systems will enhance automation, improve the usage of resources, and make better decisions through predictive analytics, climate control automation, and crop health management. In the process of integrating AI technologies, costs can be high initially. However, one of the biggest current challenges is the lack of quality data to train AI/ML models. This shortage of data increases initial costs, as it requires time to accumulate enough information or the implementation of synthetic data generation technologies to overcome this limitation [50].

These are expected to bring significant benefits in resource efficiency and higher crop yields, leading to considerable cost savings [43]. The cost structure is likely to shift toward higher upfront capital expenditure for system implementation and integration, while operational expenses decrease due to greater efficiency and automation. This might be related to higher costs of maintenance also, as these AI systems will have some particular maintenance and updating. On the other hand, these costs are expected to decrease over time, as AI technologies mature and spread more broadly, ultimately making these technologies more affordable for small and medium-sized greenhouse operators.

4.4. Technology intensity

The level of technology applied in greenhouses makes quite a big difference in the degree and structure of the cost elements involved. As technological integration increases and development deepens, costs gradually shift among various aspects. For instance, in low-tech greenhouses, much of the expenditure goes toward raw materials and human labor costs. Their investment is relatively low, although the production cost remains high due to the need for human intervention. Greater automation, on the other hand, leads to much higher initial capital investment for acquiring, integrating, and customizing advanced systems such as automated climate control and sensor networks. In highly technological greenhouses using AI and IoT, initial investments focus on hardware and software acquisition and integration, while labor costs decrease with less human involvement. However, operational costs rise due to software licensing, AI system updates, and staff training. Specialized maintenance costs may be higher initially but tend to stabilize as systems become more reliable and staff gain experience.

4.5. Perspectives and future work

One of the main limitations of this study is the lack of detailed quantitative data related to the cost structures of adopting Industry 4.0 technologies in the agricultural sector. Although the article provides an analysis of the available literature, the absence of specific empirical data prevents a more precise and representative comparison of costs between different technologies and regions. This limitation restricts the study's ability to offer more accurate and generalizable estimates to various scenarios and types of greenhouses. In particular, the specific costs associated with the integration of emerging technologies such as AI and the IoT have not yet been well documented in agricultural contexts.

It is recommended that future research focus on capturing quantitative data related to the costs of adopting IoT and AI technologies in greenhouses across different regions and a wide range of technology providers, in order to build a representative and maybe public dataset. Additionally, it would be valuable for studies to explore detailed regional cost analyses, considering variables such as labor costs, local economic conditions, and price variability among suppliers. Integrating this data with profitability analyses and economic models would contribute to a more comprehensive understanding of the costs and benefits associated with the adoption of smart technologies in agriculture.

5. Conclusion

By integrating Industry 4.0 technologies into greenhouses, there is significant potential for improving operational efficiency and optimizing resource use in controlled-environment agriculture. However, while these technologies offer many benefits, they also come with challenges, particularly regarding implementation costs. This research outlined a detailed cost mapping approach that categorizes and analyzes the financial components of adopting digital technologies in greenhouses. The map highlights six key cost categories: hardware acquisition, installation and modernization, integration and customization, software and services, operational and maintenance costs. This framework addresses both CAPEX and OPEX, offering greenhouse operators a more systematic way to understand and manage financial commitments.

Digital technologies like IoT, AI, and automation systems have made the cost structure in this sector more complex and sophisticated. While they hold the promise of long-term cost savings and production efficiency gains, the initial investments and ongoing operational costs create significant barriers, particularly for small and medium-sized producers. As modernization costs are constantly changing due to technological advances and economies of scale, careful financial planning is required to ensure low-risk investments.

Future research should focus on gathering real-world cost data and developing models to help greenhouse operators make better decisions. Aspects like regional differences, fluctuating hardware and software prices, and the rise of AI will all play a part in determining whether these technologies are economically viable. A deeper understanding of these financial factors will help farmers and other stakeholders make smarter, more strategic choices when it comes to adopting smart farming tech.

CRediT authorship contribution statement

Carolina Vargas: Writing – original draft, Methodology, Investigation, Conceptualization. **Sébastien Gamache:** Supervision, Conceptualization. **Nilson Henao:** Supervision, Conceptualization. **Kodjo Agbossou:** Supervision, Conceptualization. **Shaival Nagarsheth:** Writing – review & editing.

Declaration of competing interest

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

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Data availability

No data was used for the research described in the article.

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