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CONTEXT OF AGRI-FOOD SHORT CHAINS THROUGH AGRICULTURE 4.0: AN APPROACH TO FOOD SECURITY

Nayeli Montalvo-Romero, Aarón Montiel-Rosales, Gregorio Fernández-Lambert, Alberto A. Aguilar-Lasserre

Montalvo, N.



Master in Industrial Engineering.
National Technological of Mexico/
HTI of Misantla. Misantla.
Veracruz-Mexico.

Montiel, A.



Master in Industrial Engineering.
National Technological of Mexico/
HTI of Teziutlan. Teziutlan. Puebla-
Mexico

Fernández, G.



PhD in Logistics and Supply Chain
Management. National
Technological of Mexico/HTI of
Misantla. Misantla. Veracruz-
Mexico

Aguilar, A.



PhD in Process and Environmental
Engineering. National
Technological of Mexico/HT
Orizaba. Orizaba. Veracruz-Mexico

Abstract

Agro-industrial production has seen improvements in agricultural practices, supported by Industry 4.0, with a focus on intensifying agricultural production and post-harvest processes. However, despite the high level of scientific and technological development, the family agri-food system, as a mechanism of self-sufficiency and a driver of socio-economic development, remains stagnant. These unbalanced systems make it difficult to guarantee food security from the agricultural society itself, which is why the Short Agri-Food Chains (SAFCs) are presented as a strategy that contributes to food security and is, at the same time, an enhancer of socioeconomic development from the family nucleus, especially of the most vulnerable rural families. Based on the above, this article identifies technological/smart tools, which have the ability to be adaptable and assimilable in Family Farming, because they are low-cost and have the potential to improve the yield and quality of agro-products. A documented review based on hermeneutics was carried out under a bibliometric analysis, where the I4.0 technologies implemented in the agribusiness sector during the period 2010-2022 reported in SpringerLink, Elsevier's Scopus, and Web of Science, and in the World Intellectual Property Organization were reviewed; the main features of the studies were analyzed and processed, finding that the Internet of Things, Deep Learning, and Digital Twins can be adopted by the SAFCs as a mechanism in the intensification of sustainable food production to ensure food security. These findings lay the groundwork for the development of schemes based on emerging technologies, which can improve the self-sufficiency production system.

CONTEXTO DE LAS CADENAS CORTAS AGROALIMENTARIAS MEDIANTE LA AGRICULTURA 4.0: UN ENFOQUE PARA LA SEGURIDAD ALIMENTARIA

Keywords

Family farming, food, precision
agriculture, short marketing
circuits.

Palabras clave

Agricultura familiar,
alimentación, agricultura de
precisión, circuitos cortos de
comercialización.

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Resumen

La producción agroindustrial ha recibido mejoras de las prácticas agrícolas con soporte en la Industria 4.0, sobre todo centradas en intensificar la producción agrícola y los procesos post-cosecha. Sin embargo, a pesar de existir un alto desarrollo científico-tecnológico, el sistema agroalimentario familiar como mecanismo de autosuficiencia y motor del desarrollo socioeconómico se encuentra estancado. Estos sistemas en desequilibrio complican garantizar la seguridad alimentaria desde la misma sociedad agrícola, por lo que, las Cadenas Cortas Agroalimentarias (CCA) se presentan como una estrategia que contribuye a la seguridad alimentaria y ser, al mismo tiempo, un potenciador del desarrollo socioeconómico desde el núcleo familiar sobre todo de las familias rurales más vulnerables. A partir de lo anterior, el presente artículo identifica las herramientas tecnológicas/inteligentes, que tienen la capacidad de ser adaptables y asimilables en la Agricultura Familiar, por ser de bajo costo y con potencial de mejorar el rendimiento y calidad de los agro-producto. Se realizó una revisión documentada basada en la hermenéutica bajo un análisis bibliométrico, donde se revisaron las tecnologías de la I4.0 implementadas en el sector agroindustrial, durante el periodo 2010-2022 reportadas en SpringerLink, Elsevier's Scopus, y Web of Science, y en la Organización Mundial de la Propiedad Intelectual; los rasgos principales de los estudios se analizaron y procesaron, encontrándose que el Internet de las Cosas, Aprendizaje Profundo, y Gemelos Digitales pueden ser adoptadas por las CCA como mecanismo en la intensificación de una producción sostenible de alimentos para garantizar la seguridad alimentaria. Estos hallazgos sientan las bases para el desarrollo de esquemas basados en tecnologías emergentes, que pueden mejorar el sistema de producción de autosuficiencia.

Introduction

Agri-food systems are responsible for providing the agricultural products that human beings need to acquire the nutrients they require for their development. The production of these foods is highly sensitive because their growth is a function of both the behavior of climatic variables —*e.g.*, temperature, humidity, rainfall, wind speed— and those related to the crop —*e.g.*, soil type, pH, irrigation mode, cultivation practice, fertilizer type—. Therefore, agri-food systems are fragile —highly sensitive to changes— this is attributable to the fact that the agro-product is considered “alive”, *i.e.*, its composition is altered over time. In addition to this, various phenomena such as wars, deforestation, climate change, greenhouse gases, pandemics, among others (FAO et al., 2020), have violated the links of the Agri-Food Supply Chain (AFSC) accentuating hunger (FAO et al., 2021); a situation that becomes complex since, according to the Food and Agriculture Organization (FAO), by 2050 the agricultural sector will have to produce almost 50% more food than it did in 2012 (FAO, 2017). It is a reality that, on a global scale, COVID-19 —as one of these phenomena— has been able to change ways and means of life (Blazy et al., 2021). It is also true that this phenomenon managed to fracture the AFSC (Middendorf et al., 2021); a chain that was already fragile and unstable before the outbreak of SARS-CoV-2. The pandemic that began in 2019 contrasted that the global agri-food system was not prepared to face situations that

required the AFSC to be able to respond to the high need for healthy and quality food during the most critical stage of the pandemic.

The industrial AFSC in charge of intensified food production showed a limited capacity to cope with the demands of the world market, evidencing its fragility (Béné et al., 2021; Boyacı-Gündüz et al., 2021; Marchant-Forde & Boyle, 2020; Place et al., 2022; Pu & Zhong, 2020; Raja, 2020; Stoian et al., 2021). The agri-food long chain is made up of various interconnected links, from cultivation to offering in fixed points of sale —*e.g.*, supermarkets—. Therefore, as it is made up of multiple links, the length and time of availability of products for marketing behave exponentially.

However, it is considered that the isolation and confinement restrictions complicated the availability of labor in the crops, causing the supply of inputs and materials to decrease. In some cases, it was completely reduced.

On the other hand, the communication restrictions associated with the closure of borders only complicated the availability of food, a situation that has worsened in those countries that are food-dependent, *i.e.*, nations that need to supply the needs of their citizens need to import quantities of raw materials and food products, because national food production is insufficient. This is an effect of inequality in food production and trade (Xu, 2019).

Food dependence makes consumers vulnerable to external shocks in food availability (van Berkum,

2022), which accentuates food insecurity (Luo et al., 2022; Marrero & Mattei, 2022). These situations led to an increase in the price of the few foods available. Faced with this situation and as a response to the demand of a market to be supplied with healthy and quality food accessible promptly, the Short Agri-Food Chains (SAFC) are presented as an alternative model capable of responding to a market in need of food by helping to guarantee food security (Roubík et al., 2022; Tittonell et al., 2021).

The SAFCs developed from Family Farming (FF), despite not being a new agri-food system, represent a strategy capable of responding to complex situations (CEPAL et al., 2015; Matei et al., 2017; Oliveira et al., 2021; Tittonell et al., 2021), where their main strength related to the proximity between the producer and the consumer is minimal or non-existent (García et al., 2017), and the producer generally offers his products in local markets. The FF is the most widespread type of agriculture in both developed and emerging countries (FAO, 2018). According to the FAO, FF is:

A way of organizing agriculture, livestock, forestry, fishing, aquaculture, and pastoralism, which is managed and operated by a family, and, above all, which depends preponderantly on family work, both women and men. The family and farm are linked, coevolve, and combine economic, environmental, social, and cultural functions (FAO, 2014, pp. 26).

In addition, in the producer-consumer scheme, a bond of trust is generated between the supplier and

the customer through a direct relationship in the transaction. FF agents represent change to achieve Zero Hunger (FAO, 2021).

The main goal of FF is to satisfy the complement of the family's diet and, secondly to generate an income from the commercialization of surpluses (FAO, 2013). Family farmers can build inclusive, sustainable, resilient, and efficient agri-food systems (Blondeau & Korzenszky, 2022). Therefore, the maximum yield of agricultural exploitation is desirable by the FF producers since they represent a great strength for sustaining this group of economies. However, as they are developed fundamentally from the FF, they significantly lack the technological support that allows them to increase crop yields and, consequently, improve their positioning and economic income. This is generally attributed to the lack of economic resources to invest in technology, coupled with technological disarticulation, mainly in the elderly who today are still alien to the use of technology. This situation is lower in intensified agro-industrial production since agro-production at the macro level is accompanied by infrastructure for adopting cutting-edge technology.

Therefore, based on the experiences of the pandemic on SAFCs, it has been shown that (i) long industrialized chains are fragile in atypical situations, lacking the capacity to meet people's food needs promptly, and that in such a situation, (ii) the SAFCs from the FF was presented as an alternative that, due to their characteristics of proximity and

prompt response, proved to be a mechanism for food supply. However, the latter system, being developed empirically, lacks an efficient resource management scheme that allows their maximum use, so, given this reality, the practices of small agro-producers who carry out FF must adopt emerging technologies with greater depth that allow to assist them in maximizing their performance, and thus establish resilient and efficient SAFCs. Finally, the complementation of AFSCs —industrial and SAFC from the FF— in the face of atypical and non-atypical situations presents a comprehensive scheme that guarantees food security for future generations.

Based on the above, the objective of this study is to identify the main technologies that have been used in some AFSC links through a text interpretation process based on hermeneutics, with a descriptive, non-experimental analysis of documents retrieved during the period 2010-2022, to know the feasibility of adopting emerging technologies in the SAFC from the FF, because many of the technologies are limited for small agricultural producers. Despite this, the openness in the use of technology by the new generations is an advantage to be considered as a driver of this technological trend in such a way that it is possible to pay for food safety from the AF model with the support of technology developed from the I4.0.

This study is carried out to find out which technologies are documented in SpringerLink, Elsevier's Scopus, and Web of Science, and in the World Intellectual Property Organization, which are

considered as repositories of scientific products and patents, respectively of high quality. These technologies are identified to know which ones exist and have been successfully applied in sectors such as agro-industrial, intensive agro-production, technological developments from academic and research centers, and governmental and non-governmental entities, and that have the capacity to be adopted and adapted by Family Farming, from the Short Agri-Food Chains to improve the yield and availability of agri-food for self-consumption and sale of surpluses, in marginalized areas as a mechanism of self-sufficiency. For this, the research variables consider: the geographical distribution of the studies, the technologies in the SAFCs, the applications according to the logistics link, and the technological/intelligent tools. These variables are systematically analyzed, and the documents under study are characterized by bibliometric analysis to know the common characteristics among the studies collected.

Methodology

This document is an exploratory, descriptive, non-experimental longitudinal, quantitative study based on hermeneutics as a technique for analyzing and interpreting documents. The review covered the period 2010-2022. SpringerLink, Elsevier's Scopus, and Web of Science were the databases. In this exploration, only research articles in the English language were considered. The search by discipline and subdiscipline was not discriminated against. Irrelevant studies were discriminated that, although

they report the use of cutting-edge technology, this is of good results in intensive and complex production to assimilate on a small scale. The following search words were used: “technology” + “industry 4.0” + “agribusiness” + “prospecting” + “food security” + “sustainability”. Articles were selected for relevance. In addition, a search was carried out by the World Intellectual Property Organization (WIPO) to identify patented technological developments with the search term “agriculture 4.0”.

The studies will be managed in Mendeley Cite v1.67.0; while the traits of the studies will be stored in a knowledge management base, using Microsoft® Excel® for Microsoft 365 MSO (version 2504 build 16.0.18730.20186) of 64 bits. From the database, the information will be tabulated, and graphed considering: the geographical distribution of the studies, the technologies in the SAFCs, the applications according to the logistics link, and the technological/intelligent tools.

Results and discussion

The search in scientific databases, according to the established parameters, yielded 833 studies: 95 from SpringerLink, 488 from Elsevier's Scopus and 250 from Web of Science. Of these, 805 were discarded as irrelevant to the inclusion criteria—studies of language other than English, review studies, studies where the technology is of high cost and technical complexity for adoption, and technologies that are specific to a single crop and

that there is complexity to be transferred to other crops—for the object of study were excluded. Considering 4, 14, and 10 studies on these bases. On the other hand, from WIPO's patent database, 239 patents were retrieved, of which four were considered for this study due to their relevance—patents other than the English language were excluded, and technological developments of high complexity and significant cost—.

The identification of the technological/smart tools feasible to be adopted and adapted by the FF from the SAFCs, are proposed as tools that can be transferred and scalable to the contexts of the self-sufficiency agricultural production system. These technologies assimilated in an appropriate way will improve the quantity and quality of the agro-products that families grow to complement their diet and where the surpluses can be marketed to generate an economic income; therefore, these technologies contribute to guaranteeing food security, at the same time that they are an engine for the technological development of people who practice Family Farming.

Study Distribution

Table 1 shows the distribution of studies by continent from 2010-2022. In Africa, 6.25% of the studies were recovered, 21.88% in America, in Asia, 28.13% and 43.75% of the studies recovered were reported in Europe. Figure 1 presents the distribution of the 32 retrieved studies by country. India has the highest number of contributions

focused on the development of technologies to increase the efficiency of the agri-food industry's logistics chain performance. It has adopted Industry 4.0 approaches, representing 25% of the studies identified in this exploration.

Figure 2 shows the behavior of the studies during the period 2010-2022.

Table 1.

Studies by continent.

Continent	Studies
Africa	(Balabathina et al., 2020; Dahane et al., 2022)
America	(Badgujar et al., 2022; Calçada et al., 2019; Chehri et al., 2020; de Souza Rocha Junior et al., 2022; Hu et al., 2015; Miranda et al., 2019; Terra et al., 2021)
Asia	(Balamurugan et al., 2021; Kumar et al., 2021; Nakkella et al., 2020; Patel et al., 2022; K. Paul et al., 2022; Sundara et al., 2022; Shyni & Sundar, 2022; Van et al., 2022; Vij et al., 2020)
Europe	(Alonso et al., 2020; Alves et al., 2020; Biglia et al., 2022; Daum et al., 2022; Garre et al., 2020; Heiß et al., 2020; Kneip et al., 2020; Melesse et al., 2022; Monteiro et al., 2022; Pascual et al., 2018; Pradel et al., 2022; Román et al., 2022; Skrzypczak et al., 2022; Verderame et al., 2020)

Source: own elaboration (2025).

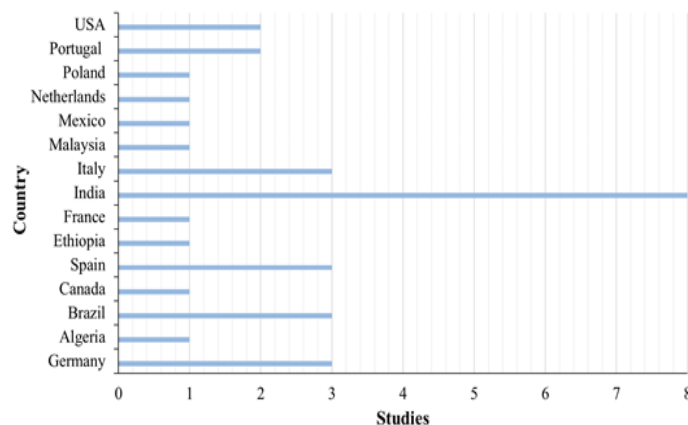
Technologies Used in SAFCs

Table 2 describes the studies by support activity that the scientific-technological community developed and reported during the search period.

Five influencing activities were identified, with 62.5% of studies focused on production contributing to a greater extent. These studies' efforts have had an impact on increasing the efficiency of link activities.

Figure 1.

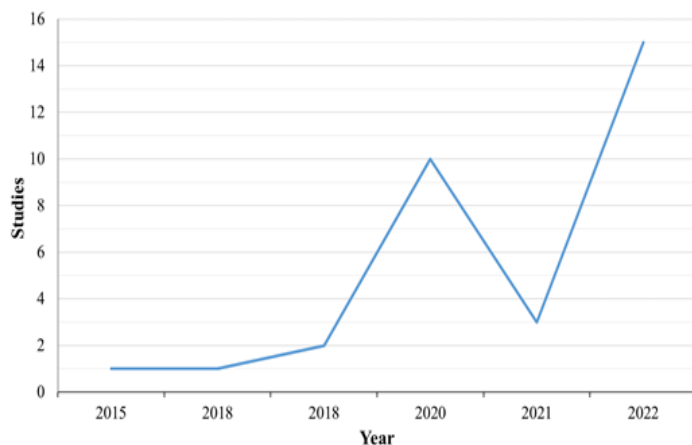
Contribution of I4.0 studies by countries that pay to the SAFC.



Source: own elaboration (2025).

Figure 2.

Studies 2010-2022.



Source: own elaboration (2025).

Table 2.

Studies by support activity.

Links	Application	Studies
Production	<i>e.g.</i> , soil erosion monitoring, pesticide optimization, agricultural practices, waste processing, fertilizer	(Alonso et al., 2020; Alves et al., 2020; Badgujar et al., 2022; Balabathina et al., 2020; Calçada et al., 2019; Dahane et al., 2022; Garre et al., 2020; Heiß et al., 2020; Hu et al., 2015; Kneip et al., 2020; Patel et al., 2022; Paul et al., 2022; Pradel et al., 2022; Román et al., 2022; Shyni & Sundar, 2022; Skrzypczak et al., 2022; Terra et al., 2021; Van et al., 2022; Verderame et al., 2020; Vij et al., 2020)
Infrastructure	<i>e.g.</i> , farm structures, agricultural robots, smart greenhouses, digital tools	(Biglia et al., 2022; Chehri et al., 2020; Daum et al., 2022; de Souza Rocha Junior et al., 2022; Kumar et al., 2021; Miranda et al., 2019; Monteiro et al., 2022; Nakkella et al., 2020)
Transport	<i>e.g.</i> , storage, traceability, crop monitoring	(Balamurugan et al., 2021; de Souza Rocha Junior et al., 2022; Melesse et al., 2022)
Product	<i>e.g.</i> , sensory analysis	(Pascual et al., 2018)
Integral	the entire logistics chain	(Sundara et al., 2022)

Source: own elaboration (2025).

It was identified that 14% of the studies are related to the livestock-poultry sector, while the complement focuses on contributions to the agricultural sector.

Figure 3 shows the co-occurrence map based on bibliographic data from the studies. Keywords were analyzed, omitting the structure of abstracts and copyright statements. The complete count method was used. The analysis identified ten relevant items and divided them into three clusters: the Internet of Things, Machine Learning, Smart Agriculture, and Artificial Intelligence.

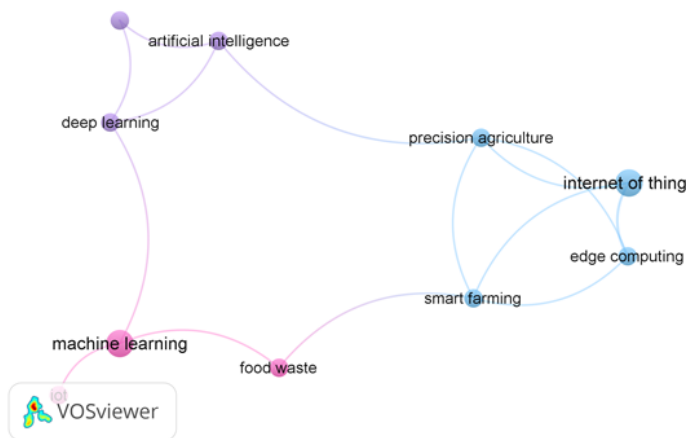
Technological/Smart Tools

The approaches that allow for improving the yield of the agro-product are derived from the implementation of various tools. However, since the agro-product is a “living being”, it requires permanent care and monitoring.

The agro-product is exposed to changes in climatological and crop parameters, and any alteration outside the tolerance parameters will affect the agro-product's performance. This potential health risk justifies its monitoring and traceability.

Figure 3.

Co-occurrence map.



Source: own elaboration (2025).

In this regard, Table 3 presents the retrieved studies by distinguishing them by type of technological tool. From this analysis, it can be deduced that the scientific-technological community has met the need for monitoring and control by using the Internet of Things, the preferred technology either individually or combined with other technologies. In this study, 37.5% of the studies report using this tool as part of the technology to achieve sustainability. Therefore, studies show a positive impact on the adoption/assimilation of technological approaches that improve agro-productive systems.

The findings of this study reflect the concern of the scientific-technological community and of the intensive agri-food industry itself to develop contributions that improve crop-breeding practices, the use of available resources, and the reduction of waste throughout the logistics chain, among other post-harvest efforts.

While it is true that these efforts have been proposed primarily for use in developing economies, there is a need to transfer this technology to FF. The rapid spread of the technology and its easy use by the new generations will allow the assimilation of this technology as a tool to support agro-industrial decision-making to increase the yield of agricultural products in the FF, thus making its resources more efficient with two basic objectives: the first is to contribute to a strategy of self-consumption, and second, to promote economic income from surplus crops.

Table 3.

Studies by Tool

Technological/ Smart Tools	Studies
Robotic System	(Pradel et al., 2022; Terra et al., 2021)
Deep Learning	(Alves et al., 2020; Kumar et al., 2021)
Digital Cufflinks	(Melesse et al., 2022; Monteiro et al., 2022)
IoT	(Alonso et al., 2020; Balamurugan et al., 2021; Chehri et al., 2020; Dahane et al., 2022; de Souza Rocha Junior et al., 2022; Miranda et al., 2019; Nakkella et al., 2020; Patel et al., 2022; K. Paul et al., 2022; Van et al., 2022; Verderame et al., 2020; Vij et al., 2020)
Remote Sensing	(Balabathina et al., 2020; Biglia et al., 2022; Hu et al., 2015)
Machine Learning	(Garre et al., 2020; Melesse et al., 2022; Vij et al., 2020)
Neural Networks	(Alves et al., 2020; Badgujar et al., 2022; S. et al., 2022)
Expert System	(Román et al., 2022)
Fuzzy System	(Heiß et al., 2020)
Other	(Calçada et al., 2019; Daum et al., 2022; Kneip et al., 2020; Pascual et al., 2018; Shyni & Sundar, 2022; Skrzypczak et al., 2022)

Source: own elaboration (2025).

Technological/smart technologies have the potential to contribute to improving the yield and quality of the agro-product, because the technologies identified in this study are low-cost and easy to scale. Properly installed and in operation, they would allow monitoring and control of agricultural parameters, would support the management of resources and would allow them to be a support tool in agricultural production decisions in marginalized areas; however, it is important to consider that achieving this requires the necessary infrastructure for the operation of systems that require connection between devices, as well as an induction for users to use these tools, with greater emphasis on limited areas in infrastructure and communication.

However, the technologies identified could contribute to: Robotic System: automating or semi-automating processes, using mechanical and electronic systems; Deep Learning: assist in the decision-making process, from the determination of behavioural patterns; Digital Cufflinks: support the decision-making process, from the generation and evaluation of decision alternatives, considering the simulation, analysis and optimization of the agricultural parameters of interest; IoT: knowing the status of the systems, from the connection and communication between physical devices through the internet; Remote Sensing: acquisition of information from a physical element without being in the presence of it; Machine Learning: create mathematical models, to predict new values from

historical data, and that improve their performance with experience; Neural Networks: determining behavior patterns; Expert System: decision support systems that consider the knowledge of people who are experts in specific areas; Fuzzy System: decision support systems that model the subjectivity of variables of interest; and, Other: those technologies that make it possible to attend the decisive event and reduce uncertainty.

The effective linkage in a triple helix model, government-family-academia, will allow the FF to assimilate Industry 4.0 technologies, thereby strengthening the Short Agri-Food Chains. The joint efforts between these actors will allow the technologies developed at the macro level to be restructured and molded to the needs and skills of small agro-producers. In contrast, the new generations with access, as a way of life, to digital technologies will facilitate the adoption of the benefits of I4.0 in small farms. Assimilation and adoption by FF present great challenges, perhaps the most challenging being to break the ideological barrier of ignorance in the use and existence of Industry 4.0 technologies. that allows the evolution of the family business model. Therefore, adopting and assimilating I4.0 technology in the FF integrated into the SAFCs will contribute to developing a resilient and inclusive agri-food system. Finally, this evolution will provide a solid agri-food system capable of facing the agri-food needs of humanity in a sustainable way from the organic production of food in an intelligent way.

The pandemic caused by the SARS-CoV-2 coronavirus, which led to the COVID-19 disease, as an atypical phenomenon, marked a before and after in the development of humanity. At the end of December 2019 in Wuhan, China, the first cases of COVID-19 were reported. The arrival of this pandemic showed that humanity, until that moment, could not face the effects of a global health crisis. This situation highlighted the need for innovative solutions supported by technology, coinciding with what was cited by (Balasubramanian et al., 2023). Humanity needed to isolate itself and carry out its activities remotely to minimize or avoid being infected by the virus. Unfortunately, not all productive activities can be transferred from face-to-face to digitalization, making exposed people more vulnerable.

The lockdown accelerated the development of technologies in different sectors —e.g., education, industry, communications, e-commerce processes increased— coinciding with (Yao et al., 2024), in which COVID-19 has accelerated the adoption of digital technologies, particularly in remote work, e-commerce, and automation. In this sense, we agree with (Hussain et al., 2024), that the pandemic accelerated online activities. Faced with the need for a humanity that had to continue its productive activities and socio-economic development to survive. Not only humanity but also productive entities were forced to migrate from traditional systems to technological systems, mainly in small and medium-sized enterprises, as mentioned in

(Avalos et al., 2024; Cong et al., 2024; Mishrif & Khan, 2023). In view of this, we agree with (Grijalba et al., 2024; Holl & Rama, 2024; Shen & Zhang, 2024), that as a result of the pandemic, the digital economy has grown rapidly. However, those companies that limited themselves to not transcending towards digitalization have lagged, a situation that has increased the gap between them and the companies that digitized in response to the pandemic, as mentioned in (Avalos et al., 2024). Therefore, we agree with (Butollo et al., 2023; Molleví Bortoló et al., 2023; Okunlola et al., 2024), that the COVID-19 pandemic accelerated digital transformation through I4.0.

One of the main sectors that did not stop was food agro-production. It is agreed with (Zambrano et al., 2024) that COVID-19 caused various impacts and responses in agricultural value chains worldwide. This sector, by its nature, could not be stopped because, in doing so, it compromised the availability of food necessary for the achievement of life. It is agreed with (Paranitharan et al., 2022) that I4.0 is useful for agriculture during the COVID-19 pandemic. However, it is important to distinguish between industrial food production and agricultural production developed by small farmers in its simplest form, Family Farming, which provides about 80% of the food consumed in the world (FAO, 2018) through the Short Agri-Food Chains. This study has shown that technological development is aligned with I4.0 in the agro-production sector of food. In Short, Agri-Food

Chains were scarce before the pandemic. While it is true that there were interesting applications, it was during the height of the pandemic that the development of technologies was enhanced. COVID-19 encouraged the need to improve the agri-food production and disposal system due to the proximity to consumers—in the context of the pandemic, long chains were insufficient and unable to promptly meet the demand for an agro-product—. This situation prompted the development of agro-products in short chains.

In this context, the study results show that before the COVID-19 pandemic, the reported applications were scarce—four studies were identified, one in 2015 and another in 2018, while in 2019, two studies were identified—. During the pandemic and given the need to provide food to meet nutrient requirements, ten studies were developed in 2020.

These studies showed the need to meet agri-food requirements through short chains because a quick acquisition by proximity was required. After the most extreme complications of the pandemic, and when deaths and concerns began to decrease due to the development and application of vaccines, three studies were identified in 2021. Finally, this study shows that with social stability, it was noted that technological contributions focused on improving the performance of short agri-food chains have increased, as identified in 2022 with 15 technological contributions. These results coincide with what was reported in (Alanzi & Ratten, 2023),

because technology made it possible to face the negative consequences of COVID-19. The agricultural industry benefits from the advantages of I4.0. The results of this study coincide with those reported by (Costa et al., 2023), with drones, IoT sensors, cloud storage, and Big Data being the most beneficial technologies for the agricultural industry. These technologies are promising in solving agricultural problems while at the same time contributing to ensuring the sustainability of agriculture and the food supply chain, as mentioned (Karmaker et al., 2023; Senturk et al., 2023). However, it is (a) lack of information about technology and (b) lack of compatibility with compatibility methods that are the main obstacles to technology adoption in agriculture, as cited by (Chanchaichujit et al., 2024).

Technological evolution has shown the feasibility of replacing work through digitalization and automation by improving working conditions due to the use of technology in heavy activities, thus promoting flexibility, as mentioned in (Mat Aripin & Brougham, 2024). The findings of this study show an increase in the advancement of technology that improves the efficiency of short agri-food chains supported by family farming.

As mentioned, the agro-production of food by small farmers is of utmost importance, as they provide about 80% of the food consumed worldwide. It is agreed with (Konfo et al., 2023; Yap & Al-Mutairi, 2024), that digital technologies

improve efficiency and sustainability in agri-food processing, contributing to achieving food safety and quality control. This study has shown that the pandemic, despite being a phenomenon that unfortunately wreaked havoc in various social sectors, potentiated technology development. In view of this, it is agreed with (Paul et al., 2024), that the various technological tools are prepared to drive the pace of digital transformation. Finally, it is agreed with (Mahmood et al., 2024), technology use in modern agriculture will increase food productivity, thus contributing to ensuring food security.

Conclusions

This study has identified the main emerging technologies that some SAFCs have used during the period 2010-2022, which the FF can adapt to efficiently develop AFCs driven by smallholder farmers. The assimilation and adoption of technology from I4.0 according to the productive capacity of the FF has proven to be a strategy that boosts agricultural production. I4.0 in the SAFC links is capable of increasing the efficiency and yield of agro-products, improving (i) the production of food for self-consumption and (ii) economic income from the sale of surpluses for the producing family; at the same time, (iii) it contributes to guaranteeing the food safety of consumers by acquiring agro-products in local markets in a “fast” way due to the proximity between producer and consumer —compared to long agri-food supply

chains—. The development of intelligent production systems in the FF and integration into the SAFCs, as an agri-food business model from the technologies developed and reviewed in this study, is feasible.

The emerging technologies derived from I4.0, implemented and adapted to the SAFCs, have the potential to support technologies in the process of monitoring and control of cultivation conditions since they allow the value of the variables to be known in real-time and from the parameters required by the crop, it is possible to supply the necessary components —e.g., water resources, nutrients—. Advances in emerging technologies represent a strategy capable of supporting the FF to improve the quality and yield of crops for self-consumption, thus contributing to self-sufficiency and marketing practices, reinforcing the knowledge they have from past generations.

In this sense, I4.0 technologies applied to agriculture have made their way through the results obtained from the emerging technologies identified in this study: robotic systems, deep learning, digital twins, IoT, remote sensing, machine learning, neural networks, expert systems, fuzzy system, among others; either in specific sectors of the logistics chain or in all of them integrally; e.g., in the evaluation of the quality of the product, sensory analysis studies are derived in the control of agroclimatic conditions in protected agriculture, intelligent greenhouses have been developed. These

contributions, assimilated and adapted to the context and reality of the rural agro-producers who are members of the FF, have the potential to assist them in the care and cultivation of agri-food, allowing them to increase the availability of food for self-consumption, which contributes to guarantee the food security of a growing population in the face of a complex scenario full of uncertainties; at the same time, in which greater performance is possible for greater and rapid socio-economic development of the family than to practice the SAFC's from the FF.

The SAFCs, as a model of AFSC, can supply food requirements in local markets promptly, even in atypical situations. Unlike long industrial AFSCs, which can supply large volumes of food, in uncertain scenarios, the supply time is considerably extended, even jeopardizing the achievement of food security. However, the SAFCs, being a model of prompt response, is a scheme that requires proximity between its links; therefore, its integral development from the FF is proposed as a hybrid strategy that allows providing healthy and quality food in a short time by being specialized in marketing in fixed and semi-fixed points, *e.g.*, markets, "tianguis", street vending.

So, the SAFCs from the FF, as an AFSC model, is a scheme that, in the face of uncertain scenarios and fluctuations in atypical phenomena, *e.g.*, pandemics, wars, natural disasters, food dependence, are presented as an alternative capable of contributing to guaranteeing food security, being

a "safe" food supply scheme that contributes to guaranteeing food security. However, for this scheme to represent the achievement of this "food security", its consolidation becomes necessary since there is still a technological gap towards the digitalization of FF, which allows the use of emerging tools of I4.0 to make agro-productive processes more efficient in the face of a future scenario of uncertain food demand, changes in food preferences, and the occurrence of atypical events. Given this need, the robustness and resilience of this model must be addressed through the adoption and assimilation of the emerging technology of I4.0, which, according to the reality of each small agro-producer, must be considered.

Therefore, the digitalization/technification of the SAFCs promoted by the actors of the FF will allow a consolidated AFSC to be achieved along the links of the SAFCs. However, from the study, it is derived that the IoT, as an emerging technology, is presented as a technological tool of high potential that allows the monitoring of the development of the agro-product; therefore, it is advisable to start with the adoption of this technology and strengthen it according to the needs and opportunities of the context of the PA actors towards the SAFCs.

The road is long but clear; digitizing/technifying the SAFCs from the FF and that AFSC complements the industrial AFSC is the scenario to be built in such a way that it is possible to reduce the risk of not being able to supply food to people in

the face of the uncertainty of uncontrollable and uncertain phenomena. Both models, working in a hybrid and comprehensive way, will guarantee food security in the short-, medium-, and long term.

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