agriculture

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Technological Capabilities for the Adoption of New Technologies in the Agri-Food Sector of Mexico

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Abstract: Agriculture 4.0 and 5.0 generate good expectations of satisfying the growing demand for food in a sustainable way. However, in order to make effective use of scientific and technological developments, infrastructure, knowledge, experience and skills are required. In this sense, the objective of this research was to analyze the technological capacity of the Mexican agri-food sector for the adoption of new technologies. The documentary research method was used, and the information was obtained from the Encuesta Nacional Agropecuaria, the Instituto Nacional de Estadística y Geografía and the Instituto Mexicano para la Competitividad. A cluster analysis was performed to generate a typology of states, in addition to an analysis of variance with the Kruskal–Wallis H Test for independent samples, for which the IBM® SPSS Statistics program was used. The variables analyzed presented very low values, indicating low technological capabilities. Three clusters of states with different technological capabilities were identified. The first was formed of four states in the north of the country with high technological capabilities, for which it was expected that they would have higher adoption rates. Next, there was a group made up of ten states in the north and center of the country with intermediate technological capabilities. Finally, there was a group of 18 states of the country made up of states from the center and south of the country, which present the lowest levels. The results indicate that the technological capacities for the adoption of new technologies in the Mexican agri-food sector are low in general, and are concentrated in some highly specialized regions linked to international markets.

Keywords: smart agriculture; technological change; science and technology; innovation; sustainability

Citation: Vargas-Canales, J.M. Technological Capabilities for the Adoption of New Technologies in the Agri-Food Sector of Mexico. *Agriculture* **2023**, *13*, 1177. https://doi.org/10.3390/agriculture13061177

Academic Editors: Kurt A. Rosentrater, Darija Lemić, Klaudija Carović-Stanko, Kristina Kljak, Jernej Jakše, Arup Kumar Goswami, Craig Sturrock and Efstratios Loizou

Received: 25 April 2023
Revised: 24 May 2023
Accepted: 29 May 2023
Published: 31 May 2023

1. Introduction

At present, society faces very complex problems derived mainly from the dominant economic development model, which affect us more and more and are more frequent [1]. This situation has its origins in the 20th century, which was characterized as a period of unprecedented economic expansion and was seen as the natural state of things, in which population growth was not conceived as a problem [2]. Global demographic trends such as population growth and aging, poverty, migration and urbanization have important implications for economic development and for the environment [3]. Consequently, it is estimated that the demand for food will increase by more than 60% by 2050, and this will exert great pressure on agri-food systems [4].

Gradually, a greater awareness of the constant crises caused by environmental, economic, social and health problems has developed. Currently, there is a certain consensus among the world scientific community that the current development model could lead to an environmental catastrophe in the long term [5]. Faced with these global problems, it is necessary to develop new forms of organization and economic integration. That is to say, a profound reconfiguration of all our economic, technological, political, social and environmental relations is required, especially of the productive systems and specifically the agri-food system.

The agri-food sector has historically experienced a series of scientific and technological revolutions that have allowed it to increase productivity, efficiency, performance, and profitability to levels never before imagined [6]. Currently, it is proposed that a digital agricultural revolution will be the change that could help ensure that agriculture meets the needs of the world population [7]. In the agri-food sector, science and technology have been adopted, adapted and developed very successfully and have managed to minimize, and in some cases eliminate, the effect of factors related to environmental conditions and resource endowment [8]. New technologies have recently emerged that have been developed in other sectors and have adapted very well to the agri-food sector; for example, the use of sensors to monitor crops, drones to carry out some monitoring activities and the application of agrochemicals, and robots to carry out activities that put the health of man at risk [9–11].

The use of digital technologies is transforming all the processes, products, and services of the agri-food systems. Their use improves efficiency and facilitates agri-food management, which increases productivity, effectiveness, profitability and the conservation of natural resources [12–14]. The positive and negative effects of new technologies have been discussed, although not enough; however, there is no doubt that the benefits are much greater in all segments of the value chain [15,16]. Consequently, digital agriculture has received considerable attention for policies in recent years, mainly aimed at complying with the principles of sustainable development, such as biodiversity conservation, waste management, soil protection and human health [17]. In addition, it is believed that the further development of the application and data transfer infrastructures and their integration into all sectors will play a crucial role in the future [18].

It is important to mention that not all countries and sectors innovate in the same way, nor do they have the infrastructures and social consensus to generate trust and information for people and organizations to manage digital technologies [19]. For example, the northern region of Mexico from its origin emerged as a highly technical agriculture and this has allowed a greater and better integration of agri-food chains. In the case of the central western region of the country, the production systems have also been modernized. The center of the country has maintained less dynamism, and in the case of the south, until a few years ago it was not characterized as an agri-food producer. In addition, from the research, no information has been generated on the consequences of heterogeneity and asymmetries between countries, sectors, regions and actors, and there is a lack of adequate measurement and evaluation instruments [20]. The foregoing is relevant because business strategies, processes, technologies, final products, relationships with suppliers and customers are conditioned by the new technological complexity [19] and the diffusion and adoption of digital technologies in society and in production systems introduce a disruptive change to the entire economic system.

Despite the benefits, the adoption rates of technologies such as smart agriculture are not uniform across countries [12]. However, the reality indicates that all countries, companies and markets are being affected by the digital transformation and more so as a result of the health emergency created by COVID-19, which forced the entire world into confinement and to adopt the use of digital tools [6]. In addition, it originated the emergence of four trends in the food sector: food innocuousness, food production with bioactive compounds, food safety and sustainability [21]. The production of functional foods enriched with bioactive compounds and antioxidants that promote health and support the immune system is necessary [22,23]. The foregoing generated changes in the usual forms of organization of production, distribution and consumption and transformed the generation, transmission and use of knowledge, the forms of recreation and leisure and, on a personal level, the ways of relating to each other and even the perception of reality [24]. Consequently, all agri-food systems are undergoing transformation to respond to the new demands of consumers.

This new dynamic is characterized by the application of digital technologies in all phases of the production process. They are not reduced only to the field of production, but rather have implications in all aspects of life, since their use enables a more complex economy based on the massive use of data and information [19]. The Mexican agri-food sector has experienced, since before the green revolution, good scientific and technological development [8]. The Mexican agricultural, livestock and fishing activity in 2020 and 2021, despite the social distancing measures, has maintained a constant growth [25]. Undoubtedly, agriculture 4.0 and 5.0 have generated good expectations about the possibilities of satisfying the demand for food. However, in order to make effective use of scientific and technological developments, infrastructure, knowledge, experience and skills are required. In other words, it is necessary to have a certain technological capacity and the necessary resources to generate and manage this dynamism [26]. In this sense, promoting the knowledge and skills necessary for companies to choose, install, operate, maintain, adapt, improve and develop technologies is a vital strategy [27].

Technological capacity is generally considered as an essential catalyst to improve the innovation, competitiveness, and performance of enterprises [28]. It is convenient to mention that the term capacities has been defined as the strengths or resources available to a community, which allow it to lay the foundations for its development as well as face a disaster [29]. Another approach to its conceptualization is the so-called freedom approach, which presents freedom understood as capacity as a basic value. The concept of capacity expresses the real freedom that a person must have to achieve what he intends to obtain [30]. The previous definitions are very general, and in the case of technological capacities they focus specifically on acquiring, using, absorbing, adapting, improving and generating new technologies [26].

The concept of technological capabilities has been in constant change, transformation and evolution since its origin. It was transformed from a phenomenon of static to dynamic analysis by incorporating different concepts. Added to the natural evolution of the concept, various ways of measuring technological capabilities have been proposed and it has been emphasized that the processes of technological accumulation come fundamentally from scientific and technological development [31]. To achieve continuous growth and competitiveness, countries, sectors and companies must accumulate knowledge to develop technological capabilities [32]. In this case, and with the vision of this investigation, technological capabilities are understood as the knowledge, experience, skills and infrastructure available to make effective use of science and technology and to generate innovation [1]. In various fields of scientific literature, emphasis has been placed on the role of productive and technological capacities as important drivers of exports, growth and development [33].

Currently, the technological capacities of a company, sector, region, or country are essential to adapt to the increasingly constant changes and transformations in the world economy. Studies on technological capabilities began in the early 1980s, and since then an extensive literature has flourished that recognizes their importance for technological and economic development [34,35]. However, there is an insufficient number of studies on the mediating role of technological capacity in this relationship [36]. In addition, it is believed that an oligopolistic concentration of infrastructure, information and knowledge about new technologies has naturally occurred [37].

The Mexican agri-food sector is divided into five regions, according to their productive vocation, in order to take advantage of the potential of their land, water and labor force (Figure 1) [38]. However, Jalisco, Veracruz, Oaxaca, Chihuahua and Sinaloa concentrate the largest agricultural production. These entities together produce one hundred and fourteen million, twenty-four thousand, nine hundred and fifty-four tons of agricultural products in a total of six million, five hundred and twelve thousand, six hundred and twenty-six hectares that are planted and harvested in the different crop cycles [39]. This suggests that the development of the Mexican agri-food sector is very heterogeneous, agricultural production is concentrated in specific areas, and there is no clarity about the technological capabilities of each region.

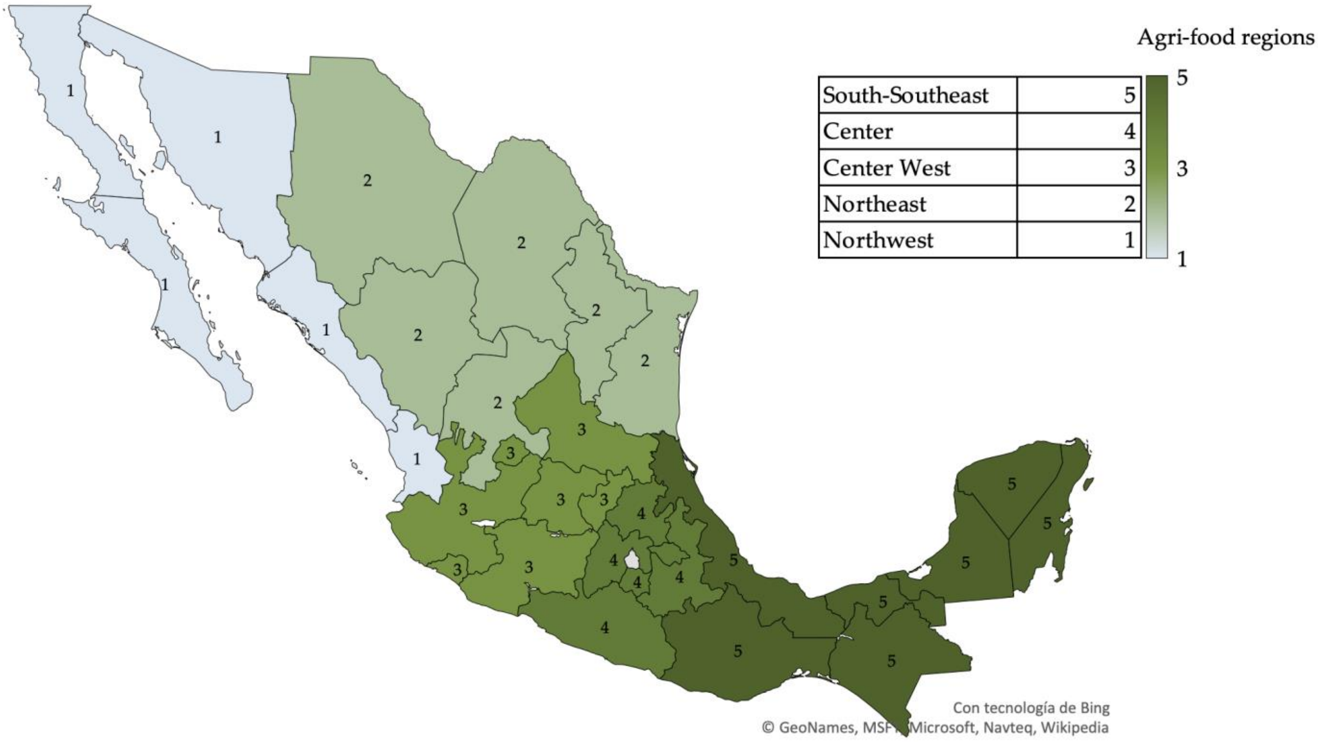

Figure 1. Agri-food regions of Mexico.

In the Mexican agri-food sector, studies of this type are very few and are oriented to variables that are far from the behavior of the sector. In this sense, the research question that guided this work was: what are the technological capacities that Mexico has in order to massively implement new technologies in the agri-food sector? That is, technologies related to agriculture 4.0, which refers to precision agriculture, the use of drones and sensors, automation, robotic machines and smart agriculture (farms and greenhouses) [9,11] and agriculture 5.0, which is a second phase of mastery, and is based on the emerging technologies of artificial intelligence, machine learning and big data analytics [40]. As a hypothesis, it was proposed that the technological capacities in Mexico for the adoption of new technologies in agribusiness are limited, and are concentrated in certain regions that have specialized over time. In this sense, the aim of the research was to analyze the technological capacity that Mexico has for the adoption of new technologies, in order to predict the dynamics of their adoption. With this information, innovation and technological-change policies could be designed that allow a more balanced development, for example, through regional innovation systems.

2. Materials and Methods

2.1. Analysis Method

The documentary research method was used, which basically consists of the search, analysis and interpretation of data obtained through secondary sources. The focus of this research is mixed, with a predominance of the quantitative type. However, it contains a small qualitative component, and its integration occurs in the interpretation and discussion of the results obtained and the evidence of other investigations. This approach offers significant opportunities to gain a deeper understanding of the phenomena. Their integration can occur at any point in the research process [41]. We worked with a non-experimental design of a transversal and descriptive type to delve into the current situation of the object and subject of study.

In this analysis, the 32 states of the Mexican Republic were considered as the fundamental geographical units to analyze the behavior of technological capabilities at the national level. It is a question of identifying the behavior of the states that present greater technological capacities, states with intermediate levels, and those that present the lowest. To define the variables to be used for the analysis of the technological capacities of the agri-food sector, the conditions that most affect or determine the adoption of agriculture 4.0 and 5.0 were identified. In this sense, the conditions that determine the digital transformation were investigated and it was determined to analyze said variables or, in the case of not having the exact variables, the ones that are closest to those found in the existing literature were analyzed [1].

Derived from the above, according to Trendov et al. (2019) [7], there are several conditions that will determine the adoption of digital technologies in agriculture, and the most important are the following: (1) information and communication technologies, (2) enablers such as the internet, cell phone, and social networks, (3) instruction, literacy, and/or knowledge about the use and management of digital technologies, (4) the agribusiness culture and digital innovations, (5) the availability of credits to promote the adoption of digital technologies and (6) policies and programs to facilitate digital agriculture. In this sense, for the present investigation we sought to obtain information related to the variables previously raised.

2.2. Information Collection and Treatment

The information on the variables related to the adoption of digital technologies was obtained from the Encuesta Nacional Agropecuaria (ENA) 2019 [42]. The survey presents a very clear and explicit methodology for obtaining information. It was designed to obtain information at the national level of each of the federal entities. Regarding the sampling units, they were defined as the economic units that carry out agri-food activities, under the control of the same administration. The sampling frame was integrated from two sources, one for agricultural products and the other for livestock products. In addition, a stratification was carried out, based on the planted area in hectares and the number of cattle heads (large, medium and small). The sampling scheme was stratified probability sampling, with simple random selection within each study domain. The sample size was calculated independently for each study domain, taking a confidence level of 95%, a relative error of 9%, and an expected non-response rate of 30%. The sample size obtained was 19,320 economic units nationwide. The results are expressed as a percentage of economic units where the variables were analyzed.

The first analysis variable was the use of computer and communication technologies in agricultural activities by state in an aggregated manner. That is, it includes all information and communication technologies used in agri-food systems. In this sense, information and communication technologies are understood as the set of equipment, systems, means and procedures used for the communication, processing and storage of information, and is made up of computers, the internet and smartphones, among other devices [42]. Subsequently, a separate analysis of the use of the computer, the use of the internet and the use of the cell phone was carried out in order to identify independent relationships of these variables and their influence on technological capabilities. In addition, the use of satellite navigation systems was analyzed, and understood as the technologies used by global positioning systems to identify the exact location of an object or person. In this case, it is being used to carry out soil sampling, monitor crops and generate yield maps, as well as for tractor orientation and topographic mapping, among other uses [42].

With respect to instruction and/or literacy, the closest available variable was used and was obtained from the level of undergraduate studies of the person who administers and manages the production units in the Mexican agri-food sector. It is convenient to mention that it corresponds to the last grade of studies within the formal academic education system. In relation to the availability of credits, the percentage of production units that requested credit or a loan to carry out agricultural activities and those that obtained it was considered. The foregoing are understood as the economic resources received by the production units for the financing of agricultural, livestock or forestry production [42].

The three variables identified in the literature that are most related to technological capabilities were analyzed: competitiveness, the capacity to produce goods and services, and successful internationalization (participation in international markets) [43,44]. For the above, the Competitiveness Index that measures the capacity of the states to generate, attract and retain the talent and investment which detonate the productivity and well-being of its inhabitants was analyzed, and was obtained from the federal entity of the Instituto Mexicano para la Competitividad for the 2019 [45].

Regarding the production capacity of goods and services, the Agricultural Gross Domestic Product for 2019 was analyzed by state, with values at constant prices for the year 2013, which is an important indicator of the economic value of the production of the sector and therefore of the productive capacity [46]. Finally, for the exports understood as the total of goods and services sold by a country in foreign territory, in this case by the federal entity, the information was obtained in thousands of dollars for 2019, specifically from the agri-food sector that includes agriculture, breeding and the exploitation of animals, forest use, fishing and hunting [46].

2.3. Statistic Analysis

Most of the statistical analyses make specific assumptions derived from the data we have and which are based on them; the decision must be made about what type of analysis is most convenient to carry out. In this sense, it was verified if the study variables complied with the assumptions to perform a parametric statistical analysis, the normality, homoscedasticity and independence of errors were analyzed [47]; the results obtained indicated that the data did not comply with these principles. Because of this, it was decided to use non-parametric statistics. The next step was to carry out the analysis of the descriptive statistics of the variables analyzed in order to obtain an overview of the data.

Subsequently, a cluster analysis was carried out in the IBM® SPSS statistical program in order to generate a typology of states with different technological capabilities, for which cumulative hierarchical algorithms were used as a classification method. For the above, the "classify" option was used, and later "hierarchical cluster analysis" was selected. The "farthest neighbor method" was used as the clustering method, and the "squared Euclidean distance" as the distance measure. This technique avoids inconsistencies and uncertainties in the formation of clusters [48]. Standardized exports were used as the discriminant variable in order to be able to compare elements of different variables and different units of measurement. The export variable was used because participation in international markets is one of the variables that, according to the existing literature, is one of the best ways to express technological capabilities [31,34,43,44] and the results obtained are consistent and coherent. It is convenient to mention that tests were carried out with the agri-food GDP and the Competitiveness Index; however, no significance was obtained. Finally, a one-way analysis of variance (ANOVA) was performed for non-parametric tests, for which the Kruskal–Wallis H Test was used for independent samples with a significance level of 0.10, which is considered the most appropriate non-parametric test according to the characteristics of the data [49]. The IBM® SPSS Statistics program was used to perform the statistical analyses.

3. Results

In general, the variables analyzed for information and communication technologies that are related to the technological capacities of the agri-food sector at the national level present very low levels (Table A1 in Appendix A). It is possible to perceive that some states of the Mexican Republic have higher levels of use, for example, Baja California, Baja California Sur, Sonora, and Chihuahua, among others. Some states, such as Chiapas, Tlaxcala, Tabasco, present the lowest levels. The use of cell phones stands out, as one in which a different behavior is presented, and there are several states that are close to 100% use in the production units; a few states present a lower level of behavior, as in the case of Tlaxcala, Mexico City and Guerrero.

Regarding the educational level of a bachelor's degree, it is important to mention that it is very low in the agri-food sector, despite the fact that in recent years there has been a significant increase. In none of the states do more than 20% of the agribusinesses have an administrator with a bachelor's degree, and it is possible to identify that there are several cases with values of 2% (Table A2 in Appendix A). In relation to the availability of credits, it is possible to observe that it is highly variable, which could suggest that it is concentrated in some states. The variables related to the measurement of technological capabilities present a similar behavior to the previous variable, with much variation among states. This suggests a geographical concentration that is the origin of a very uneven historical development (Table A2 in Appendix A).

The descriptive statistics of those related to the technological capacities of the agri-food sector in Mexico, in general, allow the identification of their behavior to be carried out more clearly (Table 1). The average indicates a very low behavior, with the exception of cell phone use. The indicators of dispersion or variation of the data suggest that there is a high variability of data with respect to the average in all the variables analyzed (Table 1). This corroborates the fact that the behavior of the states in relation to the variables analyzed is very heterogeneous. The foregoing is closely related to the origin, evolution, and orientation of the agri-food sector of each state.

Table 1. Descriptive statistics of the variables related to the technological capacities of the agri-food sector in Mexico.

Variables	N	Minimum	Maximum	Mean	Standard Error	Standard Deviation	Variance
Information and communication technologies	32	17.86	92.17	48.11	3.89	22.01	484.52
Computer use	32	0.95	20.00	6.93	0.88	5.02	25.21
Internet use	32	0.81	40.59	10.20	1.50	8.53	72.85
Cell phone use	32	70.55	97.28	89.29	1.25	7.11	50.61
Use of satellite navigation systems	32	0.01	4.28	1.25	0.19	1.09	1.19
Education level, Bachelor's degree	32	1.62	17.45	7.07	0.81	4.61	21.20
Credit availability	32	0.63	44.03	11.58	2.01	11.32	128.19
Agri-food Gross Domestic Product	32	1245.77	71,043.77	18,510.10	2949.06	16,682.44	278,303,879.80
Competitiveness Index	32	32.63	85.14	58.09	2.45	13.88	192.83
Exportations	32	80,908	57,434,140	13,049,369.81	2,754,923.82	15,584,202.56	242,867,369,300,000.00

The cluster analysis allowed the construction of a taxonomy of Mexican Republic states with different technological capacities, based on their export dynamics (Figure 2). Cluster 1, made up of the majority of the states, is the one with the lowest technological capacities and, in general, is made up of states from the south and center of the country. It is characterized by presenting the lowest levels in the use of computers, Internet use and cell phone use, presents the lowest educational levels and maintains lower export dynamics (Table 2).

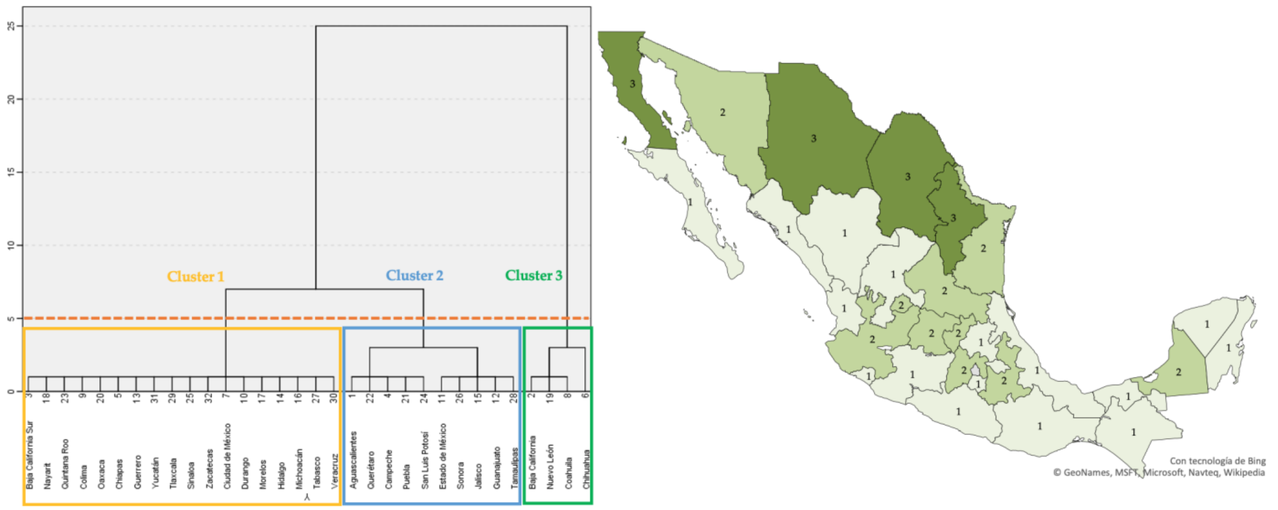

Figure 2. Typology of the technological capabilities of the states, according to the cluster analysis.

Table 2. Typology of the technological capabilities of the states, according to the cluster analysis.

Variables	General	Cluster 1	Cluster 2	Cluster 3
No. of states	32	18	10	4
Information and communication technologies	43.25	39.72 a	40.72 a	63.36 a
Computer use	5.9	4.13 b	6.25 ab	8.44 a
Internet use	7.29	5.91 b	8.88 ab	16.48 a
Cell phone use	90.44	87.34 b	90.50 ab	96.22 a
Use of satellite navigation systems	0.86	0.59 a	1.08 a	2.12 a
Education level, Bachelor's degree	6.11	6.36 ab	3.81 b	9.73 a
Credit availability	8.28	6.78 a	9.04 a	11.71 a
Agri-food Gross Domestic Product	13,345.07	9945.27 a	17,400.72 a	14,755.88 a
Competitiveness Index	58.73	56.23 a	60.61 a	63.80 a
Exportations	5,299,648.00	1,880,104.50 c	18,694,252.50 b	45,028,206.00 a

Note: Medians with different letters in rows indicate significant differences ($p \leq 0.10$), according to the Kruskal–Wallis H test.

Cluster 2 is made up of 10 states in the center and north of the country and, according to the results, presents medium technological capabilities (Table 2). It is characterized by presenting intermediate levels in the use of computers, the Internet and cell phones, and intermediate behaviors in educational levels and in its export dynamics. Cluster 3 is the smallest, and is made up of four states belonging to the north of the country, and these are the ones with the greatest technological capabilities (Table 2). It is characterized by presenting the highest levels of computer, internet, and cell phone use, the highest educational levels and higher export dynamics. Regarding the use of information technology and communications analyzed in aggregate form, there are no differences. A similar situation occurs with the availability of credit and the agri-food Gross Domestic Product (Table 2).

4. Discussion

The variables analyzed present very low levels, with the exception of the use of cell phones, for which the majority have this technology and use it for agri-food activities. Internet access, computer use, and the use of satellite navigation systems is very low, and educational levels are very low. This greatly limits the implementation of new technologies. The results obtained show that the states with the greatest technological capabilities are in the north of the country. It is the region of the country that has developed an agricultural business since its origins, which is highly technical and closely linked to international markets [1]. These results are close to those found by Pérez Hernández et al. (2017) [50], who carry out an analysis of the technological capacities of Mexico and identify the fact that they are concentrated in five entities. It is worth mentioning that their results coincide on several points with respect to the technological capabilities of the agri-food sector. The development of the different scientific and technological revolutions in the agri-food sector show very heterogeneous rates of transformation and technological adoption by country and by region [51].

To better understand the results obtained, it is necessary to highlight the fact that Mexico is a country that stands out for the heterogeneous and specialized nature of its agricultural regions. The most frequent and important barriers to the adoption of new technologies are the lack of infrastructure and the lack of accessible solutions for farmers [52], situations that have worsened over time. The regions present very different profiles in terms of innovation capacity, specialization of the economic fabric and composition of the regional innovation systems [53]. Consequently, activities with very unequal levels of productivity and remuneration are carried out [54]. In recent years, this situation has intensified in such a way that globalization has unevenly transformed the country's economic structure. The interactions that have been generated from the above are not stable; they change over time, and generate very dissimilar technological trajectories and productive results in the regions [55,56].

Currently, the Mexican agri-food sector presents a series of adjustments and technological changes that have affected its basic productivity structure. This has transformed all production systems by replacing crops or livestock breeds, and integrating plasticulture and new agricultural constructions, which further amplify economic asymmetries. This situation is becoming evident with the rapid technological and productive specialization of agricultural regions [57]. This has naturally generated a concentration of infrastructure, information and knowledge about new technologies [37]. It is worth mentioning that technological capabilities are gradually generated through learning mechanisms and incremental improvements until reaching the level of the international technological frontier [58]. It is important to accurately identify factors that favor the adoption of new technologies, especially in emerging economies [59], as well as the technical and socioeconomic obstacles to the implementation of agriculture 4.0 and the transition to agriculture 5.0 [60]. Derived from the above, the technological trajectories of the Mexican agri-food sector, understood as the coevolution of products, processes, rationalities, and the social, economic, political and technological events that have occurred at the local, regional and national level have generated very different technological capacities, and they are concentrated in some regions.

In this sense, it is possible to identify hyper-specialized regions in crop production. For example, tomato production is concentrated in Baja California, Sinaloa and San Luis Potosí [8]. Avocado production is concentrated in Michoacán, Colima and the State of Mexico [61]. In the case of strawberries, production is centered in Michoacán and Jalisco [62]. Chili production is concentrated in San Luis Potosí and Zacatecas [63] and lemon production in Colima and Veracruz [64]. However, it is worth mentioning that production is located in a few municipalities that have become hyper-specialized and have a good command of their production systems. In other words, technological capacities have accumulated in these areas over time, and are even part of the international technological frontier. New technologies are being adopted in regions and companies that are linked to global value chains and international markets [65]. These regions make up agri-food systems that focus on crops of high commercial value, respond to international demands and in some cases are companies with foreign capital. Hence, the need to decentralize scientific and technological capacities to contribute to the economic development and well-being of all regions of the country is clear, taking into account their productive vocation [50]. In addition, it is essential to continue improving technological and management capacities throughout all the value chains of the agri-food sector [66].

The agri-food sector in general has basic technological capabilities that do not meet the needs of the current competitive environment [67]. This coincides with what happens in other countries where it is observed that most of the cases of use of digital technologies are in the initial development or prototype phases [60]. However, the health crisis has accelerated the digitization process of society, and advances that were expected to take years have occurred in a few months [68]. Currently, and as a consequence of the confinement caused by COVID-19, which forced society to remain in isolation, there has been a significant increase in the use of information and communication technologies in all sectors [6]. In other words, it is certain that the data related to the analysis variables are greater today [1].

In the current knowledge society, the new challenges of the agri-food sector are faced from the perspective of the exchange of tacit and explicit knowledge and the accumulation of capacities within the organizations, which are the actors of the change and innovation [69]. In this sense, it is relevant to think about the infrastructure to increase the efficiency of the processes. This infrastructure has a human part and a strictly material part; however, both refer to the generation, development and dissemination of new scientific–technological knowledge [70]. A crucial point is having a research and development structure and facilities, and access to networks and financing [71]. In addition, it has been shown that maintaining a link and interaction with the institutions that carry out research has important benefits [72].

It is clear that great scientific and technological developments are not enough to achieve economic progress without governments creating education and training programs necessary to absorb new technologies and innovations [73]. In addition, there is a strong dependence on the exterior, with high costs in the transfer and import of technological goods and services and a late incorporation into the advancement of world changes [74]. In addition, human capital must be valued more, as the most precious resource of a nation, and its recruitment, training and development must be among the nation's priorities [75].

Digital technologies are valued by most companies; however, there is still no clear recognition of their potential in the specific field of planning, management and control of production processes [76]. In addition, some social, ethical, political, cultural and environmental concerns associated with digitization arise [14,15], and even digital technological sovereignty is questioned in relation to each country [37]. Simultaneously, other findings show that digital technologies can cause negative effects on food security, mainly due to existing asymmetries among farmers [13]. In addition, it is necessary to identify the key problems of the new technologies based on solid evidence to guide the formulation of policies and achieve greater effectiveness, efficiency and sustainability [16,77,78].

The use of mobile applications to monitor and control all processes seems to be the most viable option for starting the digital transformation in the agri-food sector [79]. In general, the integration of monitoring technologies, support for decision-making and improved administration is needed throughout the entire agri-food chain [17]. This will make it possible to manage territories as common goods and empower farmers and consumers [80]. Hence, the basis for the adoption and adaptation of new technologies in the agri-food sector will be the access and use of 5G technology that will allow the massive use of data and information for analysis and decision-making [6]. Access to information and data through platforms is used to support the knowledge and decision making of producers. With this, the interactions of all the links of the agri-food chains and the exchange of information are increased [81,82].

With these results, it is possible to start with the design of a proposal for the adoption of technologies associated with agriculture 4.0 and 5.0 in the Mexican agri-food sector. This is important for public policies in terms of avoiding excessive power asymmetries in agrifood value chains [83]. In this sense, Buenrostro Mercado (2022) [84], for example, proposes four phases, determined by the complexity of digital technologies and the possibilities of use that the incorporation of each of them makes possible. That is, with the results obtained it is possible to develop proposals according to the phases of technological development that are more balanced. However, they are changes that generate great uncertainty and complexity [20]. Obviously, it is necessary to carry out more research that serves as an input to be able to propose agri-food policies in accordance with the new realities and future needs.

The technology adoption process is uneven among industries, countries, regions, and companies, which is generating a new source of polarization among advanced countries, emerging economies, and developing countries [65]. In addition, it is important to promote public understanding of science and the greater participation of other actors in the processes of knowledge production and the appropriate interactions of institutions, organizations and economic agents for the design of public science and technology policies [85], in order to identify the capabilities and potential of the regions to make the innovation process more efficient and to generate smart specialization processes [86].

Improving agri-food systems to make them more sustainable and resilient is, more than ever, an urgent priority [87]. In Mexico, public policies are required to stimulate a broader adoption of new technologies in all sectors, in order not to allow regional asymmetries to worsen [65]. The logic of smart specialization is useful for the design of regional policies; however, it must take into account the characteristics of the territories and the existing vulnerabilities [53]. Regional innovation systems are a fundamental tool for the design and implementation of smart specialization strategies [88]. In this sense, strategies must be designed for each region, in order to adapt more quickly to changes in the world economy and maintain their competitive position [89]. In this way, it would be possible to promote regions with the capacity to maintain an adequate dynamic in their innovative processes with identity and sustainability [61,72].

In addition, education and training in emerging technologies has proven to be a good strategy, and at the same time the design of initiatives that encourage change in consumer behavior will be increasingly important [21,71,81], especially for small producers who find it more difficult to access this type of technology, and this could cause greater asymmetries in the different agri-food regions. Lastly, it is important to directly link financial and non-financial instruments such as supply and demand incentives, fiscal incentives, economic incentives and subsidies [71,90], facilitate policy making, and provide public services such as the Internet [81].

5. Conclusions

The variables analyzed generally present very low values, except for the use of cell phones. This indicates that the Mexican agri-food sector has a low technological capacity for the adoption of new technologies. Three groups of states with a different behavior regarding their technological capabilities were identified. Four states in the north of the country stand out as having the greatest technological capabilities, as a result of which they are expected to have higher rates of adoption of new technologies, followed by a group made up of ten states in the north and center of the country. Finally, there is a broader group of 18 entities in the country made up of the states in the center and south of the country with the lowest levels. This suggests that most of the country will present low rates of adoption of new technologies in the agri-food sector.

The results suggest that the technological capacities of the agri-food sector in Mexico are concentrated in regions with very specific trajectories and characteristics. It is possible to infer that these are hyper-specialized regions in the production of high-value crops, aimed at satisfying the demand for food in international markets and, in some cases, they are companies with foreign capital. The foregoing has a historical origin; that is, the technological trajectories of the Mexican agri-food sector have developed gradually. These are regions that concentrate a greater knowledge of production systems, are more closely linked to educational and research institutions, and that have managed the development of the necessary infrastructure for the success of their production and marketing systems.

The current behavior of the technological capacities of the agri-food sector suggests that if the same dynamics continue, the regional asymmetries will worsen. In this sense, it is convenient to design agri-food policies that make it possible to stimulate the adoption and diffusion of new technologies, especially with small producers. In addition, it is important to better coordinate all the agents of the sector's innovation systems, manage the infrastructure that supports agricultural technologies 4.0 and 5.0, and redesign science and technology agendas for the agri-food sector oriented towards smart specialization. Finally, it is worth mentioning that there is still a lack of research, and more needs to be carried out on the real impacts of new technologies and on how to measure technological capacities and their promotion.

Funding: The APC was funded by Universidad de Guanajuato.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Encuesta Nacional Agropecuaria. Available online: https://www.inegi.org.mx/programas/ena/2019/ (accessed on 31 March 2023). Sistema de Cuentas Nacionales de México. Available online: https://www.inegi.org.mx/sistemas/bie/?idserPadre=10200070#D10200070 (accessed on 31 March 2023). Competitividad Estatal. Available online: https://imco.org.mx (accessed on 31 March 2023).

Conflicts of Interest: The author declares no conflict of interest.

Appendix A

Table A1. Variables analyzed related to the technological capabilities of the agri-food sector in Mexico.

Federal Entities	Information and Communication Technologies	Computer Use	Internet Use	Cell Phone Use	Use of Satellite Navigation Systems
	%				
Aguascalientes	61	9	12	91	1
Baja California	91	20	22	97	3
Baja California Sur	92	19	12	96	2
Campeche	28	4	4	86	0
Chiapas	18	4	5	97	2
Chihuahua	77	7	11	97	0
Mexico City	22	16	23	73	0
Coahuila	44	10	41	96	2
Colima	69	7	7	85	4
Durango	76	4	4	90	1
Mexico State	26	5	10	91	1
Guanajuato	46	7	9	90	0
Guerrero	27	3	5	71	0
Hidalgo	27	1	6	97	1
Jalisco	69	7	10	87	3
Michoacan	43	4	6	88	2
Morelos	50	8	10	83	1
Nayarit	62	3	4	87	1
Nuevo Leon	50	7	7	94	3
Oaxaca	34	4	7	82	2
Puebla	36	6	7	90	1
Queretaro	22	9	9	91	1
Quintana Roo	37	3	31	90	1
San Luis Potosi	27	3	4	84	1
Sinaloa	70	8	8	96	1
Sonora	86	18	20	95	3
Tabasco	45	3	3	94	0
Tamaulipas	71	6	7	97	1
Tlaxcala	24	1	1	79	0
Veracruz	37	8	10	80	1
Yucatan	33	5	6	97	0
Zacatecas	42	3	5	85	1

Table A2. Variables analyzed related to the technological capabilities of the agri-food sector in Mexico.

Federal Entities	Education Level Bachelor's Degree	Credit Availability	Competitiveness Index	Agri-Food Gross Domestic Product	Exportations
		%		Millions of MXN	Thousands of USD
Aguascalientes	6	6	67	9076	11,794,073
Baja California	17	40	38	15,458	42,396,951
Baja California Sur	12	9	56	5368	291,812
Campeche	5	11	83	5751	16,579,076
Chiapas	10	2	73	19,522	820,170
Chihuahua	7	12	57	33,904	57,434,140
Mexico City	3	4	37	1246	2,667,127
Coahuila	6	11	78	14,054	47,659,461
Colima	15	1	43	5061	684,838
Durango	7	14	78	19,263	2,737,229
Mexico State	3	15	48	19,881	20,010,001
Guanajuato	4	11	59	26,645	25,065,798
Guerrero	3	1	34	12,636	966,475
Hidalgo	6	19	64	9902	2,299,343
Jalisco	2	1	58	71,044	21,659,641
Michoacan	5	11	55	55,622	5,586,480
Morelos	7	19	37	6595	3,086,705
Nayarit	8	37	66	8679	266,760
Nuevo Leon	12	3	70	6325	39,857,053
Oaxaca	3	6	59	15,255	712,575
Puebla	2	3	58	24,433	17,547,974
Querétaro	2	4	62	9844	12,868,797
Quintana Roo	5	6	54	2099	80,908
San Luis Potosi	3	7	63	14,367	15,531,677
Sinaloa	17	44	66	47,074	2,840,002
Sonora	15	29	63	40,736	19,840,531
Tabasco	7	4	33	8641	5,012,816
Tamaulipas	12	18	59	14,920	29,130,161
Tlaxcala	6	3	59	3427	1,460,866
Veracruz	6	8	57	42,870	6,697,248
Yucatan	3	3	85	9989	1,119,624
Zacatecas	4	9	41	12,636	2,873,522

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