The technology life cycle of Persian lime. A patent based analysis

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**A R T I C L E   I N F O**

**Keywords:**  
Technological life cycle  
S-curve  
Agro-industry  
Persian lime  
Technological strategy

**A B S T R A C T**

The citrus agro-industry is one of the world’s most important agricultural sectors. The Persian lime is one of six citrus fruit groups with economic significance. The technological lifecycle of Persian lime sector is assessed in this study using the growth S-curve approach. The objective is to depict the technology life cycle trajectory and current stage of the Persian lime citrus fruit, as well as each of its value chain phases, in order to facilitate better decision-making and technological strategies. The study uses technological patents collected from the World Intellectual Property Organization (WIPO) database from 1975 to 2009. The S-curve model of Persian lime and its value chain stages is generated using logistic mathematical regression. According to the findings of this study, Persian lime is in the maturity stage of the technology life cycle. As a result, the primary strategy could be cost reduction, process innovation, and price strategies to capitalize on market opportunities. When compared to other value chain phases, the transformation phase has the highest number of patents according to the value chain analysis and it is the unique value chain phase with statistical significance in the model. The transformation phase is also at the maturity stage of the technology life cycle. This creates opportunities in two ways: first, to adopt previously developed technologies in the transformation phase and improve process efficiency to reduce costs; second, to reinforce innovative technological efforts in other phases of the Persian lime value chain, such as growth, harvest, or post-harvest.

1. Introduction

The citrus agro-industry is one of the most significant sectors within the global agricultural economy [1]. It is associated with juice and essential oil production [2, 3]. The Persian Lime is one of the six citrus fruits categories of economic relevance (e.g., oranges, common tangerine, satsuma tangerine, grapefruit, lemons, and limes) [4]. Agro-industry are the activities related with the cultivation (i.e. agricultural and horticultural crops), harvest and post-harvest of fruits and vegetables [5]. Agro-industry is a subset of agribusiness, which encompasses all processes involved in the production and distribution of operating resources for agricultural operations; farm production facilities; and the storage, processing, and distribution of agricultural commodities and items made from them [6, 7]. The technological uncertainties are a crucial component in agribusiness along with other environmental uncertainties and risks (e.g. political, economic, regulatory, and socio-cultural aspects) [8]. This technological uncertainty in agribusiness, arises from variables such as weather, biologically-based production, and management, complicating decision-making [9].

Moreover, technology influences business investment decisions in order to build profitable products [10]. As a result, technology management is crucial for achieving competitive advantage through the proper integration and deployment of innovation, as well as the organization’s strategic, operational and market mission [11]. To being competitive and reduce uncertainty, businesses must develop technological or innovation strategy [12]. However, before developing a strategy, predicting technological patterns might assist in understanding the future direction and existing state of technological development [13, 14]. According to technology management and innovation theory, the technological accumulation is defined as the growth and evolution of new ideas or methods generated by firms and driven by industry to create value [15]. Technology forecasting is a method that employs growth patterns and technology maturity curves to aid in the analysis of the technology innovation process and the industry characteristics [16] to
anticipate and comprehend the potential direction, rate, characteristics, and effects of technological change [17]. In agribusiness, technology affects the production and demand for services and products, the speed of technological change, and the uncertainty and risks in the industry [9].

The technology life cycle is a forecasting method that depicts the evolution or growth of technology or industries over time [18]. Specifically, the technology life cycle describes the pattern of the development process of a technology from the technology research in the emergence phase to its decline or obsolescence [19]. It also helps to analyze the technology innovation process and industry characteristics [16]. The technology life cycle, or S-curve, predicts the direction and generation speed of the technology, which facilitates decision-making processes by reducing the risks of technology development [20]. The technology S-curve, at its core, provides an elegant and structured characterization of the dynamic evolution of technology, which, rather than being a purely technological phenomenon, also reflects the decision maker's strategic choices [21].

Despite the level of interest, few previous studies have examined the technological life cycle perspective in the agribusiness or agro-industry domain, and specifically in the Persian lime citrus fruit sector, to improve decision making and establish technological strategies. This subject would be of significant interest not only within the community of researchers on the topic of technology maturity and forecasting methods, but especially to companies and organizations involved in the agribusiness of citrus fruits, and in general to the main citrus-producing countries around the world: China, Brazil, India, Mexico, Spain, and the United States.

This article aligns with the fields of innovation and technology management studies on the shape of technological growth or technological evolution around the Persian lime citrus fruit (Citrus latifolia Tanaka) using the S-curve model, which is commonly used in management studies [22]. The objective is to reveal the technology life cycle trajectory of Persian Lime citrus fruit technologies to improve decision-making and technological strategies by using patent information retrieved from the World Intellectual Property Organization (WIPO) database from 1975 to 2019. In addition, this study classifies and analyzes the patent data from the Persian Lime value chain to improve the understanding about the potential technological strategies per phase.

2. Literature review

2.1. Persian lime agro-industry

Agro-industry are the activities associated with the cultivation (i.e. agricultural and horticultural crops), harvest and post-harvest of fruits and vegetables [5]. However, the spectrum can be broader if agro-industry is viewed as a subset of manufacturing that processes raw materials and agricultural, forestry, and fishery intermediate products [23]. This sector includes manufacturers of food, beverages, and tobacco, textiles and clothing, furniture and wood products, paper and printing products, and rubber and rubber products.

As stated, the citrus fruits can be divided into six groups of economic interest: oranges, common tangerine, satsuma tangerine, grapefruit, lemons, and limes [4]. Citrus fruits are plants from subtropical regions that have adapted satisfactorily to the tropical conditions and have reasonable yields in this business sector. The acidic lime, also called the Persian lime (Citrus latifolia tanaka), is in the family Rutaceae and in the genus citrus. It is medium to large in size, oval, oblong, or slightly elliptical, with the base usually rounded and sparse or seedless. The peel is generally thin, with a smooth surface and a pale-yellow color when ripe. The juice accounts for about 50% of the fruit weight with 6% acidity [24], and as other citrus fruits, its juices and essential oils [2, 3] are used in other industries such as food, chemicals, pharmaceuticals, and perfumes or cosmetics [25, 26].

Because of its wide range of applications, the majority of the Persian lime literature focuses on findings that improve, analyze, or observe the traits, parameters and functional aspects of the fruit and its derivatives [27, 28, 29]. For example, research is being conducted on plant development nutrients and compounds [30, 31], weed management [32], harvesting [33], and protection and preservation [34, 35]. Some studies are even held in specific countries due to their unique growth features (for example Egypt [28], Mexico [36], or Brazil [37]).

On the other hand, Persian Lime research is dominated primarily by providing solutions or enhancing the quality of Persian Lime properties by studying, for example, the treatment of diseases [31], the effect of environmental factors [38], or a combination of both [39]. Alternative quality-focused approaches have similarly been proposed, such as applying genetic research to promote vegetative development and production [40], quality on certain value phases such as postharvest [41], and on vegetative growth and mineral elements' content [42]. On the other hand, studies are centered on processes, treatments, or methods [43] with the purpose of increasing commercialization, such as cutting treatments [44], chemical management in dry seasons [32], detection of juice adulteration [45], oil extraction methods including coldpressing, solvent extraction, enzyme—assisted aqueous extraction [46], and even innovative extraction methods such as steam distillation [47]. Furthermore, there are studies interested on how these treatments or approaches affect physical properties of the Persian Lime [48, 49].

From the management perspective, the literature discusses obtaining value-added products from Persian lime fruit wastages or residual biomass [50], packaging optimization by using mathematical and problem-solving methodologies [51], competitive and productivity analysis in local economic territories [52], the impact of export international certification on the structure of production, packing, and transport [53], and potential production to assets profitability [54]. At the time of undertaking the current study, only a pair of management-related studies examined forecasting prediction or technology analysis to make better strategic decisions. The first research focus is on the design of an expert system for prediction of fruit quality and its impact on the Persian lime supply chain [55]. This study concerns the structural problem of the Persian lime supply chain in Mexico, which still leads to low production yield over short time periods with heterogeneous fruit quality and also to the emergence of excessive middlemen businesses arising from a fragmentation between orchard and exporting companies that constitute the first two links in the associated supply chain on the Persian lime production cycle. Then, the research aim is to increase production in orchards by modeling application scenarios for agricultural practices. The second study looks for a validation of a technological innovation represented by a patented continuous steam distillation process and to both physically and chemically characterize the volatile fractions of essential Persian lime oil [1].

Despite the wealth of literature available in the field of Persian lime, there is a lack of studies from a management perspective that support evidence to make better decisions in terms of a technological strategy, analysis, and prediction in the agri-business scenario. The study then tries to extend earlier works by including an analysis from a technology and innovation management approach in order to help make better decisions in the Persian lime industry.

2.2. S-curve - technology life cycle

The application of the technology life cycle research is anchored in the field of innovation strategy, however its origins may also be traced back to the domains of technology management and measurement [21]. Technological growth is defined in the sphere of innovation as the accumulation of new ideas or methods generated by firms and driven by industry to create economic value [15]. This innovation growth is a representation of technological change over time and follows a technological path [56] that enables better investment and strategic management decisions [57]. Then, managers can generate competitive advantages in the face of uncertainty by taking advantage of the structured process of technological evolution or technological development
This structured process is materialized generally by the S-curve technology life cycle [58].

As a structured technological process, the S-curve is measurable, and its application has been extended to understand the behavior and the strategies that can be implemented in each one of the phases of technology, innovation, or the life cycle of a specific area of knowledge [59]. Furthermore, the S-curve is used to make predictions about those phases in the technological or innovation lifecycle thanks to its advantage of being more reflective in the rate of growth changes when compared to other forecasting models such as regression, time series, neural networks, or grey systems [60].

The technology life cycle can be represented by a maturity curve that shows how the technology or product grows or evolves over time [18]. The assumption is that all technologies grow until they reach a plateau, followed by a period of senescence and obsolescence or a technological jump with the start of a new cycle [61]. Thus, previous research showed that the technology life cycle follows a sigmoidal shape or S-curve, with growth over time initially increasing, and after a period of time decreasing until it reaches a limit or saturation, as shown in Figure 1 [60]. The S-curve model identifies the current stage of technology development and predicts the time required to attain the saturation state; it is often used in technology development research and is an appropriate tool for analyzing the growth curve and anticipating emerging technologies [62].

The technological S-curve is composed of four phases: emergence, growth, maturity, and saturation, as shown in Figure 1 [20]. The emergence or introduction phase refers to a new technology that starts as a promising idea and requires a prior analysis of the needs, requirements, and structures for continuous improvement and innovation; the results are very uncertain, and the investment is risky, so changes are slow to come. In the growth phase, knowledge, expertise, and know-how are not yet fully disseminated, but the implementation of technical functions is increasing rapidly; the technology is evolving, the mass market is exposed, and massive investments need to be made. Maturity is a phase of rapid late growth, although the market is growing at a significantly slower rate. It is possible to develop a variety of products based on the same technology and the focus is on the exploitation of existing technological opportunities. Saturation or decline is characterized by the collapse of the technology’s innovation potential, at which point the technology moves from maturity to obsolescence.

Recently, there have been several attempts to analyze the technology lifecycle in different technologies, fields, or domains using growth curve methods. Although there is diversity among the domains studied, there is a strong focus on studies related to energy, environment, and sustainability. For example, in the energy field, Meng et al. [63], use two S-curves to find the most important parts of incremental innovation in nuclear energy projects. Madvar et al [64] conducted research to determine whether biofuels technologies are ready to meet global energy demand by analysing seven technologies and their technology life cycles. Dehghanmadvar et al. [65] propose a combination of the technology life cycle and an adaptation diagram to analyze the hydrogen production technology; their aim is to study the need to focus more on the management of energy systems and turn attention towards replacement energy technologies because of the global environmental awareness. Lastly, Skoczowski et al. [66], did research on how technologies like solar-photovoltaic and wind power spread.

The environmental research stream relates to contexts of climate change and sustainable development. Based on the increasing industrial demand for water and the increase in nutrient pollution in aqueous bodies, some studies focus on general domains such as industrial wastewater treatment [67] and nutrient recovery from waste-streams [68]. Some studies are more specific about the technologies, such as wastewater treatment by biomembrane [69] or wastewater pollution control technologies [70]. Various studies include green buildings [71] with the aim to improve energy expenditure and sustainability, and low-carbon technologies [72] to understand the technology diffusion process and its characteristics, for example the change of direction and pace over time. Others, are centered on the diffusion of electric mobility or vehicles using electric batteries [73] or, in general, on the forecast of a future development trend of drive train technologies [74] with special attention to the electric vehicle and its variants.

Nonetheless, the technology life cycle has been used to analyze specific technologies outside of energy and environmental fields. For example, Dale et al. [75] studied the electric propulsion technologies, including experiments to make data-driven analyses and outline possible future directions. Oliveira et al. [76] also used laboratory data and the S-curve technology life cycle to analyse welding processes. Lin et al. [77] studied thin film transistor liquid crystal displays, cathode ray tubes, and nano biosensors to find out the stage changes of the technologies. Stoffels et al. [78] gives an overview of the patent landscape of the hydrogenation catalysts by applying the technology life cycle and the S-curve. Mutlu et al. [79] intend to forecast the development of safety technologies in the field of occupational health and safety. Finally, some interest can be found in research based on ICT technologies; for example, Priestley et al. [15] investigated Web technologies to forecast technology based on patenting rates and S-curve growth. Gladysz et al. [80] focus on RFID technologies and how they have been impacted by the fourth industrial revolution. Zhang et al. [81], use the technology life cycle to perform a technology assessment and roadmapping analysis of the blockchain field. Adamuthe et al. technologies [18] propose a forecast of six computational fitting trend lines to a maturity or growth S-curve.

Some other studies focus on methodological improvements, combinations of tools, or the applications of the technology life cycle to other domains. Although most of the research studies use patents to make the technology analysis, some of them use only scientific articles [68, 69] or a combination of articles and patents [67, 71] to simulate the S-curve and make bibliometric analyses. The use of bibliometrics combined with patent analysis could help bridge gaps that may exist in historical data when predicting and forecasting future technologies [82]. Some studies even do not use patents or articles and base their analysis on government databases, reports, and public registries [72], or even on qualitative or notionial S-curves to show maturity as a function of time based on data from past studies [75]. Furthermore, research also involves the improvement of the model by itself, focusing on some specific characteristics like the impact of the different types of knowledge and their recombination in the model [83] or the emergence of the dominant design of the technology [84].

It is common in the literature to find research with complementary methods to the technology life cycle that improves the prediction or analysis of the technology or sector. Thus, some research aims to link not only the innovation approach or the technology diffusion, but the market size [66] or stock market behaviour over time [15] using patents on one side and variables such as unit of cost per installed capacity or the
NASDQ composite stock index on the other. Also, research uses complementary management tools to the S-curve such as technology roadmaps and technology audits [80], and specific methods like machine learning [85], the use of entropy [77], the Dirichlet allocation topic model [81], the use of time series modelling using statistical quality control charts [79], or hierarchical S-curves to analyse main technologies (e.g. systems) and sub-technologies (e.g. subsystems or components). The technology life cycle has also been used outside of specific technologies and industries. For example, it has been used to study business models [86] and industry dynamics [87] at the level of technological innovation systems.

As described in this section, the trend of a large number of innovations or technologies in literature is better explained by an S-shaped curve. Many technologies and sectors follow this theoretical behaviour of the technology life cycle, differentiating between the stages of emergence, growth, maturity, and saturation. This study follows previous research by interpreting technological growth or the maturity S-curve as the accumulation of innovations by an industry [15]. The study uses patent records as a proxy for innovation in technological industries. This article uses patents to demonstrate empirically that the general Persian lime and its correspondent value chain phases of development follow a trend with a patent growth rate similar to the S-curve technological model [20].

3. Method

The procedure for gathering, cleaning, and organizing Persian lime patents is described in Section 3.1. The accumulation of patents was modelled using the logistic regression described in Section 3.2 to examine the shape of technological growth in the Persian lime sector and the different stages of the value chain. Data collecting and processing computational activities were implemented in Matheo Patent software [88] and RStudio [89].

3.1. Data collection and organization

The study used granted patents to model the technological life cycle of the Persian lime. Patents have an important role in the development of technology because although they can provide exclusive rights and legal protections for the inventions of individuals and enterprises, their analysis is also used to extract information about a specific industry or technology in forecasting studies and allows the assessment of various aspects of technological change [20]. As a consequence, patents are seen as the link between R&D efforts and the market, and their analysis uses information from a sector or technology to forecast and make strategic decisions based on the technology life cycle [20]. Patents are not a generalizable indicator because they do not cover the whole concept of innovation [15, p. 407]. However, they are used for a number of reasons, including the information they contain about the know-how of the innovation, the possibility of commercializing the technology, how the technology could be used to make products, and the usability of structured data in organized databases [90, 91].

The patents were collected from the database Patentscope of the World Intellectual Property Organization (WIPO) in the time window from the year 1975 to the first half of 2019. The WIPO is an organization from the United Nations that oversees services, policies, cooperation, and information related to intellectual property that involve 156 countries. The Patentscope database is the WIPO global patent search system that provides access to the international Patent Cooperation Treaty (PCT) applications. The PCT is an international patent system that assists applicants in seeking patent protection internationally for their invention; by filing one international patent application under the PCT, applicants can simultaneously seek protection for an invention in 156 countries [92].

Although the use of this database could imply a bias in favor of applicant organizations using the Patent Cooperation Treaty (PCT), there are two main reasons to choose it. First, because the PCT is a strategy to achieve international patent protection, many studies have confirmed that the decision to use the PCT for their patent application is an indicator of patent value [93, 94]. Accordingly, this research assumes that if a patent is using the PCT strategy to protect its intellectual property rights in other countries, then the firm owning that patent is confident that the technology embedded in the patent will represent an economic and strategic return that has to be even higher than the cost invested in the process itself. Second, although there are other regional organizations in charge of patenting processes, only one was chosen in order to have consistency, reliability, and comparability because different countries have different patent systems in terms of applications, protection, and granting [95]. For example, in PCT there is a prescribed form for the international application, and this form must be accepted by all designated offices, so there is no need to comply with a great variety of widely different formal requirements in the many countries in which protection may be sought [96].

The search in the database was made using specific keywords and a thesaurus to locate patents related to “Persian lime” (e.g., tahiti lemon, tahiti acid lime, citrus latifolia tanaka, lima bears). This resulted in 3034 patents. Each one of the 3034 resulting patents was manually reviewed to filter out the non-relevant documents. Several patents unrelated to Persian lime were eliminated; for example, various patents were related to metallurgy and chemistry, and others to building and civil engineering that did not have any relation to the citrus fruit. This resulted in a final set of 507 patents. The first of the 507 patents had been assigned to the year 1981 (e.g., the first patent appeared in this year); however, we use 1975, six years before 1981, to include some years with zero patents in order to support the mathematical and regression model without altering the patents and their corresponding years. This helps to understand the results visually and to make a better interpretation of them without altering the results. Then, the time window used to make the regression model with patent data is 1975–2019. A further cleanup and verification process was performed on the data set to correct the formatting as much as possible (i.e., spelling mistakes). This data is the dataset used to make the first analysis or the general analysis of the Persian lime S-curve in this study, which used the total number of patents found.

This study made an additional analysis of the technology S-curve of Persian lime but centered on the value chain. Once the dataset was complete, these patent documents were manually reviewed one at a time to categorize them into the different stages of the Persian lime value chain. This process prepared the data to be analyzed at each of the stages of the value chain and helped identify some characteristics otherwise not visible in the first, or general, analysis that included the total number of patent documents. The value chain consists of the stages of growth or cultivation, harvest, post-harvest and distribution, transformation, and consumption. This study focused on the stages of growth, harvest, post-harvest, and transformation (e.g., the five stages of the value chain), which are directly related to the affairs of the Persian lime; the consumption value chain stage has not been included because this stage is not the subject or scope of the present research since it is more related to strategic positioning and promotion and less to technology development.

3.2. S-curve modelling

In order to create the S-curve model of Persian Lime and its value chain stages, the data was organized in MS Excel, processed, and analyzed in the R software [89]. Then, the same procedure was applied not only to the general analysis of the Persian lime using the total of patent documents to model the technology S-curve, but also to each one of the Persian lime value chain stages, where one technology S-curve model was made per value chain stage according to the categorization of patent documents made at the data collection and organization described in Section 3.1. In general, although several mathematical models would have been used to construct the S-curve based on the data obtained, studies often use the Gompertz or the Logistic curves to model the technology growth life cycle [97, 98]. This study follows the approach of...
Priestley et al. [15] and Andersen [99] in using a logistic model to describe the patent behavior of Persian lime. The logistic model can be expressed mathematically as follows:

\[ y = \frac{a}{1 + be^{-cx}} \]  \hspace{1cm} (1)

From the logistic function, \( y \) represents the cumulative technological development of the sector over time, which is expressed as the cumulative number of patents per year; \( a \) represents the limit, saturation, or maximum value reached by the function; \( b \) is the slope of the technology curve, and is described as the minimum number of published patents, \( \frac{1}{a-c} \); \( c \) is the inflection point of the S-curve and equals the percentage increase in publications over time; \( x \) is the variable to be evaluated, which is represented by the time in years between 1975 and 2019. Accordingly, the parameters \( a \) and \( b \) determine the shape of the logistic S-curve. The S-curve is a symmetrical model about the inflection point \( c \).

In contrast to some studies [15, 98], this research uses four stages of development in the technological S-curve model: emergence, growth, maturity, and saturation or decline. Although these stages are the most common in the literature related to the technology S-curve, most studies are not explicit about the limits between stages in the S-curve model besides the initiation of the emergence stage and the end at the saturation stage. For example, Yuan & Cai [74] calculates the technology maturity indicator as a proportion of the S-curve upper limit, which helps to comparatively understand the development stages of the S-curve. Haupt, et al. [91], used patent indexes looking for indicators with statistically significant differences among the life cycle stages; however, it does not clarify the limits of the different technology maturity stages. Li & Qin [98] also use intervals as percentages of the upper limit to create boundaries between the S-curve stages (e.g., 10% and 90% of the upper limit); however, in this analysis the S-curve has only three stages: introductory, growth, and maturity. Escobar & Zarta [59] calculate the inflection point in the models to decide about the current phase in the technology lifecycle; however, merely knowing the inflection point is not sufficient to understand the development stages of the S-curve. Li & Qin [98] use of cosmetics or similar toilet preparations.

To improve the understanding of the limits of the different stages in the S-curve technology life cycle, this study uses the first and second derivatives of the logistic function. The first and second derivatives can be expressed mathematically as follows:

\[ y' = \frac{abcxe^x}{(b + e^{cx})^2} \]  \hspace{1cm} (2)

\[ y'' = \frac{abce^x(b - e^{cx})}{(b + e^{cx})^3} \]  \hspace{1cm} (3)

The maximum value of the first derivative, \( y' = 0 \), represents the inflection point of the S-curve, and indicates the change from the growth stage to maturity in the technological life cycle. The maximum and minimum values of the second derivative, \( y'' = 0 \), respectively, indicate a transition from the emergent to the growth phase and a transition from the maturity to the saturation phase. Figure 2 shows how the first and second derivatives help to differentiate between the technology cycle stages in this study: emerging, growth, maturity, and saturation.

4. Results and discussion

To study the trend of Persian lime technology lifecycle and propose technological strategies, this research uses the S-curve to fit the data obtained by collecting the patents from WIPO. In general, a logistic curve regression is obtained to analyze Persian lime. A general analysis of each stage of the value chain is also performed to delve deep into the details of how the patents are distributed and how the weights affect the overall results found.
other technological fields have shown [18]. Figure 5 shows the collected data and the model from 1975 to 2019; the horizontal axis shows the time window starting in the first year (1975) and ending in the year 45 (2019). The vertical axis represents the cumulative patents per year collected and cleaned from the WIPO database, which are shown in the figure as small red circles, and the blue dashed line is the logistic regression curve that best fit this cumulative patent data. Table 1 shows the parameters and statistics of the resulting S-curve regression model. This model can be expressed mathematically as:

\[
y = \frac{a}{1 + be^{-cx}} = \frac{1012.339}{1 + 1779.532e^{-0.1675867x}}
\]

With a \( R^2 \) and a \( R^2 \) adjusted of 0.99, the logistics model has a good adjustment to the number of patents accumulated per year for the Persian Lime. Table 1 shows the statistics for the logistic S-curve used to fit the patent data. The coefficients \( a, b, \) and \( c \) of the regression are significant with a p value <0.005. This result shows that the S-curve is a highly feasible model that fits the patent data collected, as indicated in other studies and research areas [60]. Furthermore, an additional analysis was made by using the Gompertz regression model to fit the collected data and results were similar; with the \( R^2 \) and a \( R^2 \) adjusted also of 0.99. However, the AIC and BIC criteria had lower values when using the Logistic model. Then, the Logistic regression seems to be a better model than the Gompertz regression for the collected patent data documents from the WIPO databases.

Once the Logistic regression model that better fits the collected patent data in the time window 1975–2019 is attained, the next step is to obtain the forecast for the years forward using the complete S-curve model. Figure 6 shows the S-curve model not only up to the observation year 2019 (e.g., as shown in Figure 5), but for a time window of 100 years, from year one (1975) to year one hundred (2074); the horizontal axis corresponds to the years in the time window. In Figure 5, the left vertical axis continues to indicate the cumulative patent data of the Logistic regression model, which is shown in small black circles; the year of observation, year 45 (2019) when the patent data was collected, is shown as a vertical dashed line. Figure 6 also shows the first and second mathematical derivatives of the obtained Logistic regression model. These first and second derivatives are the continuous lines in blue and green colors, respectively. The mathematical derivatives were scaled and translated in the plane of the logistic regression model to offer a better understanding and interpretation of the maximus, minimuns, and inflection points and their relationship with the Persian lime S-curve model, specifically the limits of the different stages. The right vertical axis indicates the sculation and translation made to the first and second derivatives in the plane where it is assumed that the logistic regression model was symmetrical around the origin. These scales and translation are made to see both the projection of the maximum value of the first derivative to localize the inflection point in the regression model and therefore the transition from the growth stage to the maturity stage; and the maximum and minimum values of the second derivative to localize the transition from emergence to growth and from maturity to decline stages, respectively, in the egression model.
It is possible to imagine Figure 6 divided into two sections. The first section includes the left half of the figure from year 1 (1975) to year 45 (2019) until the vertical dashed line. The logistic regression model was developed to fit the data obtained from the patent database during these years. Until the first half of 2019, the number of cumulative patents obtained from the WIPO database for Persian lime was 507. The transition from the emergent to the growth phase of the technology lifecycle was completed in 2011, or year 37 in the horizontal axis; this transition coincides with the maximum value of the second derivative shown in green color, when \( y_{\text{max}} = 0 \). The observation year, 2019, in the vertical dashed line, coincides with the maximum of the first derivative in the blue color of the logistic regression function. This means that the inflection point of the S-curve regression function was reached in 2019, or that a transition from the growth stage to the maturity stage took place that year, when \( y_{\text{max}} = 0 \). However, in this case of transition between stages, the maturity stage belongs to the second section of Figure 6.

The second section includes the right half of the figure from the vertical dashed line, and ranges from year 46 (2020) to year 100 (2074). This section of the figure corresponds to the forecast made of cumulative patents per year based on the S-curve regression model developed with the data obtained from the first section of the figure. The change from the stage of maturity to saturation is expected to be in 2027 (year 52), when the second derivative reaches its minimum or \( y_{\text{max}} = 0 \) with an estimation of 811 cumulative patents. The logistic regression model and Figure 6 show that the upper limit is expected to be 1012 cumulative patents in the year 100 (2075). The cumulative patents in the saturation stage approach the upper limit year by year; for example, the cumulative patents in the saturation stage for the years 60, 70, 80, and 90 (2035, 2045, 2055, 2065) are 940, 998, 1009, 1011, respectively. It is possibly expected that after 2027, in the obsolescence or saturation stage, a new S-curve or a new cycle will be initiated [61]. However, it is also possible that a new discontinuous technology will replace or substitute the current technologies in the maturation stage before it reaches its limits in 2027 by overcoming market limitations.

Since the Persian lime is in transition between stages of growth and maturity, it is reasonable to consider the best of both worlds. Because it is initiating the maturity stage, it is recommendable to have or be prepared to have an increase in investment in fixed capital as well as the initiation of the development of skills and experience in existing technologies in order to be able to compete with market leaders [101]. In other words, investments should begin by focusing on the adoption of existing technologies in order to pursue an opportunistic strategy that allows for innovation, particularly in production processes, to increase efficiency, while not excluding exploratory innovation to support the next technological discontinuity that may be on the horizon. However, because it is ending the growth stage, the efforts may be focused more on innovation projects than on R&D projects. The fixed capital investment starts to be high compared to previous stages, and the scientific and technological knowledge is less important at the end of this stage of growth because it tends to standardize in the next stage of maturity, which is initiating.

### 4.3. Persian lime value chain

In order to improve the understanding of the value chain of the Persian lime, this study also focused on the phases of cultivation or growth, harvest, post-harvest, and transformation. After categorizing the patents in each phase of the value chain, an S-curve logistic regression of each phase was modelled. Table 2 shows that, although the values of \( R^2 \) and \( R^2 \) adjusted of all stages of the value chain are close to 1, indicating a good fit to the data, the p-values of the regression coefficients for the different stages are not always significant.

Table 2 shows the coefficients and statistics for the different stages of the value chain modeled by a logistic regression. Transformation is the only stage in the value chain where all the regression coefficients are significant with a p-value < 0.05. The transformation is also the stage of the value chain with the highest number of patents and, therefore, has a higher impact on the overall Persian lime S-curve. Then, this study refers to the transformation stage in more detail, as this is the only stage that has a model with some reliability based on its statistics.

Figure 7 shows the patents per year for each stage of the Persian lime value chain. It is obvious that the number of patents at the transformation stage is different from those at other stages in the value chain, which should explain the statistical results about the p-values of the coefficients.
in the regression models. In the 45-year study window beginning in 1975 until the year of observation 2019, the transformation stage accumulated 371 patents from the total of 507 of Persian lime, followed by the cultivation or growth stage (117 patents), the post-harvest (12 patents), and the harvest (7 patents). Then, for the stages with a low number of patents, it would be difficult to state that a prediction can be made based on the data collected.

On the one hand, the statistics of the mathematical model show that the transformation stage is the only one that has some reliability. However, when the different stages of the value chain were analyzed, some descriptive information emerge. For example, the cultivating or growth stage had an accelerated increase in the number of patents from 26 patents in 2011 to 41 patents in 2012 and continued this acceleration until 2019. Before 2011, the higher increase of number of patents was only 3 patents per year. The harvest stage had different discontinuities due to a lack of patent increments in different periods of time, like 1992–2007 and 2011–2016; besides, it is the stage with the lowest number of patents, only 7 patents. There were also no patent increments in the post-harvest stage from 1997 to 2008, but unlike other stages, post-harvest has no patents since 2018.

On the other hand, the transformation stage does not exhibit discontinuities in cumulative patents that occur at other stages of the value chain and does not have long periods of time in which the number of patents does not increase year after year. Table 2 shows the logistic regression model for the stage of transformation in the value chain of Persian lime, which can be expressed mathematically as:

$$y = \frac{a}{1 + b e^{-cx}}$$

$$\frac{579.5719}{1 + 1738.592e^{-0.1793x}}$$

(5)

The transformation stage is in the maturity stage in 2019 as the S-curve has passed the inflection point. According to the logistic regression model of the transformation stage, the change from the emergence stage to growth stage was made in 2008, and the change from growth stage to maturity stage was made in 2016. The transformation stage is a significant component in the analysis of the Persian lime S-curve, with both in the maturity stage and a three year difference between inflections points. For the transformation stage, the total number of patents accumulated is 371 in 2019, and it is expected to be 457 by 2023 when it enters the saturation stage. The upper limit in the saturation stage is predicted to be 579 cumulative patents in 2075. The transformation stage at the time of observation in 2019 is approximately in the middle of the maturity stage (2016–2023). As stated before, in the maturity stage, the technologies are already widely known and potentially offered in the market, requiring high investments in fixed capital and efforts focused on more innovation projects [101].

Therefore, most of the technologies developed and associated with the Persian lime are focused on the transformation phase, probably because this is a stage where the economic benefit is higher. Then, it gives the chance to move the development of technologies to other stages that could improve and increase the value of the various products made from, or made for, Persian lime.

5. Conclusions

Persian lime belongs to one of the six groups of economic interest in the citrus agro-industry. At present, to the best of the author’s knowledge, general studies on the technological life cycle analysis method of the Persian lime sector are not reported in the academic literature. The trend of a large number of innovations or technologies is better explained by an S-shaped curve. Then, a majority of the technologies follow the stages of emergence, growth, maturity, and saturation. The present study follows previous research by interpreting technological growth as the accumulation of innovations by industry [15]. This article uses patents from the World Intellectual Patent Office (WIPO) and demonstrates empirically that the Persian lime sector innovations and its value chain transformation stage follow a trend similar to the S-curve technological model.

Results show that the Persian lime sector has a non-linear trend and is fitted to the logistic regression model following the technological S-curve. In general, the Persian Lime has had the emergence phase from 1975 to 2011, the growth phase from 2012 to 2019, and is expected to have the maturity phase from 2020 to 2027 and the saturation phase from 2028 to 2074. The global Persian lime sector was in the year of observation 2019, at the inflection point of the S-curve model, transiting from the growth stage to the maturity stage. The Persian lime value chain analysis shows that only the transformation stage has statistical significance, and that was the only stage analysed in detail in the study. The transformation stage was at the maturity stage of the model S-curve in 2019.

The period from 1975 to 2019 (45 years) is characterized by progress in the generation of technologically innovative knowledge for the Persian lime sector, reflected in the number of patents. Most Persian lime patents are filed by first-world countries led by the United States, South Korea, and Japan; however, alongside the United States, citrus fruit production is led by India, Mexico, Brazil, and Spain. While not a homogeneous comparison, this analysis can give an idea about how value is created and captured by each leading country and the focus of their efforts. This is a first look that could aid policymakers in developing strategies to improve value capture in regions and countries that not only produce Persian lime.
but also focus on science, technology, and innovation in the sector. Practitioners and managers can benefit from the forecasting of the technology S-curve development stages of Persian lime because this model would help to control and give direction to investment and strategies in Persian lime technologies and innovations in a scientific and efficient way. Additionally, this leads to improved parameters and characteristics of Persian lime in general and in each stage of its value chain (e.g., quality, efficiency), with projected benefits for the citrus agro-industry.

The Persian lime is in the transition between growth and maturity stages of the S-curve technology life cycle. Because it is ending the growth stage and initiating the maturity stage, the scenario would be characterized by increasing the acceptance of the existing and diffused technologies to ensure their market presence. Therefore, the main strategy for the Persian lime in this stage could be the reduction of costs, efficiency in the production processes translated into process innovation, and pricing strategies to take advantage of the opportunities that the market offers. However, due to the proximity of the obsolescence stage and the potential creation of a new S-curve, the technological leaders would use an offensive strategy focused on the possibility of exploring new technologies that exceed the current functionality of the technologies developed so far. Other non-leadership organizations would use two strategies. First, the organization would use a defensive strategy by following the technological leader when approaching the saturation stage, in order to retain a market position when the new S-curve emerges; and second, the organization would employ an imitative strategy in specific environments focusing on production technologies, and thus cost reduction, with a minimum of innovation.

Transformation is the phase in which most of the patents in the Persian lime value chain have been accumulated. Therefore, transformation is the phase in the value chain where most of the innovative technological efforts have been concentrated. Then, this is the factor with the highest weight affecting the general technology life cycle of the Persian lime sector. It was the only phase that could be analyzed to make predictions according to the statistical tests of the coefficients in the logistic model. The status of the transformation phase is in the maturity stage of the technology lifecycle. This brings opportunities in two ways: first, to adopt already developed technologies in the transformation phase and improve process efficiency to reduce costs; but also, to reinforce innovative technological efforts in other phases of the Persian lime value chain such as growth, harvest, or post-harvest.

This study, like most studies in this field, has certain limitations. The fundamental shortcoming is that patent data is used as a variable that encompasses the entire concept of technological innovation. Patents, as mentioned in the methods section, are not a generalizable indicator of technological innovation; in fact, many inventions are not protected by patents or use alternative intellectual property strategies (e.g., industrial secret). Future research could incorporate other metrics besides patents in the analysis to supplement and improve the current research’s results and conclusions.

Another limitation of the current study is that data was collected from only one database (e.g., WIPO). Future research should include other patent databases to obtain a broader landscape of Persian lime technologies and their value chain. However, incorporating other databases requires the task of homogenizing observations and data from various methods and formats. Another drawback of the study is its narrow emphasis to a single sector. Therefore, future analysis could encompass the entire agro-industry in general, and then separately analyze the six groups of world economic interest mentioned: oranges, tangerines, lemons and limes, and grapefruit. In terms of policy making, future research could analyze the asymmetric information phenomena reflected in patents to explain the approaches of technologically innovative countries and their differences from the most productive countries. Also, some studies could analyze the sector at a regional level using patent information (e.g., companies, ownership, inventors, etc.) that could inform the proposed strategy; the regions could be countries or sub-regions within the countries characterized by production or technological capabilities. The research findings have some limitations because they are heavily reliant on current policy instruments and external factors unique to each country, region, or organizations. While some strategic recommendations are included in this study, their implementation is dependent on policies and contexts unique to countries, regions, and clearly organizations. Consequently, future studies should consider external factors (e.g., political, legal, cultural, and social) that would produce changes in the forecasting model of the sector. Finally, it would be beneficial to examine the evolution of technological systems in other sectors of the agro-industry using the s-curve to assist the decision- and policy-makers.

Declarations

Author contribution statement

Hugo Martínez_Ardila, Ph.D: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Angie Corredor_Clavijo, Industrial Engineer; Vivian del Pilar Rojas_Castellanos: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Juan Camilo Lesmes, MBA; Orlando Contreras, PhD: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data will be made available on request.

Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] J.D. La Padilla-de Rosa, et al., Innovation in a continuous system of distillation by steam to obtain essential oil from Persian lime juice (citrus latifolia tanaka), Molecules 26 (4172) (2021) 1–18.
[2] H.-S. Hou, et al., Extraction of essential oil from Citrus reticulate Blanco peel and its antibacterial activity against C. acnes (formerly Propionibacterium acnes), Heliyon 5 (12) (2019), e02947.
[3] C.A. Ledesma-Escobar, M.D. Luque de Castro, Towards a comprehensive exploitation of citrus, Trends Food Sci. Technol. 39 (1) (2014) 63–75.
[4] M. Agusti, C. Mesejo, C. Reig, A. Martínez-Fuentes, Citrus production, in: G.R. Dixon, D.E. Aldous (Eds.), Horticulture: Plants for People and Places, Volume 1, Springer Netherlands, Dordrecht, 2014, pp. 159–195.
[5] S. Bayineni, R. Babu Vooka, Development of agro-based industries in India, The IUP Journal of Agricultural Economics (3) (2004) 53–61.
[6] Concept of agribusiness [Online]. Available: https://agris.fao.org/agris-search/search.do?record_id=us201200473408, 1957.
[7] A. Mrówczyńska-Kaminska, B. Bajan, Importance and share of agribusiness in the Chinese economy (2000-2014), Heliyon 5 (11) (2019), e02884.
[8] M.F. Neves, The Future of Food Business: the Facts, the Impacts and the Acts, second ed., World Scientific, Brazil, 2014.
[9] M.A. Gunderson, M.D. Boeble, M.F. Neves, S.T. Sonka, Agribusiness organization and management, in: Encyclopedia of Agriculture and Food Systems, Elsevier, 2014, pp. 51–70.
[10] H.X.G. Ming, W.F. Lu, C.F. Zhu, Technology Challenges for Product Lifecycle Management, 2004 [Online]. Available: https://scholar.google.com/citations?user=j9kvlalaasajampcrl=es&amp;oi=ara.
[11] A.M. Badawy, Technology management simply defined: a tweet plus two characters, J. Eng. Technol. Manag. 26 (4) (2009) 219–224.
M. Priestley, T.J. Sluckin, T. Tiropanis, Innovation on the web: the end of the S-curve? Internet Histories 4 (4) (2020) 390-412.

H. Lee, S. Lee, B. Yoon, Technology clustering based on evolutionary patterns: the case of information and communications technologies, Technol. Forecast. Soc. Change 78 (6) (2011) 953–967.

A.K. Firat, W.L. Woon, S. Madnick, Technological Forecasting: A Review, Massachusetts Institute of Technology, 2008 [Online]. Available: http://skat.ihmc.us/rid1ncnmm9z943-1197xjf-5cgb/2008-15.pdf.

L.D. Escobar, J.W. Zartha, Application of the technology life cycle and S-curves to forecast energy and technology databases, Technol. Forecast. Soc. Change 73 (7) (2006) 835–842.

M. Bengisu, R. Nekhili, Forecasting emerging technologies with the aid of science and technology databases, Technol. Forecast. Soc. Change 78 (6) (2011) 159–174.

R.R. Alvarez, The transnational state and empire: U.S. Certifying the technology life cycle and S-curves to forecast energy and technology databases, Technol. Forecast. Soc. Change 73 (7) (2006) 835–842.
