



# Infrared Drying Trends Applied to Fruit

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**Aims:** This article seeks to identify the main products to which drying is applied, mainly by infrared, as well as the mathematical models used to evaluate a product.

**Background:** The drying of agro-industrial products is a very important unitary operation to avoid post-harvest losses.

**Objective:** This article looks to respond to the following questions: Which raw materials are subjected to far-infrared drying? What are the mathematical models used in the application of far-infrared?

**Method:** To identify the most focused articles on the topic, we worked with the search equation “TITLE-ABS-KEY (‘infrared drying’) AND fruits AND [LIMIT-TO (SUBJAREA, ‘AGRI’) OR LIMIT-TO (SUBJAREA, ‘ENGI’)],” which was run in the Scopus database for scientific articles.

**Result:** After knowing the different technologies, more than 23 applications in agro-industrial products were identified. In these applications, it is observed how quality is one of the most important factors in the preservation of dehydrated products; far-infrared drying helps retain sensory quality in products such as sweet potatoes, grapes, *Cordyceps militaris*, and mangoes.

**Conclusion:** A common factor that could be found from the articles and patents was the application of this infrared drying technique in fruits and vegetables with high water content, such as kiwi, chives, and mushroom varieties. These articles and patents based their studies on optimizing the technique by varying drying times, temperatures, and pressures, even sometimes combining different drying techniques—all to preserve the organoleptic characteristics of the product, avoiding damage to thermolabile compounds and obtaining a dry food of very good quality, performance, and characteristics.

**Keywords:** drying, far infrared, fruits, mathematical models, agro-industrial products, unitary operation

## INTRODUCTION

Drying in food and non-food agro-industrial products is a unitary operation of great importance both at a business level and at an academic and research level, since the sectors of application are quite broad, such as fruit, flowers, grains, meat, dairy, spices, and dyes. It is also an operation before many size reduction operations, increasing the useful life of the products by eliminating the highest available water content and therefore reducing costs in product transportation freight. Among various types of drying such as microwave, hot air, and some hybrid systems

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(Cuccurullo et al., 2019), drying by forced convection is the most used in this unitary operation due to the benefits of cost and time drying, but despite the abovementioned, the affectations on the nutritional and organoleptic characteristics to which the products are submitted are quite high, which have taken to the innovation in other more efficient techniques and conserve better the nutritional and organoleptic characteristics of these products. Among the most efficient techniques are freeze drying (FD), far-infrared radiation drying (FIRD), heat pump drying (HPD), hot-air drying (HAD), and hot air combined instant controlled pressure drop drying (DIC). Some of these techniques have been well-studied, but other more emerging techniques such as far-infrared drying have not had as much theory published, so this article seeks to answer the following questions: Which raw materials are subjected to far-infrared drying? What are the mathematical models used in the application of far-infrared? To answer the two questions posed, this document consists of four phases. In the first phase, a theoretical framework is presented that relates the main concepts or definitions about the unitary operation of far-infrared drying. In the second phase, the methodology is explained with emphasis on the search equation used in Scopus. In the third phase, the results are explained in terms of countries of origin of publications, type of journal, time series of the articles and topics, raw materials evaluated in the articles, and the mathematical models. The last phase contains a discussion and an analysis of patents and contributions that will give answers to the questions raised as the main axis of this article.

## CONCEPTUAL FRAMEWORK

Among the most important challenges at present worldwide is the conservation of food, mainly fruits, and vegetables, which a great loss occurs in the post-harvest process. One of the alternatives that offer better results in conservation is drying, one of the oldest techniques (Cheng et al., 2019), which is one of the methods that allow the separation of water from a solid (Ocon and Tojo, 1977) and consists of reducing the moisture content to a safe level where deterioration by microbial conditions can be significantly minimized (Cheng et al., 2019).

The drying is usually by evaporation in a gaseous stream, and the most commonly used gas for the drying application is air (Zartha and Palacio, 2011). This treatment can extend the shelf life of these products with great success (Wu et al., 2019), making them more acceptable for marketing or further use (Valiente and Tlaczin, 1991). Currently, dry products are well-received by both consumers and transporters because the dry product facilitates transport and storage reducing costs (Wu et al., 2019). In the last decades, different drying techniques have been developed or implemented among which are HAD, FD, microwave drying, and infrared drying (Wu et al., 2019).

HAD is a process in which food is exposed to a flow of hot air. This process has no special requirements for expensive equipment and is commonly used because of its low process costs; however, this process has low energy utilization efficiency. Hot-air-dried products can reach a shelf life of ~1 year (Wang,

2019). But the long drying time causes a significant decrease in the quality of the final product (Zhao et al., 2019).

Freeze-dried food is considered the benchmark of high-quality dry products, which could preserve as much as possible several original properties of fresh materials such as appearance and nutrients (Zhao et al., 2019).

Microwave drying allows the food material to be placed in an electromagnetic field where, due to the friction and collision of the water particles, its temperature is increased and the process of water evaporation is accelerated (Wang, 2019). This method is compared to forced convection drying with hot air; microwave drying has a shorter drying time, has higher energy efficiency, and improves properties such as aroma, color, and rehydration, along with nutritional properties (Leanerts et al., 2018).

One of the drying methods that has gained great relevance in recent years at an industrial level is infrared drying, which years ago did not appear as an option for the industry, but due to the research on this type of drying that has been carried out and the advantages it has over other drying methods, it has begun to be implemented.

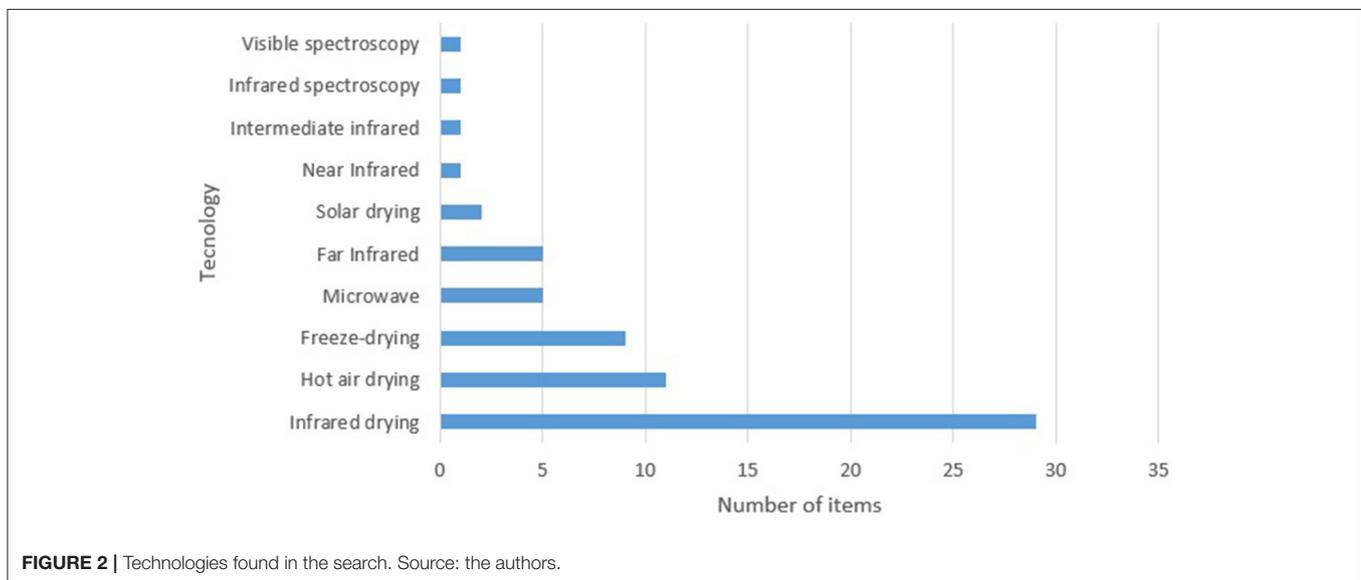
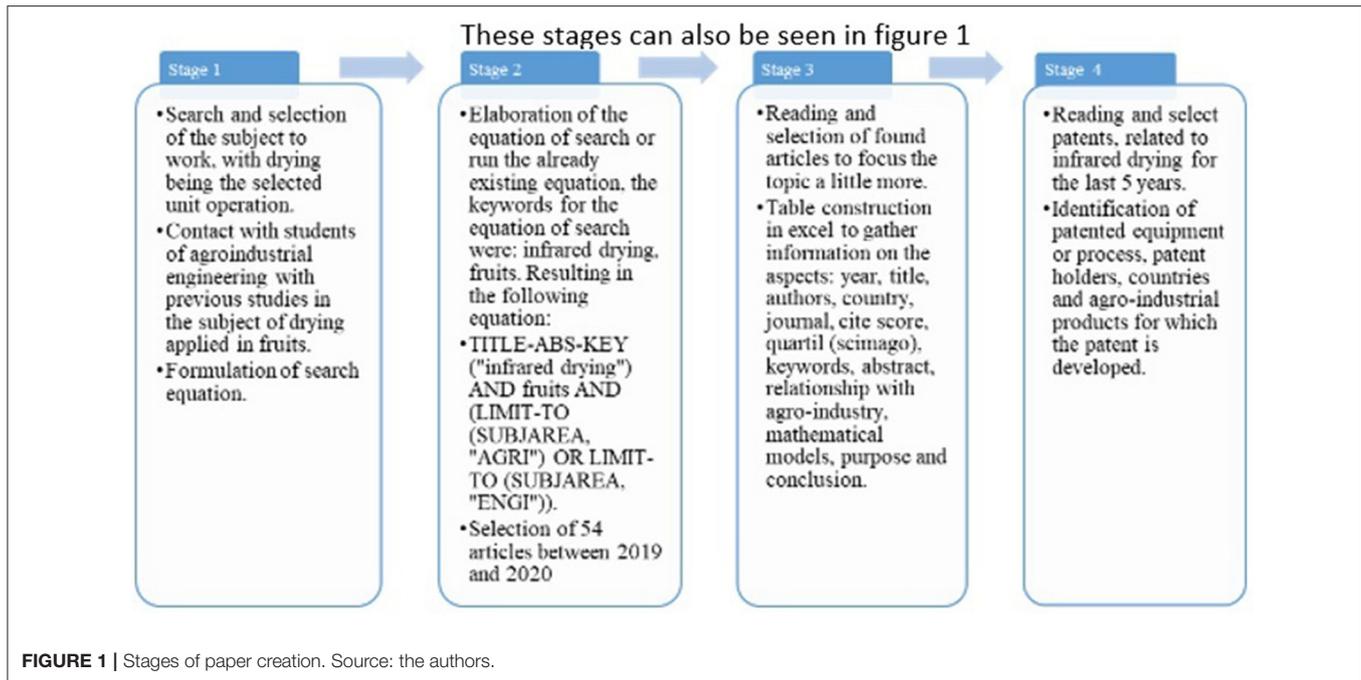
Infrared drying is based on electromagnetic radiation. Compared to other drying media, especially HAD, infrared produces savings in energy consumption, which is an important step toward conserving available energy sources (EL-Mesery et al., 2019). In similar conditions, infrared drying has great advantages over traditional air drying. Studies have shown that infrared has an effective moisture diffusivity and a higher thermal sensitivity than air drying (Wu et al., 2019).

In the industry, there are three types of infrared drying (far-, near-, and medium-infrared drying), of which the most emerging has been the far-infrared drying. This can be widely implemented in the food industry, as it can be used to dry a wide variety of agricultural products. This type of drying has several advantages if compared to traditional drying, ranging from efficient heating of products and excellent energy efficiency to a high quality of dry products because this type of drying does not allow the organoleptic and chemical characteristics of the products to be lost.

Several studies determined that drying of agricultural material through far-infrared is one of the most efficient, since the heating that takes place in it manages to promote the rate of dehydration of the products and also helps to improve the quality of these. This type of drying is very versatile, since it can be used alone or as a complement to other operations (Liu et al., 2019).

Infrared drying is quite practical due to its uniform heat distribution, fast drying speed, and simplicity of the equipment. Among the infrared technologies, FIRD was found to be more suitable for food processing, as most food components could absorb radioactive energy in the far-infrared region (Zhao et al., 2019).

Infrared radiation has become an alternative technique for food drying because the equipment required for this process is versatile and simple, which allows faster heating and therefore reduces drying times. Infrared drying works when the infrared radiation penetrates the material, and it is converted into heat energy and thus removes water more evenly. Infrared drying allows a more uniform distribution of heat than convection



drying, and therefore, a higher-quality product is obtained (Rashid et al., 2019).

## METHODOLOGY

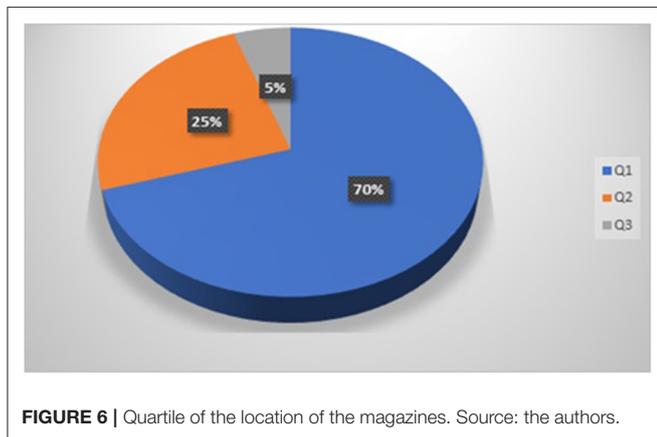
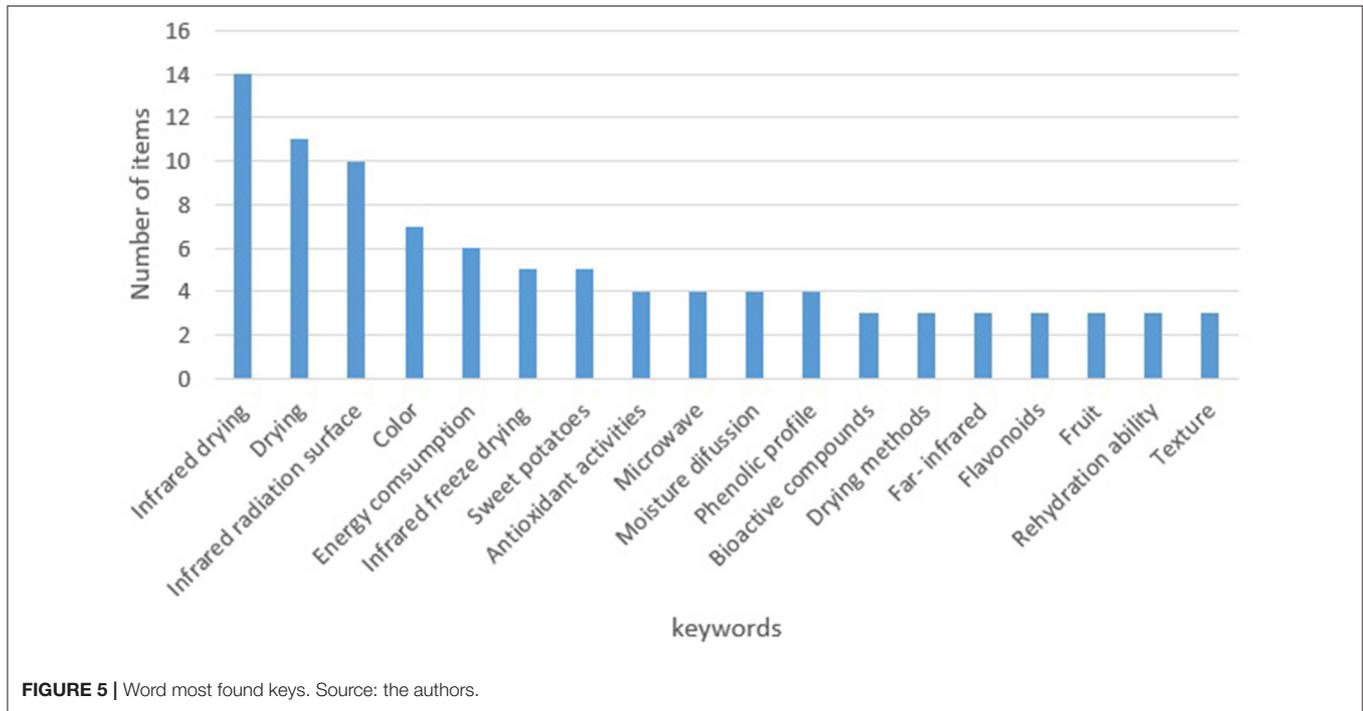
To obtain good results in the reading, the work was divided into four stages as follows:

- **Stage 1:** Search and selection of the topic to work on. The topic of drying was chosen because it is an old method that is very useful for the industry today. Subsequently, contact was made with agro-industrial engineering students who had

already made progress in drying technologies applied to fruit. The search equation with which the work was developed was obtained.

- **Step 2:** Elaboration of a search equation or run of the already existing equation to obtain articles
- To expand the topic, the keywords used for the equation were Infrared drying, Fruits, resulting in the following equation:
- TITLE-ABS-KEY ("infrared drying") AND fruits AND [LIMIT-TO (SUBJAREA, "AGRI") OR LIMIT-TO (SUBJAREA, "ENGI")]. As it was an equation previously worked with, only 54 articles were taken into account between 2019 and 2020.





the technology that appears in the lowest number of articles is drying by visible spectroscopy mentioned in two articles. But in this case, although the infrared drying is the most studied, it is not emerging. There are reports of its application from more than 10 years ago, which is why it is discarded, and far-infrared drying is selected, which was studied in five articles of the year 2019 and 2020, which shows that it is an emerging technology that brings multiple positive effects in the drying of agro-industrial products, leaving it in an advantage over the other technologies.

After knowing the different technologies, the products worked in all the articles were identified, and **Table 1** is created in which the author, the product that this author investigated, and the purpose of this investigation are shown. This table is made to

extend a little more information about the products and the purpose of these for each author, besides that it is possible to understand more widely the discussion that is later on.

Taking into account that the drying process is a very important operation for the conservation of food and the quality of the final product, which leads to innovate in new drying processes or evaluate the different technologies that exist to determine which is the most appropriate, taking into account the type of product and the process to which it will be submitted after the drying to ensure the higher performance of the product and longer duration, that is why in **Figure 3**, we can see which are the countries that have most evaluated the drying technologies applied to raw materials, China being the country with the highest percentage of publications of articles with 34%, followed by Iran, which had a participation of 11%, and the United States, with 8% of publications. We can also find to Colombia with a participation of 2% and 19 other countries that made publications of the drying technologies.

**Figure 4** shows a compilation of the journals publishing the articles studied, in which 21 journals are reported, among which food science and technology, food process engineering, and food chemistry present the three first places concerning a greater number of publications of articles with a percentage of publications of 11, 7, and 6, respectively.

Keywords are an important part of an article, since just by reading them, we can deduce the subject of the article as well as make it easier to find the articles in the databases. For this reason, **Figure 5** shows a compilation of keywords of the articles evaluated, giving a total of 18 keywords being infrared drying, drying, and infrared radiation Surface, the frequent keywords, participating in 14, 11, and 10 articles respectively.

**TABLE 1** | Identification of products worked by each author.

References	Product	Purpose
Rezaei et al. (2019)	Potato slices	Measure the shrinkage of the potato slice area during the drying process
Rashid et al. (2019)	Sweet potato slices	The study aims to determine the drying of sweet potatoes with multi-frequency ultrasound pre-treatment (U.S.A.). UU. (20, 40, and 60 kHz) at three different infrared (IR) drying temperatures (60, 70, and 80°C) and evaluate the phytochemical and textural effect.
Onwude et al. (2019)	Sweet potato slices.	Determine the performance of different combined infrared (IR) and hot air strategies for sweet potatoes.
Qu et al. (2019)	Black Tea	Identify the types of drying for the tea leaves, which guarantee the best nutritional, organoleptic and sensory characteristics of the final product
Khampakool et al. (2019)	Banana snacks.	Preserve features, plus cost savings for processing and transforming raw materials, such as fruits.
Lin et al. (2019)	Mushroom slices and whole mushrooms	Investigate the impact of microwave vacuum drying (MVD) on moisture uniformity in Mushroom slices and whole mushrooms ( <i>Agaricus bisporus</i> ) by hyperspectral imaging in the near-infrared (NIR) in combination with multivariate analysis.
Rojas et al. (2019)	Potato slices	This work explored the use of ethanol and perforations individually and combined to improve both infrared drying and rehydration of potato slices.
Zhou et al. (2019)	Peaches	To evaluate the effect of infrared dehydration as a function of diffusion humidity, when using this integrated with a convective drying method
Yao et al. (2019)	Mango slices	Dry mango slices by 2 methods, hot air drying, and far-infrared drying, evaluating the effects on the physicochemical and organoleptic characteristics of the product.
Selvi et al. (2020)	Rose petals	To evaluate the effects of infrared drying at different temperatures and times on rose petals, evaluating color change, phenolic content, and dry area.
Sadeghi et al. (2019)	Kiwi fruit	To evaluate the physicochemical behavior of kiwifruit when subjected to infrared drying and to determine the variables of drying.
Ratseewo et al. (2019)	Rice varieties	To evaluate the effects of convection and far-infrared drying, in pigment rice, concerning bioactive compounds.
Kayacan et al. (2020)	Khaki Fruit	To evaluate the effects of 4 drying techniques (convection drying, infrared, freeze-drying, and ultrasound with vacuum), against chemical compounds in khaki fruit and to determine the most efficient drying.
Darvishi et al. (2019)	Tasty herbs	Evaluation of the drying variables, such as wind speed, temperature, infrared power, and the relationships with rehydration, color change, and energy consumption, to optimize the drying process and guarantee its quality.
Quispe-Fuentes et al. (2020)	Machia berries	To evaluate the effects of four drying techniques (convection drying, infrared and vacuum drying, freeze-drying, and sun-drying), against the physicochemical compounds of machine-goats.
Cheng et al. (2019)	Mango slices	A comparison of traditional solar and tunnel drying methods was carried out, and a control sample dried using an electric dryer, and it was observed that the samples dried by traditional solar drying were the ones with the greatest variation.
Wu et al. (2019)	<i>Cordyceps militaris</i>	The moisture ratio was measured to determine the factor that most affects the drying kinetics and the final properties of the product.
EL-Mesery et al. (2019)	Biomass	The total energy consumption (Et) and the specific energy consumption (SEC) were calculated to determine how expensive a biomass drying process can be and to analyze which process can be more economical.
Shchitov et al. (2019)	Animal Feed	Infrared drying for animal feed on a farm
Gao et al. (2019)	Lemon	The main purpose of this research was to determine the effect of various methods of dehydration on the phenolic components and antioxidant activity of the lemon.
Wang et al. (2019)	Shiitake mushrooms	Perform comparative analyses on drying kinetics, color, rehydration ratio, polysaccharide content and composition of aromatic components of shiitake mushrooms dried by hot air drying, infrared drying and microwave-assisted intermittent hot air drying
Wu et al. (2019)	<i>Cordyceps militaris</i>	In this study, a new laboratory-scale apparatus was developed that uses infrared lamps to replace the electric heating plate for the freeze-drying of <i>Cordyceps militaris</i> .
Zhou et al. (2019)	Shiitake mushrooms	The purpose of this study was to evaluate the effect of different drying methods on the sensory and nutritional attributes of shiitake mushrooms.
Hasan et al. (2019)	Fruits and vegetables	To apply drying technologies (infrared) on fruits and vegetables to extend the shelf life and means of conservation.
Cuccurullo et al. (2019)	Apple slices	Compare the performance and color change in the product, using different drying methods and temperatures
Zeng et al. (2019)	Kiwi slices	To analyze the behavior and changes in characteristics of kiwifruit slices using the far-infrared radiation technique.
Khaing Hnin et al. (2019)	Yogurt that melts pink flavored	Compare two different drying techniques to determine which has better effects on the product
Safarov et al. (2019)	Rosehips	Establish the appropriate drying parameters to be applied to the product to have the expected results.
Sadeghi et al. (2019)	Kiwi slices	To evaluate different effects such as coarseness, the distance between samples, cut thickness, etc. When evaluating moisture diffusion and drying speed of kiwifruit pieces
Sadeghi et al. (2019)	Evaluation of different mathematical models	Determine the drying curves between a large number of mathematical models and artificial neural networks

*(Continued)*

TABLE 1 | Continued

References	Product	Purpose
Hnin et al. (2019)	Agricultural products for healthy snacks	Compare three drying methods to establish their efficiency and which both contribute to the organoleptic characteristics of different agricultural products as well as measuring water activity, expansion ratio (ER), and bulk density, as well as other aspects.
Nalawade et al. (2019)	Mint leaves	The effect of four dried types on the quality of the product was evaluated in terms of chlorophyll, total carotenoids, essential oil yield and composition, color, browning index, and rehydration ratio.
Wang et al. (2019)	Chives slices	The effects of vacuum, ethanol pre-treatment, and infrared hot air-drying methods on the characteristics and quality of spring onion slices were examined.
Liu et al. (2019)	Kiwi slices	This study was conducted to observe the effect of ultrasound on moisture migration while performing the far-infrared drying process.
Illa et al. (2019)	Bacterial cellulose	The effect of drying on the physicochemical, morphological, and structural properties of bacterial cellulose produced by Fourier transform infrared spectroscopy was systematically studied.
Vega-Gálvez et al. (2019)	Chilean papaya	The effect of 5 different types of drying on bioactive compounds and biological activity of Chilean papaya was evaluated.
Carvalho et al. (2019)	Macadamia nuts	Evaluate the oxidative stability of intact macadamia nuts using near-infrared spectroscopy, oven-dried for 4 days at 30°C, 2 days at 40°C, and 1 day at 60°C to achieve a grain moisture content of 1.5%.
Nogueira et al. (2019)	Acerola ( <i>Malpighia emarginata</i> D.C.)	Use the residues of the acerola, drying them, to be able to take advantage of its bioactive compounds.
Onwude et al. (2019)	Sweet potatoes	Improve the quality of the dry product, by intermittent infrared and convection (IIRCD)
Fu et al. (2019)	Grape Seeds	To determine the effects of infrared radiation combined with the heating on the grape seeds and the quality of the oil.
Yu et al. (2019)	Asparagus stalks	To evaluate the properties of asparagus stems after different drying methods.
Borda-Yepes et al. (2019)	Blueberry Leaves	To evaluate the effects of infrared drying and microwave drying on the polyphenol content of blueberry leaves.
Yan et al. (2019)	Bitter Gourd	Evaluate different drying methods on the quality of the bitter gourd.

Source: the authors.

In **Figure 6**, we can see the classification of the quartile of the magazines that published the articles of the drying technologies. This allows us to evaluate the importance of the magazines within their area, which is divided into four quartiles, classified from highest impact to lowest impact (Cheng et al., 2019), with those in Q1 having the greatest impact on the scientific community. In this case, we have 70% of journals in Q1, 25% in Q2, and finally 5% in Q3.

## DISCUSSION

Journals that publish scholarly articles have a different focus each, although they may be in the same area each focusing on something different, some may generalize the topic while others zoom in and reduce the information further, making it more accurate and focused on some specific topics. In the research, in general, it was found that all the magazines talk, mostly, about topics focused on food, technologies, innovation, engineering, and research.

The journal in which more publications were found in the “food science and technology” followed by the “food process engineering,” both journals focused on a food field, one in science and technology and the other in engineering processes. These journals seek to publish progress on these issues, and to determine the progress, the best option is to compare it with what already exists or with other techniques to determine which is the most effective, and this is as several authors express it,

as Carvalho et al. (2019), Wang (2019); and Fu et al. (2019), among others who made comparisons between different methods of drying and comparison between the product by applying the treatment and without applying it.

This is what these journals are looking for—to publish the improvements that have been found by different researchers worldwide, to improve access to information, and to generate benefits for the readers who are carrying out their research. The journals also have an impact level that is determined by the quartile SCImago in which it is located, the quartile what it looks for is to locate the publication in a journal according to its level of importance and impact, achieving this way that the publications are ordered so that the readers can facilitate their search of information (COLCIENCIAS, 2018), taking into account the previous thing and that the quartiles are Q1, Q2, Q3, and Q4, where Q1 is composed of the journals with the greatest impact, the current review is based on 70% of publications in Q1 journals, which suggests that the articles used for the study have a great impact among readers of research-related topics.

The research focused on the reading of publications on drying especially with the infrared technique, that is why in the search of keywords exposed by the authors of the publications, the main ones that are found are “infrared drying,” “drying,” “infrared radiation surface,” and some of the different products that are applied to the drying. The keywords are important because they allow the reader to identify which is the central topic of the article you are reading. This is why if the research was based on the search for infrared drying information, the most keywords found

were related to these topics. Some of the authors who mention the most repeated keywords in the articles are Rashid et al. (2019), Daniel and Onwude (2019), Khampakool et al. (2019), and Borda-Yepes et al. (2019), among others.

They in their publications gave reason for the advances they have achieved with this drying technique compared to other techniques and with the improvement in the retention of the nutritional compounds of the products. Based on the above, it was possible to identify more easily the issues related to the research.

## Products or Found in the Reading

The drying of raw materials is a unitary operation of great importance in the handling of raw materials and their use, as can be seen in **Figure 7**. The range of products evaluated with the drying technologies is quite wide at 30 raw materials for different agro-industries, the shitake fungi being the most studied, followed by the kiwi. Most of these raw materials underwent evolution to determine the most efficient drying technology in terms of conservation of physicochemical and organoleptic properties. The objective of the investigations consulted, as it has already been expressed, is to achieve an improvement in a certain process. For the present case, it is to identify the improvements in the process of drying fruits and some vegetables using infrared, and for that, it was necessary to measure the differences that were achieved, comparing the process of drying with another type of drying, for example, HAD, lyophilization, and spray drying, among others.

To observe the improvements, the results were analyzed by the different authors applying some mathematical models. Rezaei et al. (2019) used linear and algorithmic models to determine the shrinkage or reduction of the area of potato slices, managing to optimize the adjustment of the power of the microwave with which the infrared used for drying is applied. Borda-Yepes et al. (2019) used the drying curves to determine the moisture present in a product, which was dried by infrared and by microwaves, concluding that microwave drying preserves better qualities than infrared does. Wang (2019) compared HAD, infrared drying, and microwave drying and determined which of these was more appropriate and presented better conditions for processing shiitake mushrooms, determining that microwave drying considerably reduced drying time and higher polysaccharide content compared to the other methods. Besides Zhao et al. (2019) made a sensory, texture, and nutritional evaluation of shiitake mushrooms dried by four different methods, cold drying, far-infrared drying, heat pump drying, and HAD, determining that far-infrared drying was the one that obtained better overall quality in shiitake mushrooms.

The products to which the different treatments are applied are varied, but they have something in common, that is, the search for the different changes and improvements in the conservation of the same ones. Some mushrooms are worked by Wang (2019), Lin et al. (2019), Wu and Zhang (2019), Wu et al. (2019), and Zhao et al. (2019). Potatoes and sweet potatoes are among the most investigated products found, investigated by Rezaei et al. (2019), Rashid et al. (2019), Daniel and Onwude (2019), Rojas et al. (2019), and Onwude et al. (2019). All the

authors investigated the products to adjust the drying processes and seeking to obtain a high-quality product while reducing costs. The authors also express that with research and making the respective adjustments to the equipment and the process, infrared drying can become a very useful technique for drying.

The agro-industrial products that are subjected to drying are very diverse, but more often, we are starting to work with exotic fruits, which have a lot of potential in the agro-industry because of the high nutritional component they possess, also for these times where the tendency is to rescue or discover other foods that reinforce diets, healthy, and without the addition of chemicals, giving other alternatives for consumption in places where there is still food insecurity.

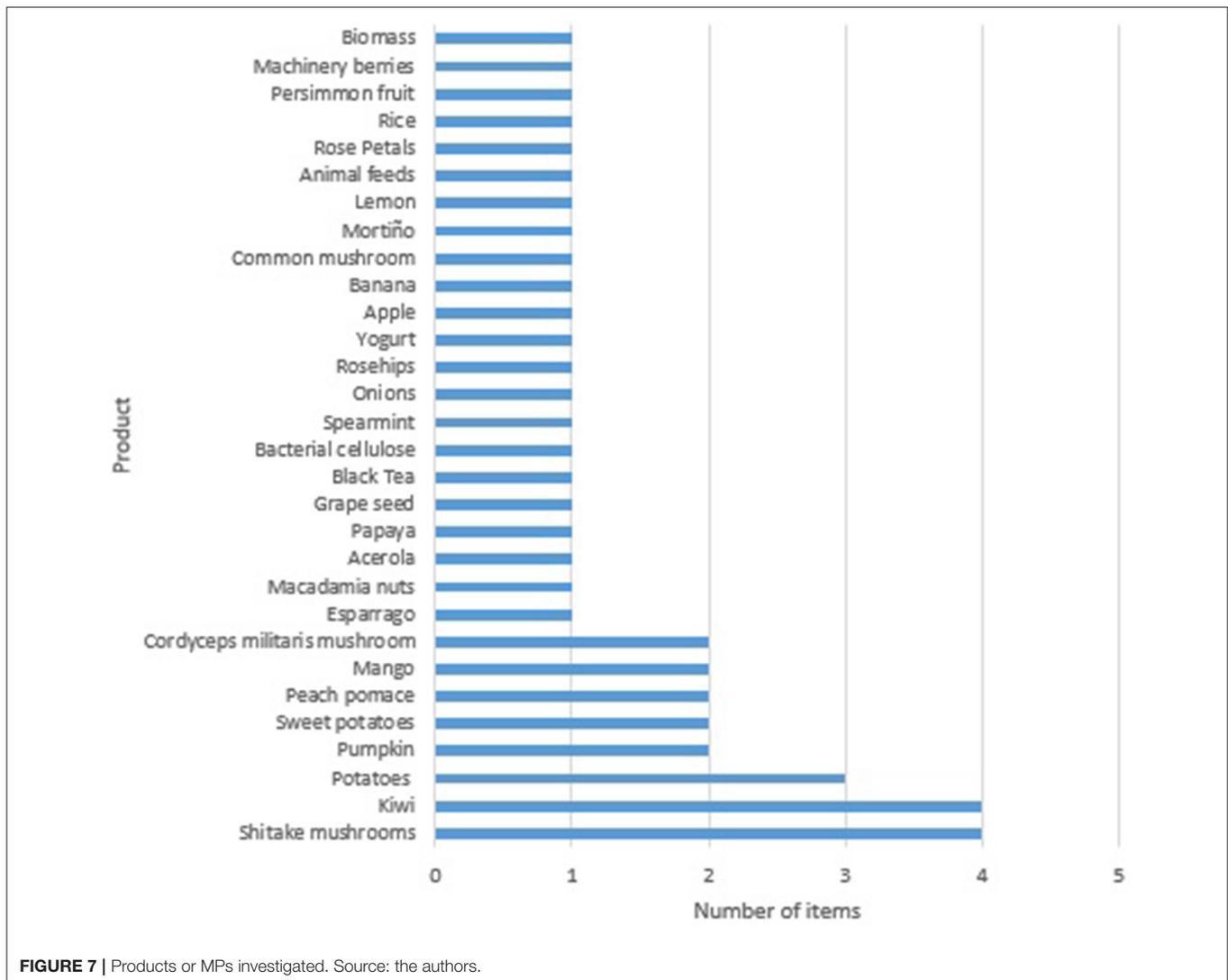
## Mathematical Models

We were able to identify the most important and most implemented mathematical models (which are repeated more in the literature) in far-infrared drying, which are shown in **Table 2**, in this same table, you can see the implementation given by the different authors to each of the models. Only three mathematical models were extracted, and these are repeated in two or more articles, and because in others they only used some formulas for simple calculations, so importance was given to the most advanced.

Many of the articles are comparisons between various drying techniques to determine the most efficient, but others focus on the description of mathematical models. To standardize the drying processes by determining the optimal variables to carry out the drying operation efficiently, in these, drying curves, optimal temperatures of drying, wind speed, the distance of the product to the infrared radiation, and the power of the same are determined. The models are very varied, as can be seen in **Table 2**; this depends on the object of study and the results expected in each product.

The study also identified a statistical model, analysis of variance (ANOVA), which is implemented in infrared drying to determine the most significant processes of the same but also implemented to determine the most optimal variables to perform the drying process, variables such as humidity, temperature, time, etc. Cheng et al. (2019) used this model to compare two drying methods, one with far-infrared and the other without far-infrared, giving favorable results for the method that implemented far-infrared.

Most of the mathematical and statistical models used in the articles have the purpose of predicting or determining an important variable in the drying process, either the drying speed, drying temperature, or the amount of humidity that a product to be dried may present. In some cases, these mathematical models are implemented with the purpose of being able to calibrate the equipment in the most optimal way to obtain the best results for its later analysis (Cheng et al., 2019). These are fundamental in this process, since they are in charge of determining if the product to which this process was carried out lost all the humidity that it presented when initiating the process of drying (Rojas et al., 2019). These are fundamental, since when making them, it is possible to be avoided that a finished product is commercialized with humidity, which can generate losses either



because it does not fulfill the wished characteristics or by the growth of microorganisms or fungi in the product due to the humidity content. Although drying many mathematical models can be taken into account in this article, they look for the same thing as those exposed and that is to determine a specific variable in the drying process, whether it is infrared drying, spray drying, or FD.

The applications of far-infrared drying found vary greatly, such as studying the effects on products, as in the case of pumpkin (Yan et al., 2019) or asparagus stems (Yu et al., 2019). Another application found was the study of properties on products, such as the determination of polyphenols in blueberry leaves (Bordas-Yepes et al., 2019) or the study of the oxidative stability of the macadamia nut (Carvalho et al., 2019). Infrared drying is one of the most versatile that can be found in the industry. It can be coupled with other processes in a very easy way, not to mention that this is one of the most economical for its low consumption energy and the high quality that it provides the final product (Liu et al., 2019).

## Effects on Quality Through Infrared Drying

Quality is one of the most important factors in the preservation of dehydrated products. Far-infrared drying helps retain sensory quality in products such as sweet potatoes, grapes, *Cordyceps militaris*, and mangoes, as explained by different authors (Fu et al., 2019; Onwude et al., 2019; Wu and Zhang, 2019; Yao et al., 2019), where they identified that the taste and smell of the product remained very similar to fresh samples of it. Another important component to verify the conservation of quality is the color that the product or food takes after the drying process. Some authors identified that the color is quite preserved in the product, which is very important in its marketing (Cheng et al., 2019; Nalawade et al., 2019; Wu et al., 2019; Zhao et al., 2019). The infrared drying method also provides a faster operating time compared to other drying methods while maintaining compositional and sensory characteristics at high levels (Ebrahim et al., 2019; Hasan et al., 2019; Qu et al., 2019; Zeng et al., 2019). **Table 3** shows in detail the contribution of the authors concerning quality.

**TABLE 2** | Identification of mathematical models worked by the different authors.

Mathematical model	Implementation
Algorithmic linear models.	$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_i X_i$ <p>Where Y is the dependent variable, <math>\beta_0</math> is the intercept, <math>\beta_i</math> is the slope for <math>X_i</math> and X is the independent variable.</p> <p>This model is implemented in far-infrared drying to determine a variable of the drying or a variable of the product, an example of this is what is done in the article (Rezaei et al., 2019) in which they use this method to predict the percentage of moisture that has the product to be dried, in the same article this model is again used to calibrate the power of the drying equipment.</p>
Drying curves	<p>Show us the moisture content over time, as shown</p> <p>Time, t [s]</p> <p>A-B: initial drying period  B-C: constant drying rate period  C-D: drying speed drop period  D-E: critical drying period</p> <p>If we talk about drying, we must also talk about drying curves, which are implemented to determine if the product or food to which the drying is being done is the right one, the amount of water required was eliminated since it is well-known that if after drying the product still contains water, it can develop microorganisms which affect the physical or organoleptic properties of the product, generating losses because of were commonly found in the literature review.</p> <p>The model Page: <math>MR(t) = e^{(-ktn)}</math></p> <p>This model is implemented to set the drying data, data coming from the drying speed or other process constants</p>

Source: the authors.

## Complementary Analysis From Patents

To analyze the usefulness and implementation of the far-infrared drying system, the patents applied for and obtained in the last years were reviewed. For this purpose, the search equation “TITLE-ABS-KEY (‘infrared drying’) AND fruits AND [LIMIT-TO (SUBJAREA, ‘AGRI’) OR LIMIT-TO (SUBJAREA, ‘ENGI’)]” was run again in Scopus, obtaining more than 600 patents in all years. To reduce the search and make it more current, we chose to work only with the last 5 years in which 146 patents were found. When performing the analysis, we found that only 10 patents use far-infrared drying applied to fruits or agro-industrial products; the rest of the patents, several have nothing to do with far-infrared drying or with fruits, others include drying methods or equipment but none is far-infrared, and there is another group that uses far-infrared drying but not applied to fruits. After analyzing the 10 patents directly related to the topic, a consolidation was made with the information as shown below:

### Products to Be Dried

Products vary slightly between the different patents, but generally, it was found that systems, equipment, or methods are used for a wide range of products because changing products

only requires extending the time or intensity of the infrared rays. Among the products mentioned in the patents are sweet potatoes (Kiburo, 2019), fruits and vegetables in general (Kyoon, 2017; Musco et al., 2017; Kisaburo, 2018; Wicherski, 2018), nuts (Takamasa, 2017; Wicherski, 2018), grains (Jiménez and Gopi, 2018), plant leaves for making tea (Pan and McHugh, 2017), and agro-industrial products (Bing et al., 2017; Altser, 2018). The products worked on in the patents are very similar to those who worked on in the articles, and they also seek to conserve, extend the life, and preserve the properties of the articles.

### Equipment, Systems, or Methods

In general, they are constituted by cameras or equipment in which the main drying is made with the application of rays of distant infrared. With these systems, one looks to improve the yield of the production, diminishing the costs of the process and simultaneously looking for better control in the process as far as the times and temperatures, which are very important variables at the time of working with fruits and vegetables in general due to which the physical–chemical properties can be deteriorated.

**TABLE 3** | Effects on the quality of infrared drying.

Authors	Product	Quality
Cheng et al. (2019)	Mango	El VIS-NIR spectrum is well adapted to measure fruit maturity and the NIR spectrum has a great potential to investigate and control dryer performance. The latter demonstrated that the tunnel dryer provides a much smoother and more uniform drying process compared to the traditional dryer. In contrast, samples from the traditional dryer showed chemical changes/decomposition.
Wu et al. (2019)	Cordyceps militaris	Higher drying temperature favors the storage of dry products. Drying at 40°C is beneficial for color retention and volatile compounds. For non-volatile flavor, the relatively high drying temperature was more effective in reducing bitterness and aftertaste.
Zhao et al. (2019)	Shitake mushrooms	The shitake mushroom showed better appearance, less shrinkage, less hardness, higher rehydration rate (7.55), higher protein retention (2.30 mg/g), higher polysaccharide retention, shorter drying time (66.5% less), and overall better quality in far-infrared drying compared to freeze-drying, hot air heat pump drying and instantaneously controlled pressure drop.
Qu et al. (2019)	Black Tea Leaves	The infrared drying compared to the hot air drying, improves the quality of the Tea specifically the compounds volatiles and the taste. Obtaining total sensory scores of 85.2 which is higher than the 83.1 obtained in the hot air drying.
Yao et al. (2019)	Mango	Infrared drying maintains the quality of the mango very similar to fresh mango samples, in aspects related to color, flavor, aroma, and nutritional compounds.
Sadeghi et al. (2019)	Kiwi fruit	Infrared is a suitable heating method for the production of high-quality dry food at low cost to reduce drying time. Rehydration is one of the quality indices used by the food industries.
Wu and Zhang (2019)	Cordyceps militaris	IRFD could reduce 7.21–17.78% of the drying time and 11.88–18.37% of the energy consumption at a constant drying temperature compared to TFD without compromising the quality of the dry product.
Hasan et al. (2019)	Fruits and vegetables	The infrared drying provided a higher drying speed, lower shrinkage percentage, and also decreased color deterioration (an important aspect to verify the quality of the drying).
Zeng et al. (2019)	Kiwi fruit	An increase in FIR temperature decreased L*, but increased to * dry kiwifruit values and affected total phenolic content, total flavonoid content, and vitamin C content.
Nalawade et al. (2019)	Food in general	It maintains the sensory quality of food, reduces processing time so it can be explored as an alternative to drying heat-sensitive products such as spearmint.
Onwude et al. (2019)	Sweet potatoes	Infrared drying is superior to conventional drying techniques in terms of drying time, energy consumption, and the sensory and nutritional quality of the dryer.
Fu et al. (2019)	Grapes	Infrared drying helps to maintain food quality without degrading it and at the same time helps with the inactivation of aerobic and mold yeast bacteria.

## Countries

Countries do not vary much from those publishing the articles, and among them, we find Japan and the United States with three patents each and Korea, Poland, China, and the United Kingdom with one patent each.

## Companies or Applicants

Companies, if they are more diversified, as only one entity found, has two patents, and is the U.S. Secretary of Agriculture. The other companies belong to the agro-industrial sector, energy, technology, and among others, the companies are PAPER TACHIBANA DESGASTE KK, SHANGHAI RELI TECH GROUP CO. LTD., HOKUETSU DENKEN KK, WICHERSKI ENERGY, TEMPONOVO LEASING LTD., RISE PRODUCTS INC., AND HOKUETSU DENKEN CO.

This paper makes contributions that allow complementing and updating information about drying operation from the point of view of teaching in faculties of agro-industry, agribusiness, food and related engineering, in books as Ocon and Tojo (1977), Treybal (1986), Valiente and Tlaczin (1991), Warren McCabe (1991), and Geankoplis (2006). Theoretical elements are provided on the types of drying, the operation of some equipment, as well as a mathematical model to solve drying problems under constant conditions and continuous drying;

however, these texts do not delve into the infrared drying of agro-industrial products, including the book on technology entitled *Unitary Operations in Food Engineering* by Ibarz and Barbosa (2005), which also does not mention aspects of infrared drying of food.

This paper also provides important information on the characteristics based on organoleptic quality, obtained by agro-industrial products that are subjected to infrared drying, where it is explained how these products retain their qualities of flavor, aroma, and color, information that is presented by different authors who present recent studies on the subject, such as Cheng et al. (2019), Wu et al. (2019), and Yao et al. (2019), among others, the way providing theoretical components based on the different practical applications useful for food conservation.

Additionally, this paper compiles information that had not been found in other reviewed papers. Although there is another review on drying (Hasan et al., 2019), none covers the subject so broadly, so this paper sought to create a much broader vision of the subject, including its definition, areas of application, results obtained from the different studies carried out, and something very important, which are the patents that have been obtained on equipment focused on infrared drying, which is why the paper becomes a great review tool for subsequent research in the area.

## CONCLUSIONS

It was possible to identify drying as one of the most useful techniques for food preservation and that infrared drying was entering as a promising emerging technique for this treatment, and effectively, as expressed by the different authors, it was possible to identify what the drying process consisted of and how infrared is a technique that is well-implemented and with the respective adjustments can be effective in preserving fruit or food.

Drying is an operation that not only allows us to remove moisture from a product but also helps to make studies on the properties of these easier. In addition to combining new techniques such as far-infrared radiation, traditional drying methods better preserved the characteristics of these products.

Far-infrared drying aims to be one of the most widely used drying techniques in the future due to the benefits it brings such as low energy consumption and other features such as sensory quality, rehydration ability, and high nutrient retention that it provides to the final product.

Over time, the most effective way of preserving food has been studied, starting with sun drying and evolving into much more sophisticated techniques where the control of multiple variables is fundamental to guarantee the integral preservation of products—both their physicochemical and their organoleptic properties. This review of these technologies allows us to identify far-infrared drying as a very efficient drying technique that allows the dehydration of agro-industrial products with less physical-chemical impact.

A common factor that could be found from the articles was the application of this infrared drying technique in fruits and vegetables with high water content, such as kiwi, chives, and mushroom varieties. These articles based their studies on optimizing the technique by varying drying times, temperatures, pressures, even sometimes combining

different drying techniques—all to preserve the organoleptic characteristics of the product, avoiding damage to thermolabile compounds and obtaining a dry food of very good quality, performance, and characteristics.

Drying is an operation that has accompanied human beings from their beginnings. This one is in almost all the industries, from the nourishing industry, for the elaboration of kinds of milk, in the dust, coffee, sugar, or dry fruits, until the no nourishing industry like the chemistry, this is an operation like the man has come evolving with time, obtaining several advances, like more optimal equipment to dry certain products, with more capacity and less power expense or equipment that maintains all the characteristics of the product that one of the most important factors today at the time of carrying out the drying process.

The articles presented in the paper are recent in 2019 and 2020 and give a basis for two things: a comparison is being made between traditional drying techniques, exposed by different authors, and a modern technique, exposed by the authors of recent studies on drying, and in turn that the information found, mainly on quality, is very current, being important to bring the technique to the practical exercise.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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