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Electrohydrodynamic Drying in Agribusiness: Literature Review

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In agribusiness, drying is a unitary operation that optimizes the production and preservation of products and raw materials. Drying is performed through different traditional methods, one of the most recently studied is the electrohydrodynamic drying EHD which uses an electric field that allows decreasing the processing time thus increasing the drying speed of raw materials and consuming less energy. In this article, a review was carried out through Scopus using a search equation with the keywords "Electrohydrodynamic drying," "food" and "AGRI" which resulted in a total of 145 articles; which were analyzed through in-depth reading, analyzing aspects such as year, author, keywords, countries, quartile, journal, relationship with agroindustry, mathematical models used and applications in agro-industrial products, this analysis was complemented with the application of Vantage Point software through co-occurrence matrices and cluster analysis. Recent applications were found in Carrot, Chicken, Sea Cucumber, Goji Berry, Peppermint Leaf, Quince, Potato, Blueberry, Aquatic Products, Banana Slices, Grape Pomace, Blueberry, Apple, Mushroom, Wheat, and Mushroom Slices, mathematical models with application in EHD drying were also found, such as Henderson and Pabis, Page, Logarithmic, Quadratic, Newton/Lewis, Diffusion and exponential.

Keywords: electrohydrodynamic, drying, food, agroindustry, trends, mathematical models, applications

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INTRODUCTION

The unit operation of drying is an important operation for the preservation of food and non-food products, likewise, to give added value to different raw materials or by-products of it (Collazo et al., 2018; Guiné, 2018; Zhou and Wang, 2018); this process decreases the amount of water in a product to eliminate or reduce microbial activity that may alter it, extending its shelf life (Omolola et al., 2015), but rather seeks to preserve its nutritional and organoleptic characteristics for the consumer, reduce packaging, transportation, storage, and processing costs (Xia and Mujumdar, 2020). The best-known types of drying are natural convection drying, radiation drying, forced convection drying, refractive window drying, and spray drying (Collazo et al., 2018).

Conventional drying methods present limitations, such as, product quality is not uniform due to excessive drying times, in turn, drying time is prolonged due to low energy efficiencies between the drying medium and the raw material (Mujumdar and Law, 2010). On the other hand, color change in dehydrated products is a factor and parameter that determines the final quality, being the most important from the point of view of a consumer (Rubiano et al., 2016), this is due to biochemical browning reactions during drying modifying not only color but also flavor, texture and even showing losses in nutritional value (Marzec et al., 2020). This results in low drying yields and high operating costs, therefore, it is essential to research and develop new drying methods adapted to the new emerging technologies in the world, allowing to solve the limitations of conventional drying while satisfying the quality and stability requirements of the product, and at the same time reducing operating costs and energy expenditure (Mujumdar and Law, 2010; Qadri et al., 2019).

The application of infrared heating to drying food is of special interest recently, a technique based on the property of water to absorb infrared radiation. This heating technique is especially suitable for drying thin layers of substance with a large surface area exposed to radiation (Salehi and Kashaninejad, 2018). Additionally, IR radiation has been used in combination with various drying methods because it has the advantages of increasing drying efficiency, that is, increasing the actual absolute humidity change in the dryer compared to the saturated absolute humidity change, equally, seeks to reduce the drying time of products (Salehi, 2019). Another contemporary technology to counteract the implications of conventional drying is based on heat pump (HP) technology, which is increasingly used in the food industry today due to its low energy consumption, less quality loss, high thermal efficiency and high drying performance. The energy saving of HP drying is based on the principle of the reverse Carnot cycle (refrigeration cycle), it could recover energy from the exhaust and independently control the temperature and humidity of the air (Salehi, 2021).

Although new technologies are being studied that offer a possible solution to the disadvantages of traditional drying in the food industry, there are other techniques that have been little studied and that are projected as new trends for agribusiness, such as electrohydrodynamic drying (EHD) that being an unconventional drying alternative promises to be a new non-thermal technology proving to be effective in addressing the main limitations of conventional drying by managing lower energy consumption during the process (Iranshahi et al., 2020). As a sustainable drying technology, electrohydrodynamic drying is a potential technology if one wishes to replace poor drying methods, however, some problems have hindered the commercial implementation of this technology, exemplifying, little is known about the different moisture transfer mechanisms that occur during drying and presents a challenge to scale up EHD drying from pilot scale to industrial applications (Iranshahi et al., 2020).

The purpose of this article is to provide a literature review of the research and information currently collected on electrohydrodynamic drying, to provide future researchers with an approach to the subject and some theoretical bases. In addition, we seek to answer the following questions: What are the applications of EHD drying in agribusiness. What are the advantages and disadvantages of foods dried by this new technology? For this purpose, the paper is divided into four parts. Initially, a theoretical framework is presented with the main terms on unitary operation for a good interpretation of this; in the second part, the methodology used is presented with emphasis on keywords, the use of the Scopus platform with search equations, and in-depth analysis of each document; for the third part, a discussion on the axes of mathematical models and trends in the application of agro-industrial products was carried out. Finally, the conclusions of the study are presented.

CONCEPTUAL FRAMEWORK

In generic terms, the drying process involves the removal of unbound (free) moisture from the surface first and then the bound moisture from inside the food product until a defined limit is reached. It involves simultaneous heat and mass transfer operations (Babu et al., 2018). EHD drying refers to the removal of water from the wet solid exposed to a strong electric field due to the aerodynamic action of the so-called corona wind, ionic wind, or electric wind (Martynenko and Kudra, 2019). Both airflow and ionic wind play a crucial role in enhancing water evaporation. Ionic wind provides charge transfer to the surface of the wet material, which is measured as total current or current density distribution (Bashkir et al., 2020).

The ionic wind disturbs the boundary layer developed from the grounded surface on which the biological material is placed, impinging on the wet biological material by disturbing the saturated air layer, which enhances evaporation thus improving mass transfer between the biological surface and the ambient air (Singh et al., 2012). This wind originates from a sharp end of the electrically conductive pin (needle) or thin horizontal wire as a result of ions leaving this pin/wire and impinging on the surface of the material being dried (Martynenko and Kudra, 2019).

The kinetics of EHD is similar to that of conventional convective drying, following drying periods of constant and decreasing speed due to the nature of the generated ionic wind. Depending on the nature of the dielectric material, the EHD curve varies. Most of the high humidity model materials, such as agar gels and wet fabrics, are reported to exhibit a relatively longer constant velocity drying period (Anukiruthika et al., 2020).

The electric current generated in the so-called drift zone is represented by heat transfer types such as the combination of conduction (in which ion movement occurs under an electric field), convection (involving charge transport with airflow), and diffusion mechanisms (Anukiruthika et al., 2020).

Mathematical modeling to determine mass and energy transfer in this type of drying starts from analytical and numerical models (Elmizadeh et al., 2018; Kudra and Martynenko, 2019). For Kudra and Martynenko (2019) the variables to be known at EHD can be categorized into four:

a. Electrical characteristics such as voltage, current, and electric field strength.
b. Discharge and collection electrode geometry.
c. Environmental conditions such as temperature, humidity, pressure, and airflow.
d. Material properties such as thickness, porosity, surface roughness, among others.

Commonly, EHD drying needs to start with corona discharge by creating a non-uniform electric field with a starting electric field strength Ei, however, it will depend on the geometry of the discharge electrode, and particularly for each case it is determined from the formula of Peek, Equation 1, exemplifying, if it is desired to calculate the electric field strength at the spherical tip of the pin it can be determined how (Kudra and Martynenko, 2019):

$$\mathbf{E_i = 3.1\ x\ 10^6 \left(1 + \frac{0.308}{r}\right)} \tag{1}$$

Where r is the radius of curvature of the tip of the pin at the discharge electrode (cm).

The intensity of the charge flow is the product of a strong electric field, which can be quantified using Equation 2 by measuring the electric current between the two types of electrodes, collector, and discharge. Generally, in the vicinity of the collector electrode, the electric field strength is calculated as the ratio of the voltage to the space $E = V/d$. Starting from the above hypothesis, Equation 2 can be presented in the written form of Equation 3 (Kudra and Martynenko, 2019).

$$\mathbf{I} = \frac{\mathbf{g_0} > \varepsilon_0 \mathbf{bA}}{\mathbf{d^3}}(\mathbf{V} - \mathbf{V_0})^2 \tag{2}$$

$$\mathbf{I} = \frac{\mathbf{g_0}\varepsilon_0 \mathbf{bA}}{\mathbf{d}}(\mathbf{E} - \mathbf{E_0})^2 \tag{3}$$

Where V is the voltage applied to the electrodes, (V); V_o corresponds to the onset voltage required to initiate corona discharge (V); A is the surface area of the collector electrode (m^2); ε_0 represents the vacuum dielectric permittivity equal to 8.86 $x10^{-12}$ F/m; b represents the ionic mobility, which is equal to 1.6 $x10^{-4}$ $m^2/(V{\cdot}s)$ for positive ions and 2.1 $x10^{-4}$ $m^2/(V{\cdot}s)$ for negative ions; d is the spacing between the discharge and collection electrodes (m), and g_o represents the dimensionless geometry factor (Kudra and Martynenko, 2019).

Subsequently, electrohydrodynamic drying results from the conversion of electrical to mechanical energy and has a convective nature, to determine the ionic wind velocity in the electric field it is quantified with Equation 4 (Elmizadeh et al., 2018):

$$\mathbf{v} = \mathbf{i}\sqrt{\frac{\varepsilon_0}{\rho}} \tag{4}$$

Where v is the airflow velocity or corona wind (m/s), i is the electric field strength (V/m) and ρ is the density of air (kg/m^3). In **Figure 1**, Defraeye and Martynenko (2018) schematized the EHD process by postulating two characteristic regions or phases of EHD, the ionization phase, and the drift phase.

The specific energy consumption (SEC) is defined as the amount of energy required to evaporate the unit mass of water in $kJ{\cdot}kg^{-1}$. Using Equation 5 one can determine the specific energy consumption for EHD drying in $kJ{\cdot}kg^{-1}$ (Yang and Ding, 2016).

$$\mathbf{SEC} = \frac{\mathbf{V\ x\ I}}{\mathbf{m_0 - m_t}}\ \mathbf{x}\ \Delta\mathbf{t} \tag{5}$$

Where V is the voltage (kV), I is the ionic wind current (μA), m_o is the weight of the body to be dried (kg), m_t is the weight of samples at a time t, Δt is the time (h) (Yang and Ding, 2016).

To know the energy efficiency of the high voltage power supply, Equation 6 is posed, for such, the input and output current-voltage ratio (Dalvand et al., 2014) is to be measured.

$$\eta = \frac{\mathbf{I_s\ x\ V_s}}{\mathbf{I_e\ x\ V_e}} \tag{6}$$

Where I is the current (A) and V is the applied voltage (V), the index s means output, while e means the input of the power supply.

Because the application of EHD is performed at ambient temperature and pressure conditions, it is considered a suitable alternative to conventional processes using high airflows at elevated temperatures as in turn this technology can be classified as a non-thermal process and a novel alternative that can be used to dry heat-sensitive materials (Singh et al., 2012).

Because the application of EHDEHD drying has been used to dry wheat (Cao et al., 2004), tomato slices (Esehaghbeygi and Basiry, 2011), carrot slices (Ding et al., 2015), mushroom slices (Taghian and Havet, 2015a,b), apple slices (Martynenko and Zheng, 2016), potatoes (Yu et al., 2017), among others, improving their shelf life, preserving the quality of the food, increasing the drying speed thus decreasing the prolonged time in said.

METHODOLOGY

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

- Stage 1: Starting with the search and selection of the topic to be worked on. Drying was taken as a topic to work on; subsequently, we chose to work specifically on electrohydrodynamic drying for which we investigated trends and emerging technologies where this process is used in the agro-industrial sector. At this stage, the keywords used later for the search equation were also chosen.
- Stage 2: For this stage, the construction of the search equation was carried out to access articles to find applications, trends, and others regarding this type of drying. Keywords such as electrohydrodynamic drying, food, and agri were then applied for the construction of this equation; finally, for this stage, the following equation was arrived at: ALL (((“Electrohydrodynamic drying”) AND (food)) AND (LIMIT-TO (SUBJAREA, “AGRI”)) applied in Scopus, this equation was also bounded for the range of years from 2015 to 2021; with this equation, a total of 145 articles were found.
- Stage 3: Review of articles and selection of those that apply. All articles found with this equation to date (145 articles) were reviewed. For the selected articles an Excel template/format was developed which collects the following information on each article: year, title, authors, countries, journal, cite score (journal rating), Scimago quatil, keywords, summary, relationship with the agro-industrial sector, mathematical model, the purpose of the article and its news/conclusions. This information was used as input for the application of Vantage Point technology watch software, which uses natural

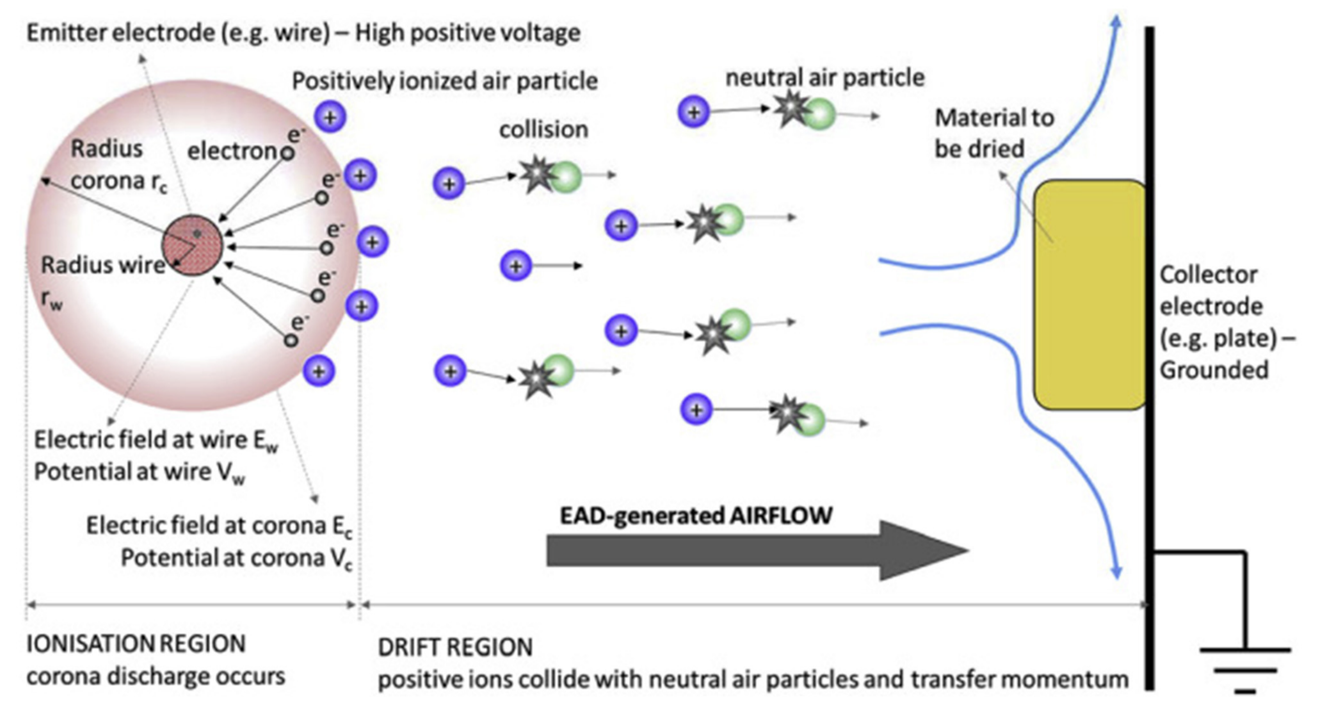
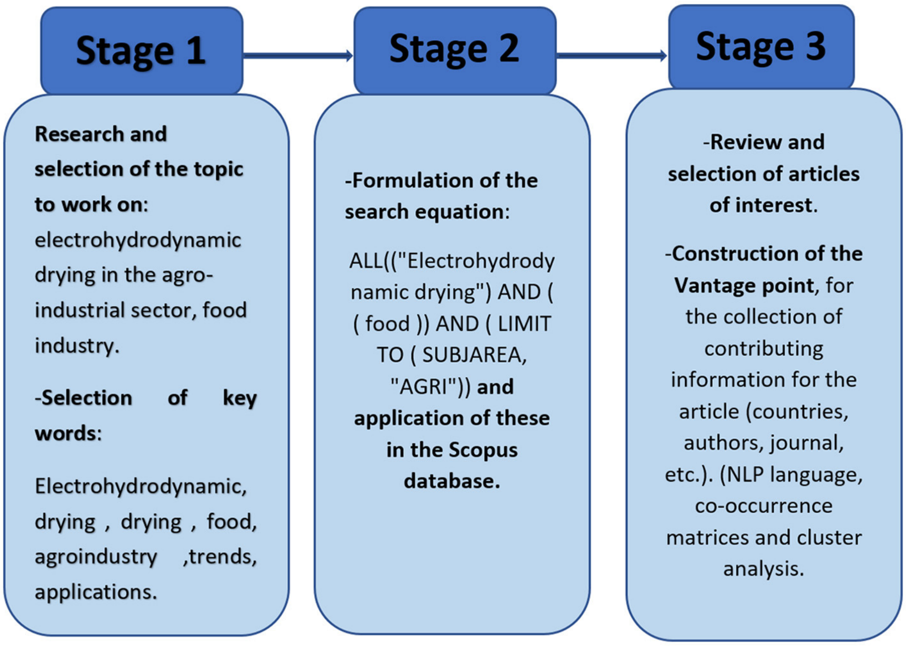


FIGURE 1 | EHD process. Source: Defraeye and Martynenko (2018).



Research and selection of the topic to work on: electrohydrodynamic drying in the agro-industrial sector, food industry.

-Selection of key words:

Electrohydrodynamic, drying , drying , food, agroindustry ,trends, applications.

-Formulation of the search equation:

ALL(("Electrohydrodynamic drying") AND ((food)) AND (LIMIT TO (SUBJAREA, "AGRI")) **and application of these in the Scopus database.**

-Review and selection of articles of interest.

-Construction of the Vantage point, for the collection of contributing information for the article (countries, authors, journal, etc.). (NLP language, co-occurrence matrices and cluster analysis.

FIGURE 2 | Stages of the creation of the paper. Source: the authors.

language processing - NLP, co-occurrence matrices, and cluster analysis.

These stages can also be seen in **Figure 2**.

RESULTS

In taking data from articles and patents, the following results were obtained from the search equation: ALL

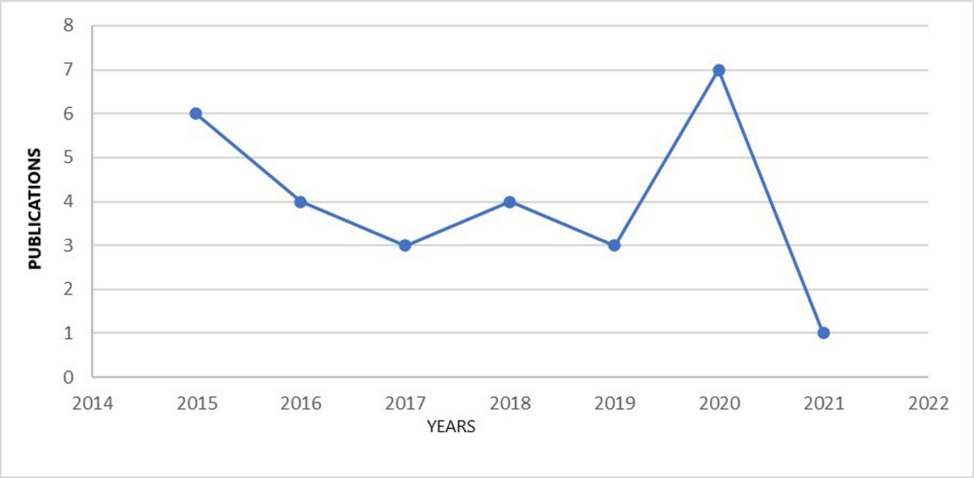


FIGURE 3 | Number of items per year. Source: Authors.

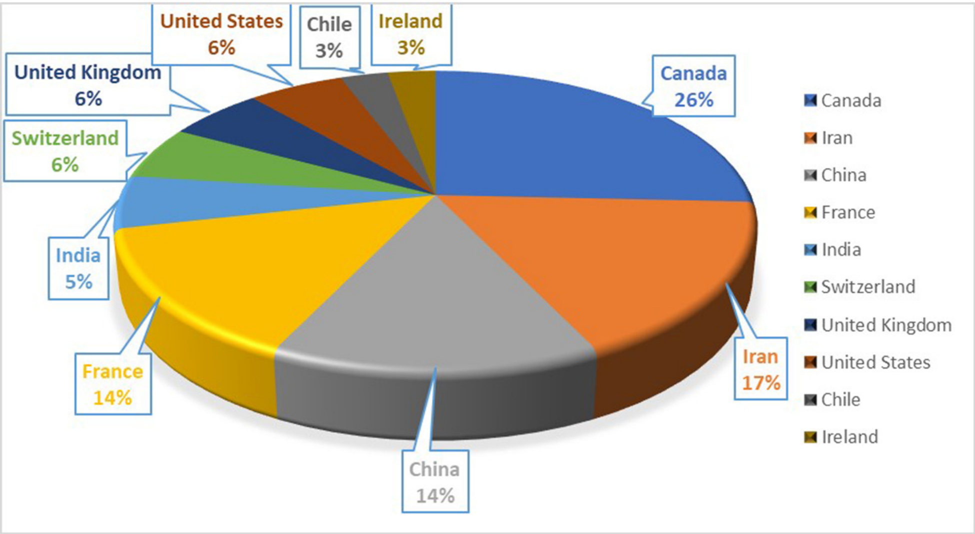


FIGURE 4 | Countries that made publications. Source: Authors.

(("Electrohydrodynamic drying") AND (food)) AND (LIMIT-TO (SUBJAREA, "AGRI")), 145 scientific articles were found, these results are comprised between the years 2015–2021, from the articles found 28 were selected that are related to the drying electrohydrodynamic of food, especially effects such as drying kinetics, color degradation, and energy consumption (Martynenko and Zheng, 2016). The analysis of the results obtained from the selected articles was classified and related to countries, years, authors, keywords, number of publications, which were represented by graphs shown in **Figures 3–8**.

The Vantage point is a text engineering software that uses techniques such as analysis through the NPL language, co-occurrence matrices, cluster analysis, among others. The insight provided by Vantage Point allows you to quickly find who, what, when, and where, allowing you to clarify relationships and find critical patterns, turning your information into knowledge (VantagePoint - The VantagePoint, 2021), giving operators early warning of trend changes (Auckenthaler, 2021). From the database extracted from Scopus, data were filtered, and later these data were imported to the Vantage point software to finally obtain different matrices and graphs of keywords, key phrases, and phrases related to countries.

In **Figure 3**, we observe the number of articles that have been published on the emerging technology of electrohydrodynamic drying in the last 5 years 2015–2021, As shown by the year 2020 where the highest number of publications were made regarding the topic. This technology is growing in research and development. It is an innovative technology that takes advantage of the phenomenon of electrically induced dehydration in intense electric fields. It has recently gained

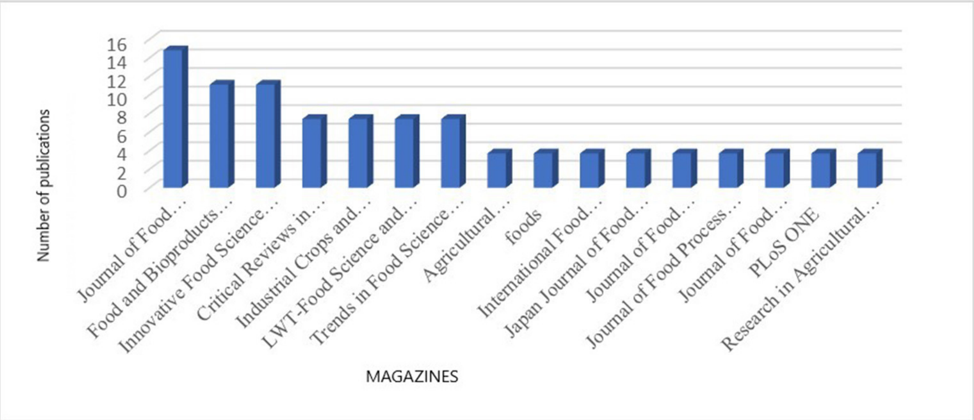


FIGURE 5 | Journals that made the publications. Source: Authors.

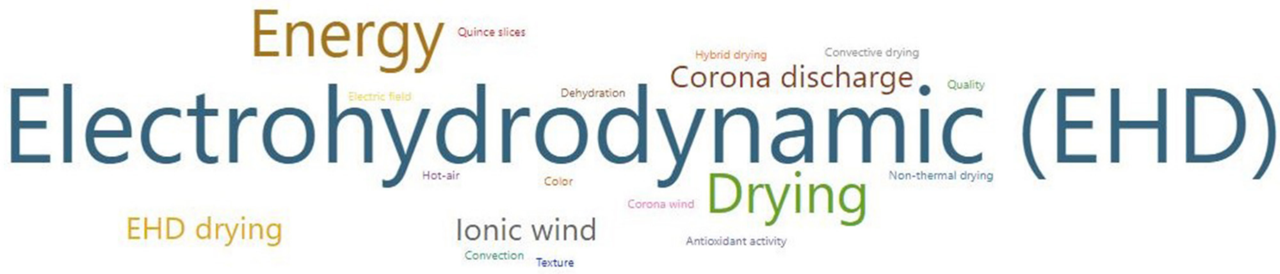


FIGURE 6 | Keywords found. Source: Authors based on Vantage Point software.

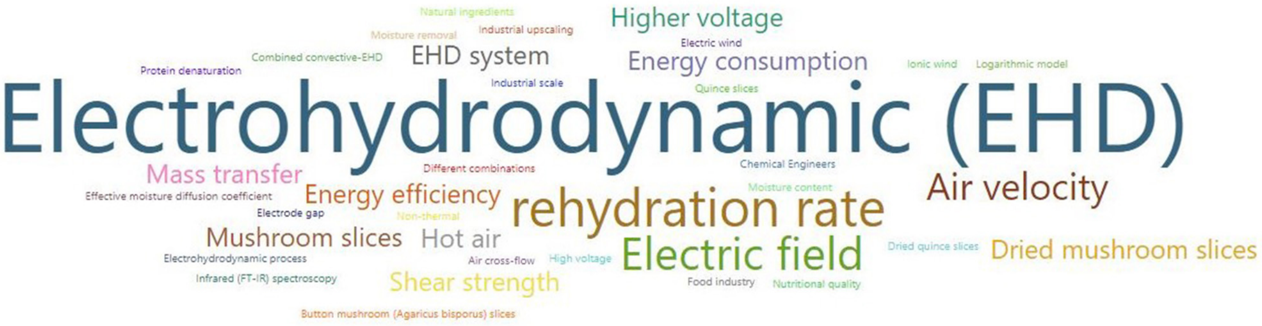


FIGURE 7 | Key Phrases. Source: The authors are based on Vantage Point software.

a great deal of interest due to its non-thermal nature, particularly suitable for heat-sensitive biomaterials such as food, medicinal plants, and other biomaterials. (Martynenko and Kudra, 2019).

Publications by Countries

High-quality food drying can be defined as a drying technology, which protects the qualities of fresh foods such as color, flavor, nutrients, rehydration, appearance, and uniformity during the drying process. Some high-efficiency, energy-saving, and environmentally friendly drying technologies have gradually replaced traditional drying technologies to simultaneously shorten drying time and improve product quality (Zhang et al., 2017). Therefore, **Figure 4** shows the countries that have published publications on the EHD drying study, the highest percentage of participation corresponds to Canada with 26% being the country with more publications on the subject, followed by Iran with 17%, China with 14%, highlighting

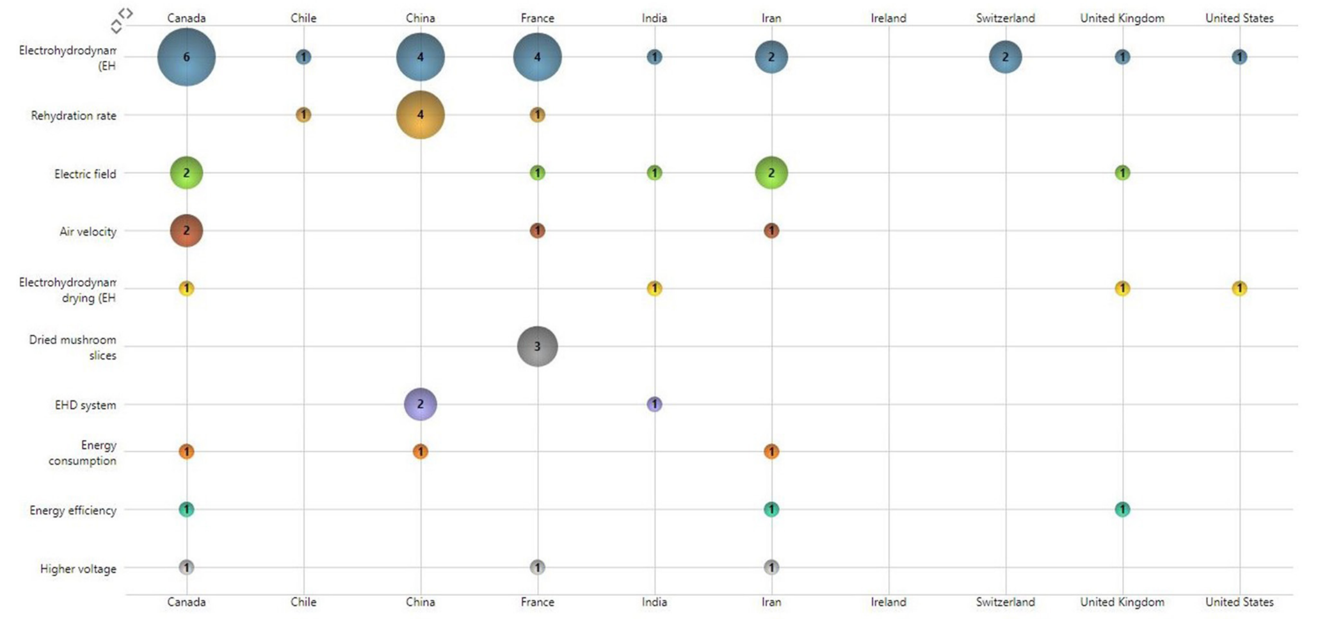


FIGURE 8 | Co-occurrence Matrix - Key phrases related to Countries. Source: Authors based on Vantage Point software.

Chile Latin American country with a participation of 3%, in total 10 countries have published publications on this emerging technology.

Scientific Journals

In **Figure 5** the relationship between scientific journals and the number of publications made on the EHD section taken for the study of this article is shown. Driving interests by continuing research in the development of new innovative drying technologies. In addition, there are emerging challenges (e.g., food security, resource depletion, climate change, etc.) around the world that are further driving the food industry in the search for technological innovations to add value to these commodities to remain competitive and profitable in a sustainable manner (Sabarez, 2021). Particular interest is expressed for scientific journals focused on food or agribusiness in this technology, with the *Journal of Food Engineering* having the most publications with a 15% share, followed by *Food and Bioproducts Processing* with 11% and *Innovative Food Science and Emerging Technologies* with 11%.

Keywords

Keywords are important because they connect the content with what is being searched for through search platforms, making it easier and more practical to obtain information. **Figure 6** shows the most important keywords found in articles related to this emerging technology. The Keywords with the highest mention is *Electrohydrodynamic* (EHD) being the word most found in the articles studied, followed by *Energy, Drying, EHD drying, Corona discharge.*

Key Phrases

To determine the key phrases in the selected articles, the computational methodology of body language processing (NLP) is used, which allows the analysis of the text, giving easy and reliable results. **Figure 7** shows the number of important key phrases related to the publications of the studied topic. The phrase with the highest mention was *Electrohydrodynamic* (EHD), followed by *rehydration rate, Electric field, Air velocity, Dried mushroom slices.*

Phrases Related to Countries

Electrohydrodynamic drying technology (EHD) is particularly suitable for improving the drying of heat-sensitive materials, mainly food products. It is a promising method to convection dry high-value agricultural products without using heat (Sabarez, 2021). It has been used to dry food products, such as chicken breast (Rahbari et al., 2020), apple (Martynenko and Zheng, 2016), mushroom (Somayeh, 2015). In **Figure 8**, we observe the relationship of the most important phrases with the countries that have researched EHD drying, it is worth noting that Canada is the country where the phrase *Electrohydrodynamic* (EHD) is mostly found in its publications, followed by China and France.

As shown in **Table 1**, the information found with the search equation was tabulated to synthesize and demonstrate the current findings on EHD drying and to identify the mathematical models in EHD drying. This synthesis was segmented by year of publication of the article, author(s), the product covered, or if it had a theoretical purpose under theoretical reference and the purpose of the article.

TABLE 1 | Synthesis of the Scopus database search.

Year	Authors	Product	Purpose
2021	Anukiruthika, T., Moses, J., Anandharamakrishnan, C. (Anukiruthika et al., 2020)	Theoretical reference	Review which provides a comprehensive resource on the applications of electrohydrodynamics for food drying. Various EHD design and process parameters are detailed with information on technological perspectives.
2020	Salehi, L., Taghian Dinani, S. (Salehi and Taghian, 2020)	Carrot	The objectives of this literature were as follows: (i) examination of the effects of EHD extraction time and EHD extraction voltage on dependent factors, (ii) investigation of the probable morphological changes of carrot pomace powder during selected extraction treatments by scanning electron microscopy, and (iii) determination of probable changes of functional groups of extracts during selected EHD extraction treatments by Fourier transform infrared spectroscopy.
2020	Rahbari, M., Hamdami, N., Mirzaei, H., Jafari, S. (Rahbari et al., 2020)	Chicken breast	The main objective of this work was to study the possible changes made in the texture and microstructure of chicken breast during HVEF thawing, and the comparison with the changes resulting from conventional thawing.
2020	Tamarit, Y., Batías, J., Segura, L., Díaz, R., Guzmán, M., Quevedo, R. (Tamarit et al., 2020)	Chilean sea cucumber	Apply in freeze-drying (FD) as drying method, electrohydrodynamic (EHD) as pretreatment combining various voltages and application times of <1 h with DF. In addition, its influence on drying parameters, moisture content, rehydration ratio, and water absorption capacity was determined by applying the Weibull model.
2020	Menon, A., Stojceska, V., Tassou, S. (Menon et al., 2020)	Theoretical reference	Critically analyze the reported energy efficiency values of various non-conventional drying technologies used in food processing by gathering a representative number of related studies on non-conventional drying technologies that have the potential to reduce energy consumption and GHG emissions.
2020	Ni, J., Ding, C., Zhang, Y., Song, Z. (Ni et al., 2020)	Goji berry	To study the effects of different pretreatment methods (chemical solutions) on the microstructure of goji berry during the EHD drying process by scanning electron microscopy and infrared spectroscopy
2020	Martynenko, A., Astatkie, T., Defraeye, T. (Martynenko et al., 2020)	Theoretical reference	The paper aims to determine to what extent the three factors: airflow, ion flow or electrostatic field contribute to EHD moisture transfer. For this purpose, they designed a targeted experimental setup, which sheds more light on the different mechanisms of EHD drying.
2020	Esehaghbeygi, A., Karimi, Z. (Esehaghbeygi and Karimi, 2020)	Peppermint leaf	The objective of the present investigation was to compare the rate of moisture loss, energy consumption, and an assessment of the color quality of EHD, oven, and natural drying methods for mint leaves and to find the best prediction model.
2019	Defraeye, T., Martynenko, A. (Defraeye and Martynenko, 2019)	Theoretical reference	This simulation-based study evaluates the impact of various emitter-collector configurations for EHD drying in order to assess their potential for industrial scale-up.
2019	Martynenko, A., Kudra T. (Martynenko and Kudra, 2019)	Thermolabile foodstuffs	Bibliographic and theoretical reference of EHD based on mathematical laws, its basis in drying, new food and non-food applications, history, and current development of the method.
2019	Ni, J., Ding, C., Zhang, Y., Song, Z., Hu, X., Hao, T. (Ni et al., 2019)	Goji berry	To investigate the characteristics and mechanisms of electrohydrodynamic drying (EHD) in multiple needle-to-plate electrode systems by blocking the ionic wind and changing the needle spacing in multiple needle-to-plate electrodes of goji berry China.
2018	Misra, N., Martynenko, A., Chemat, F., Paniwnyk, L., Barba, F., Jambrak, A. (Misra et al., 2018)	Theoretical reference	Research of innovative technologies at industrial scale and publications on these topics, in particular non-thermal technologies.
2018	Elmizadeh, A., Shahedi, M., Hamdami, N. (Elmizadeh et al., 2018)	Quince	Comparison of two drying processes at different conditions, for this case the analysis was performed for electrohydrodynamic drying and hot air drying and at a voltage (5,7,9 kV) and temperature (50,60,70 °C) conditions. The following factors were analyzed: remaining moisture in the final product, shrinkage, water absorption capacity, shear strength, and color.
2018	Yu, H., Bai, A., Yang, X., Wang, Y. (Yu et al., 2017)	Potatoes	To identify the possible physicochemical changes in potato slices after electrohydrodynamic drying. The influence of the voltage used during the process and the needle spacing was specifically analyzed. It was sought to analyze moisture content, appearance, morphology, rehydration, reducing sugar content, etc. It then suggests the proper process of dehydration of potatoes.
2018	Chen, Y., Martynenko, A. (Chen and Martynenko, 2018)	Blueberries	Search for the best combination of processes for the preservation of the qualities of the blueberry even expecting as a final product a pure; observe the changes that enhance each of the processes, positive and negative aspects.
2017	Martynenko, A., Astatkie, T., Riauud, N., wells, P., Kudra, T. (Martynenko et al., 2017)	Theoretical reference	It seeks a better understanding of the factors that play an important role in EHD drying and, therefore, the industry needs to facilitate practical applications of EHD in bioprocessing and food engineering.
2017	Elmizadeh, A., Shahedi, M., Hamdami, N. (Elmizadeh et al., 2017)	Quince	Comparison of the effect of two drying methods on drying kinetics, energy consumption, potent antioxidant activity, and phenolic compounds of quince slices.

(Continued)

TABLE 1 | Continued

Year	Authors	Product	Purpose
2017	Zhang, M., Chen, H., Mujumdar, A.S., Tang, J., Miao, S., Wang, Y. (Zhang et al., 2017)	Aquatic products	Review of recent developments in high-quality drying of vegetables, fruits, and aquatic products and recommendations are made for future research.
2016	Martynenko, A., Zheng, W. (Martynenko and Zheng, 2016)	Apple	To study the effects of EHD on drying kinetics, color degradation, and energy consumption in apple slices.
2016	Martynenko, A., Kudra, T. (Martynenko and Kudra, 2016a,b)	Biomaterials	Collect and analyze the fundamentals of electrically induced physical processes relevant to EHD drying theory.
2016	Pirnazari, K; Esehaghbeygi, A; Sadeghi, M. (Pirnazari, 2016)	Banana slices	Investigate electrohydrodynamic drying kinetics and moisture diffusivity using Fick's second law equation as a basis and compare the derived empirical and numerical models for the drying of banana slices.
2016	Martynenko, A; Kudra, T. (Martynenko and Kudra, 2016b)	Grape pomace	The energy efficiency of the non-thermal electrohydrodynamic (EHD) technology applied for grape pomace drying was extensively studied.
2015	Taghian, S; Havet, M. (Taghian and Havet, 2015a,b)	Mushroom	A combined convective-EHD-drying system with two voltage variables on drying kinetics, remaining moisture content, porosity, shrinkage, rehydration ratio, shear strength, color, and microstructure of mushroom slices was proposed.
2015	Ding C; Lu, J; Song Z. (Ding et al., 2015)	Carrots	Carrot slices were dried in an EHD system to study the effect of different voltages on the drying rate.
2015	Singh, A; Vanga, S; Nair, G; Gariepy, Y; Orsat, V; Raghavan, V. (Singh et al., 2015)	Wheat	This study investigates the electrohydrodynamic drying characteristics of wheat and their effect on the conformation of the wheat protein.
2015	Havet, M; Bardy E; Manai, S; Hamdi, M; Rouaud, O. (Havet et al., 2015)	Theoretical reference	Experiments were conducted to analyze the drying kinetics during the EHD and forced convection (FC) drying experiments.
2015	Taghian Dinani, S; Hamdami, N; Shahedi, M; Havet, M. (Taghian et al., 2015a,b)	Mushroom slices	In this study, hot air combined with an electrohydrodynamic (EHD) drying system was designed and examined to dry the fungus. button (*Agaricus bisporus*) slices. The effects of three voltage levels and electrode spacing on the solid and bulk density, porosity, shear strength, water absorption capacity (WAC), and total color difference (MI) of EDH-dried mushroom slices compared to oven-dried mushroom slices.
2015	Taghian Dinani, S; Hamdami, N; Shahedi, M; Havet, M; Queveau, D. (Taghian and Havet, 2015a,b)	Dried mushrooms	In this article, the drying of mushroom (Agaricus bisporus) cuts was investigated with an innovative hot air drying technique combined with an electrohydrodynamic (EHD) drying process combined with an electrohydrodynamic (EHD) drying process. To analyze the effects of different hot air treatments combined with EHD drying treatments on the temperature EHD drying treatments on mushroom slice temperature, drying time, final color, and protein denaturation characteristics.

Source: Authors.

DISCUSSION

Mathematical Models

We were able to identify seven mathematical models most used in electrohydrodynamic drying, which are presented in **Table 2**, in this same table you can see the application that each author has given to these models. In these studies, the objective was to compare each model and define the most efficient one, the models are suitable to simulate drying curves, establish a simple relationship between average moisture content and time, but some studies require establishing the relationship between the drying curve and other physical phenomena such as diffusion (Singh et al., 2015).

In addition, the use of statistical models, SPSS Version 16.0 for Windows and one-way ANOVA [single-factor analysis of variance) was identified to calculate the moisture ratio between carrot slices under alternating electric field and no electric field (control)] (Ding et al., 2015). Some studies have identified theoretical models based on Fick's second law, used to determine moisture content and diffusion (Pirnazari, 2016). It is worth mentioning that these models discussed in the review are models that are not found in the conventional literature.

Trends in the Application of Agro-Industrial Products

During the literature review and as evidenced by the equation used for the paper's search, emphasis was placed on agriculture and even more specifically on food. As a result of these particularities, the main results were classified in **Table 3**; thus, we have berries, carrots, mushrooms (specifically mushroom), potatoes, and, as processed food, quince (snack in some countries).

The berries were tested for pretreatment, changes during electrohydrodynamic drying, changes in the fruit, and other variables. Very generally, berries subjected to conventional drying (such as forced air), have changes in color, damage to the skin of the fruit, loss of components, etc. However, it is said that EHD drying brings improvements in these issues. The drying rate and quality of the fruit improved, the skin of the fruit was less affected, no color changes were noted and it was able to deactivate

TABLE 2 | Mathematical models.

Mathematical model	References	Equation	Implementation
The Page model	Ding et al. (2015)	MR(t) = e^(−ktn)	This model is used to describe the drying characteristics of the raw materials, through the velocity curve (Ding et al., 2015).
Henderson and Pabis	Singh et al. (2015)	MR(t) = αe^(−k)	This model was implemented to establish the relationship between the drying process parameters (Singh et al., 2015).
Logarithmic	Singh et al. (2015)	MR(t) = αe^(−k) +b	This model was implemented to establish the relationship between the drying process parameters. (Singh et al., 2015).
Quadratic	Pirnazari (2016)	MR(t) = α+bt+ct^2	The quadratic model with a non-linear regression analysis has proved appropriate to describe the drying rate of fish with drying voltage, ambient temperature, and drying time as the parameters involved (Pirnazari, 2016).
Newton/Lewis	Singh et al. (2015)	MR(t) = e^(−kt)	It is one of the simplest models used to simulate the drying curve, but its limitations include underestimation of the beginning of the drying curve and overestimation of later stages (Singh et al., 2015).
Exponential<segment 0038 >	Singh et al. (2015)	MR(t) = αe^(−kt(^n))	This model was implemented to establish the relationship between the drying process parameters (Singh et al., 2015).
Diffusion	Pirnazari (2016)	MR(t) = αe^(−kt) +(1-α) ^(−kbt)	This model is applied to predict the behavior of moisture during drying (Pirnazari, 2016).

Source: Authors.

TABLE 3 | Principal products.

Products	Authors
Berries	Ni, J; Ding, C; Zhang, Y; Song, Z; Hu, X; Hao, T; Chen, Y., Martynenko, A.
Carrots	Salehi, L; Taghian Dinani, S; Ding C; Lu, J; Song Z.
Mushrooms	Taghian Dinani, S; Hamdami, N; Shahedi, M; Havet, M; Queveau, D.
Potatoes	Yu,H., Bai, A., Yang, X., Wang, Y.
Quince	Elmizadeh, A., Shahedi, M., Hamdami, N.

enzymes without losing other important components. In case some of the characteristics are compromised, pretreatments such as scanning electron microscopy or infrared spectroscopy are proposed, which, for example, save time and contribute to the maintenance of berry quality (Yang and Ding, 2016). In the case of mushrooms for example these variables were also analyzed, although it was not very useful, it was found that EHD drying is a good method for this food, but equally the color was negatively affected, the porosity will be very high and the shear strength increases (so it is difficult to cut it) (Somayeh, 2015; Taghian and Havet, 2015a,b).

Studies were also conducted on the effects of this drying method on carrots, which are usually dried to extract carotenes, and this was precisely one of the characteristics analyzed in these studies. The drying speed improves with this method and as a result of this increase, a higher carotene content, better product quality, and higher rehydration; the time also improves these characteristics and a very important one which is the extraction yield and antioxidant activity (Ding et al., 2015; Salehi and Taghian, 2020).

Rehydration could be greatly affected by factors such as voltage and distance from the needles this is reflected in products such as carrot, potato (Yu et al., 2017) and even and in fact in higher proportion in quince slices, the latter was also found that unlike the other mentioned products the shear strength decreased and the color, although changed, is not considered unpleasant (Elmizadeh et al., 2018).

Current Limitations and Future Guidelines

Although electrohydrodynamics can offer several benefits in the context of food and bioprocessing, its application in the drying of food materials is relatively limited, only because the approach remains underexplored. About 379 publications on the applications of electrohydrodynamics in food processing have been reported from 1990 to 2020. However, no detailed information is available on commercial applications of EHD dryers.

EHD is a complex phenomenon involving electric field applicability with the convective flow and ionic wind. This scenario increases the difficulty of coupling electrostatic field interactions with heat, mass, and momentum transfers. In this regard, a solid understanding of the process and product variables attributed to EHD is critical to understanding the industrial relevance and commercialization of this novel drying technology (Anukiruthika et al., 2020). One of the constraints is by applying a strong electric field through a dielectric barrier, does not increase the drying rate or efficiency of EHD drying (Martynenko et al., 2021). The effects of environmental factors, such as airflow, temperature, and relative humidity, on EHD drying efficiency, are crucial for the future scale-up of EHD technology. It appears that the application of elevated temperatures could be beneficial only under diffusion-limited drying conditions. The transition from constant drying rate to diffusion-limited drying changes the efficiency of EHD considerably. Therefore, further optimization of EHD drying should consider drying kinetics and material properties, as well as control the temperature regime at the critical moisture content (Martynenko and Misra, 2021).

After an analysis, the authors suggest the optimization of the EHD design, which can reduce energy consumption in certain parts of the process and increase its efficiency. The combination of the technique with traditional and non-thermal methods is proposed to reach a wide range of agro-industrial products, optimizing the performance of the drying speed, time, temperature, physicochemical properties, allowing to highlight the organoleptic properties of the products.

CONCLUSION

The classic texts and types of drying *review*, although they mention emerging drying techniques such as infrared drying, microwave drying, and others, are found little in the literature, especially at the level of innovation, industrial application, and enterprise, EHD drying is in pure basic research, basic applied, experimental development-oriented, prototype stage at the development level. EHD drying in its growth boom will enter the quest for commercial implementation, because of its great potential as an efficient and cost-effective alternative to current drying methods. Classical drying technologies will continue to play an important role in the manufacture of agro-industrial products as long as these technologies remain viable.

The mathematical models applied in EHD drying are iterative, these models are based on the classical drying under continuous and continuous conditions, adding variables to the modeling such as the use of electric fields, diffusion, electric voltage, etc. For the application of the mathematical models, speed, humidity, temperature, time, among other process parameters, are taken into account, generating drying curves, drying kinetics, and thus determining the properties of the process.

Throughout history, there have been multiple conventional drying methods e.g., sun drying, hot air drying, different types of ovens, etc. and they have been widely used on cereals and some fruits; unlike these types of drying, EHD is much more versatile and does not only cover products such as cereals, fruits, and vegetables but also on vegetables such as carrots, mushrooms, potatoes or even on animals such as sea cucumber whose worldwide consumption continues to grow.

The development of new emerging drying technologies such as EHD drying is evolving in the search for solutions to the limitations generated by current drying technologies. Developing sustainable drying with a significant reduction in the environmental footprint, being at the global forefront in the trend of sustainability with the reduction in drying times, savings in energy consumption Kw/h, and maintaining a good quality of products, contributing to the improvement of health and wellness.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All the authors have made contributions in the construction of this paper.

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