Advances in Sustainability Science and Technology

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INCREaSE 2023

Proceedings of the 3rd INternational CongRess on Engineering and Sustainability in the XXI CEntury

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Preface

It is our pleasure to present the proceedings of the 3rd International Congress on Engineering and Sustainability in the XXI Century (INCREaSE 2023). This book of proceedings aims to bring together valuable and novel scientific contributions to the sustainable development in a multidisciplinary way, that have an impact in diverse and fast-changing research areas, both in academia and industry, reflected in the fields of civil, electronics, food, and mechanical engineering. This book presents 31 works from authors from different countries in several transversal areas, such as big data and data analytics, climate change and mitigation, carbon reduction, sustainable food processing and safety, sustainability in water management, sustainable energy generation and management, construction sustainability, and other subjects related to the sustainable development.

This year's INCREaSE was organized by the Institute of Engineering and hosted by the University of Algarve during July 5–7, 2023, in Faro, Portugal.

All members of the organizing committee, authors, and reviewers played a key role with their dedicated work and efforts.

INCREaSE 2023 had an excellent group of keynote speakers: Enrique Cabrera-Rochera—University of Valencia, Spain, Paulo Sérgio Duque de Brito—Polytechnic of Portalegre, Portugal, and Jorge A. Saraiva—University of Aveiro, Portugal. We are thankful to these leading experts for their participation in INCREaSE 2023.

We wish to express our gratitude to all the above participants who contributed to the success of the third edition of INCREaSE.

July 2023

Jorge Filipe Leal Costa Semião
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Rui Mariano Sousa da Cruz
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Revisiting Solar Dryers for Small to Medium Production

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Abstract. This article presents an overview of passive solar dryers, an ancient technique that may be revived for food drying capacities below one ton/day. The art of dehydrating food has existed for centuries and was developed to preserve food by extracting its water content, thus delaying its natural deterioration. This article reviews traditional solar dryers and proposes a verification parameter k, parametrising the solar collector's size by the drying capacity. The modelling and parametrisation of the k constant allowed the evaluation of the examples of traditional models from the literature systematically. Results showed that 80% of the evaluated constructed solar dryers might underperform due to lower solar collecting surfaces than those projected by the k parameter.

Keywords: Solar dryer · Food drying · solar dryer parametrisation

1 Introduction

In the Western world, food dryers are often considered craft equipment associated with permaculture when discussing drying equipment. These models are usually one-off designs employing reclaimed or recycled material for a specific site, aiming for low investment and reduced operational costs besides labour. Alternatively, industrialised dryers are available for large productions requiring high investment and energy costs, deemed unsuitable for a small startup to a medium size company.

There is no standardised categorisation regarding the dryer's capacity. For clarity in this article, a producer classification based on daily drying capacity is proposed (24 h). [Table 1]. Small producers are at most 100 kg and medium

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Table 1. Producer classification based on the magnitude of the daily mass drying capacity in kg.

0<	Small	$\leq \times 10^2$
$\times 10^2 <$	Medium	$< \times 10^3$
	Industrial	$\geq \times 10^3$

until 1000 kg. Industrial productions exceed a daily capacity of 1000 kg, requiring specific industrial equipment with continuous operation.

With the appropriate designs, instruments and measures, drying can be carried out economically sustainably and industrialized. The drying process becomes more controlled and efficient without incurring high costs for purchasing machines, such as continuous flow dryers. A critical step is to collect data continuously and efficiently communicate to the operator.

It is essential to highlight the two distinct sectors of the food drying industry and the gap between them. This gap creates a space that can be exploited to improve the technical side of food drying, society's belief in it, and how communities can benefit from pre-dried food.

Solar drying technology is worth mentioning, catalogued as dated, unattractive, low-tech, or presently forgotten. However, this technology can be revised and modernized to bridge the gap between low/amateur and industrialized drying.

Food logistics worldwide has been in demand in the last centuries. The transport of certain foods, such as fruits or vegetables, has escalated to levels of crossing continents for final consumer delivery, implying a high energy demand which is directly proportional to the transported weight. The consumption of pre-dried food, either directly (final consumer) or indirectly (food industry), would significantly reduce not only operational costs but would also have a direct impact on the reduction of greenhouse gas emissions. Approximately 91% of the fruits' composition is water; in the case of vegetables, the water content increases to 95% [25]. For example, Spain imported 2011 more than 25.4 million tons of food that travelled an average of 3,827 km [28]. In specific cases, a chickpea travels an average of 7500 km.

The world's leading fruit and vegetable-producing region by far is East Asia, followed by South Asia (Fig. 1 and Fig. 2). Other important producing regions are South America, Southeast Asia and Southern Europe (for fruits), and Southeast Asia (for vegetables). Northern and Western Europe produce relatively little, so they must import much of their consumption [25].

Food drying would not only reduce the energy cost of logistics but also impact the local economy, benefiting the medium farmer by increasing our added value in food without prior processing. In 2018, the world produced 868 million tons of fruits and 1,089 million tons of vegetables [25]. Northern and Western Europe farm relatively minor, so they must import much of their consumption, whereas Asia and Latin America are the largest producers.

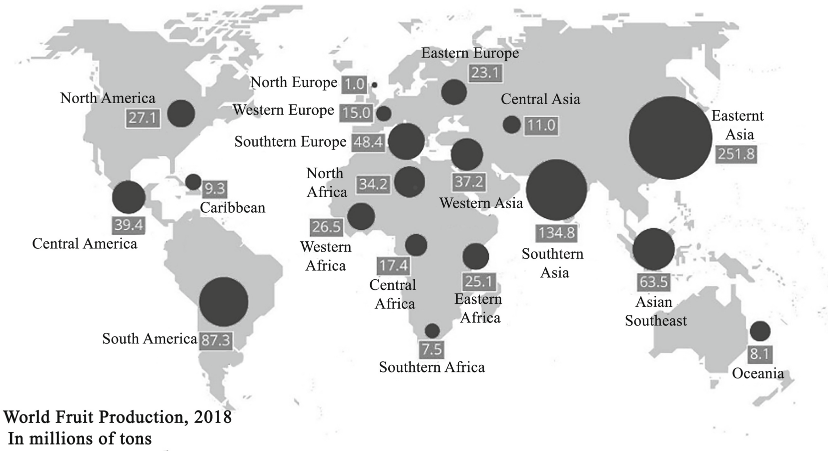

Fig. 1. Fruit production [25].

Worldwide, more than 50% of fruits and vegetables are grown on farms of less than 20 hectares (most of which are family farms). In developing countries, these farms grow the vast majority of horticultural products, more than 80% in most of Asia, sub-Saharan Africa, and China [25]. Since this category (fruits and vegetables) has excellent potential for applying drying techniques, it would directly impact the economy of family farms if it could be carried out efficiently.

Figure 3 shows the world exports of certain foods, most of which can be dried, especially in the main categories.

Problems of distribution and access mean that many people need help to obtain the types or quantities of food they need [25]. A considerable proportion of the harvest is lost or wasted before it reaches consumers' plates. Figure 4

In East and Southeast Asia, losses were greatest during storage (averaging more than 20% loss), processing and packaging. The highest loss levels in sub-Saharan Africa occurred at the farm gate and wholesale markets. Losses and wastage in Central and South Asia tended to be lower, with losses during transport being the highest [25].

Food drying technology is the cheapest method (particularly solar drying), especially suitable for communities with no other preservation possibilities. Applying this technology could significantly reduce storage and transportation losses and transportation costs.

The global dehydrated food market is forecast to register a CAGR (Compound Annual Growth Rate) of 4.8% during the forecast period (2022-*2027) [27]. In 2020 the dried fruit market was expected to reach 4 million tons [29]. EMR estimates the Latin American dried fruit market to reach USD 4.15 billion by 2021. During 2023–2028, the market is anticipated to grow at a compound annual growth rate of 4.77%.

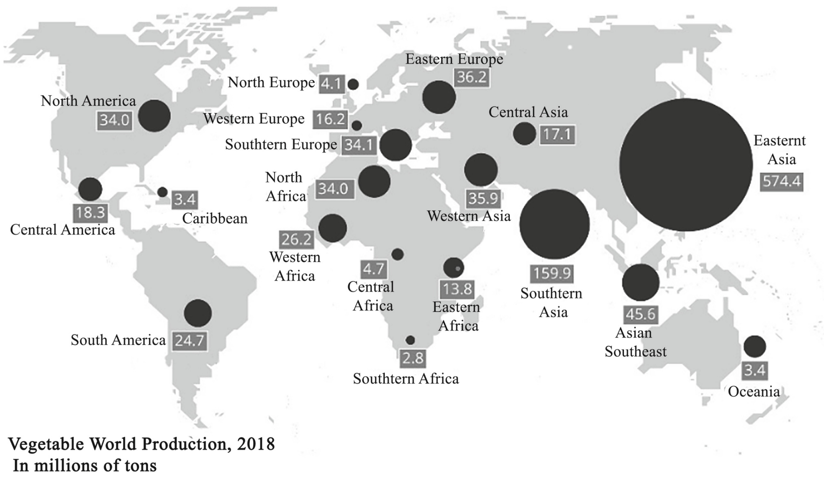

Fig. 2. Vegetables production [25].

Much of the drying technology is applied in North America and Asia. It correlates with Asia's world-leading position in fruit and vegetable production. In 2004, it led the market by more than 50%, Figure 5. On the contrary, North America produces little but dries much of its food, and South America, where fruit production is high but drying is low. The statistics for South America and Africa must be taken with a grain of salt because often, the records of these types of activities are scarce, leading to a distorted perception of the use of these technologies, Fig. 6.

The continuous search for innovation sometimes leads to ignoring low or so-called dated technologies, quickly forgotten or perceived as obsolete. Such is the case of solar drying, a technology that, by some criteria, may not fit into the terms of technology simply because it does not possess electronic complexity or continuous innovation. While it is an ancient technology dating back millennia, it is a technology that, when applied correctly, can currently bring many benefits where simplicity and self-sustainability are a virtue. Revisiting this technology and parametrising the dimensions of principal components with a contemporary lens will lead to even better performance and fulfil the job with an impressively low carbon footprint.

2 Dryers

Food drying is a process by which the product is subjected to certain conditions of temperature and humidity to achieve a transfer of mass and heat. This can be defined as applying heat under controlled conditions to remove a certain amount of water in the food by evaporation. This mechanism works through

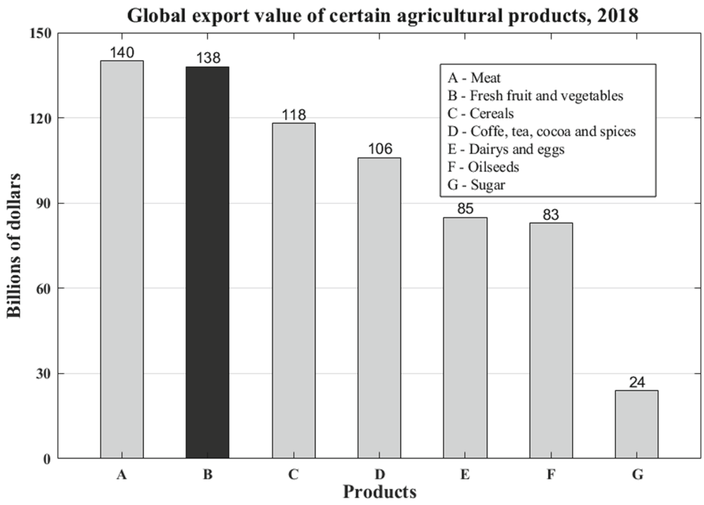

Fig. 3. Production [25]

the difference in humidity between the air in contact with the product and the product's moisture.

"Drying is a physical method of preservation. It consists of reducing, by evaporation, the amount of water contained in the food to prevent or limit microbial growth. By controlling the action of enzymes that chemically deteriorate the food, its shelf life is prolonged" [26].

The critical factors to consider for drying are temperature, relative humidity of the drying agent (air) and the pressure at which this phenomenon occurs.

This process can be carried out in different ways, either in a "natural" way or through dryers. However, there is no standardization of the types of dryers since more than 500 types have been recorded [15]. A classification is accepted according to the technology: Natural (N), Fuel (F), and Solar (S). Table 2 shows the specific parameters of this type of dryer, highlighting particular characteristics that can help one choose according to the needs: investment, drying time, losses, and operating costs.

The investment required to acquire a solar dryer is medium or even low compared to an industrial dryer. This fact already places it in an advantageous position against high-capacity industrial dryers, Table 1. While it is true that the production volume is lower than a fuel dryer, it has to highlight the gap between industrial and home-made dryers for production of up to 1000 kg per day.

As previously presented, one of the primary drying objectives is to reduce product losses due to microbial activity growth, which generates losses of up to 20% in storage, for example. These savings are one of the significant benefits of solar-type dryers. Given the degree of investment and ease of use, reasonably small or even zero losses are obtained in cases where drying is controlled with

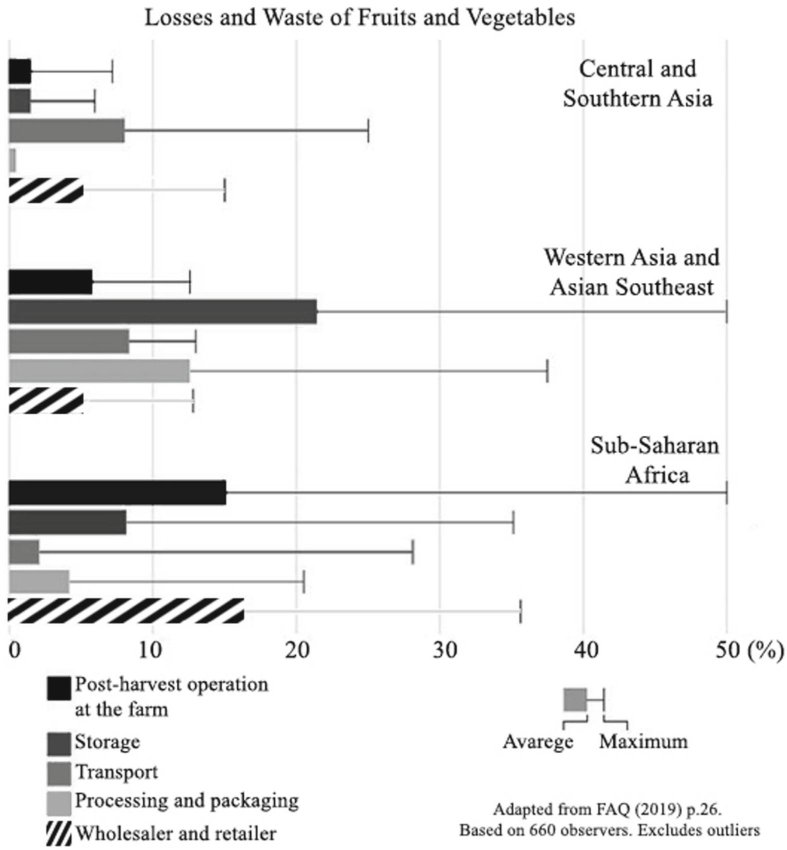

Fig. 4. Losses and waste of fruits and vegetables [25].

the right design and type of solar dryer. This fact positions this dryer category as ideal for a medium sector of food drying producers.

The drying time between the different types of drying is well-marked since natural drying can take days to a week, mainly due to the lack of control over the drying parameters, temperature and humidity. Although drying with fuel accelerates the drying to hours, it can damage the product and expose it to high temperatures generating a loss of nutritional properties. Solar drying can significantly reduce the natural drying time. Drying high-temperature that can damage the quality of the final product can be avoided by monitoring the drying parameters. Moreover, it is acceptable for a medium production volume when the product achieves absolute quality with daily drying rounds. From Table 3, it can be verified that solar dryers are positioned with a specific advantage to make this choice if referring to a start-up or even a medium-sized company. The investigation of this type of dryer and its constituent components is further explored in this document.

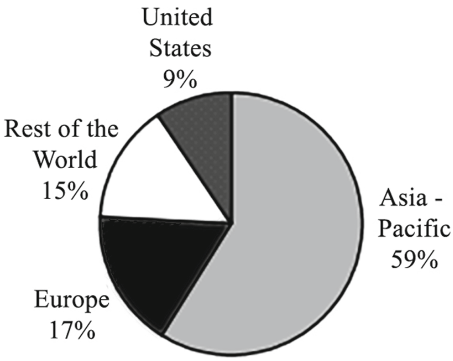

Fig. 5. Distribution of dehydrated market [30].

Table 2. Investment, operational costs, and lost product against the type of dryers: Natural (N); Fuel (F); and Solar (S).

	None	Low	Medium	High
Investment	N	S	S	F
Operating costs	N/S	S	F	F
Lost product	F/S	F/S		N

3 Solar Dryers

Solar technology dryers are equipment used for food preservation by drying using the heat generated by solar radiation [26].

Drying using solar energy is based on obtaining the necessary power to increase the temperature of the circulating air to reduce its relative humidity and thus increase its capacity to absorb moisture from the product. This moisture harnessing is accomplished through one or different components of the dryer.

Being an old technology and not very standardized, the types of solar dryers are vast, and their designs vary in complexity. Although there is no standardization of the types of solar dryers, it has been concluded that the following classification is widely accepted: Direct (D), Indirect (I), and Mixed (M).

The *direct* dryer collects solar energy to increase the air temperature through the roof of the device, i.e., solar radiation not only manages to improve the air temperature but also impacts the product. The ultraviolet radiation degrades the produce, inducing a high rate of losses or low quality of the final product through the loss of food properties, Fig. 7 (a).

The *indirect* dryer collects solar radiation to increase the air temperature. In this case, it is done via an element with an exclusive purpose. The collector is a surface before the drying chamber aiming to capture solar radiation to heat

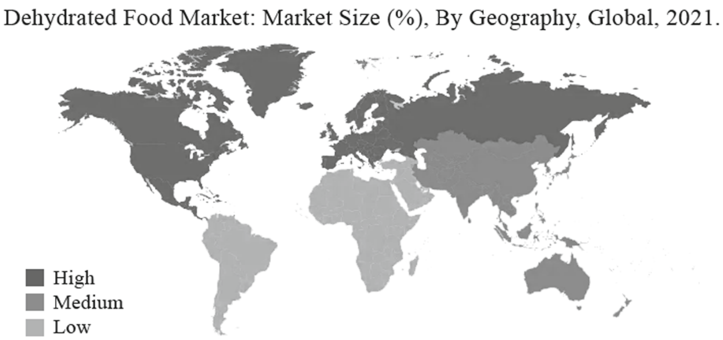

Fig. 6. Dehydrated food market [27].

Table 3. type of collector relationship between type of dryers/Dryin time.

	Natural	Fuel	Solar
Hours		x	
Days			x
Weeks	x		

the air. The produce is placed in the drying chamber, protected from ultraviolet rays. In such designs, product losses are low or null, Fig. 7 (b).

The *mixed* dryer combines a direct and an indirect dryer. The solar radiation is captured in the collector and the roof of the drying chamber, permitting incoming ultraviolet rays to deteriorate the final product, Fig. 7 (c).

Table 4 shows how the different types of solar dryers are positioned, with the indirect type (I) on the left side of the table, the mixed type (M) predominating on the right side and a transition of the 3 classes in the middle. However, having a low or medium production volume may seem at first sight a disadvantage. It is important to remember that we are looking for a dryer capable of achieving medium production volumes and adaptable to medium-sized producers. The indirect solar dryer is better positioned to occupy this space.

The efficiency of a solar dryer is determined by the amount of heat provided by solar irradiation to the amount of heat delivered to the product to achieve evaporation of the water it contains. The indirect type solar dryer achieves this inefficiently, but this is usually due to design errors or poor construction techniques that can be remedied.

Indirect solar dryers can vary on the prospective market. However, all passive indirect solar dryers always contain the same components: collector, drying chamber, and chimney.

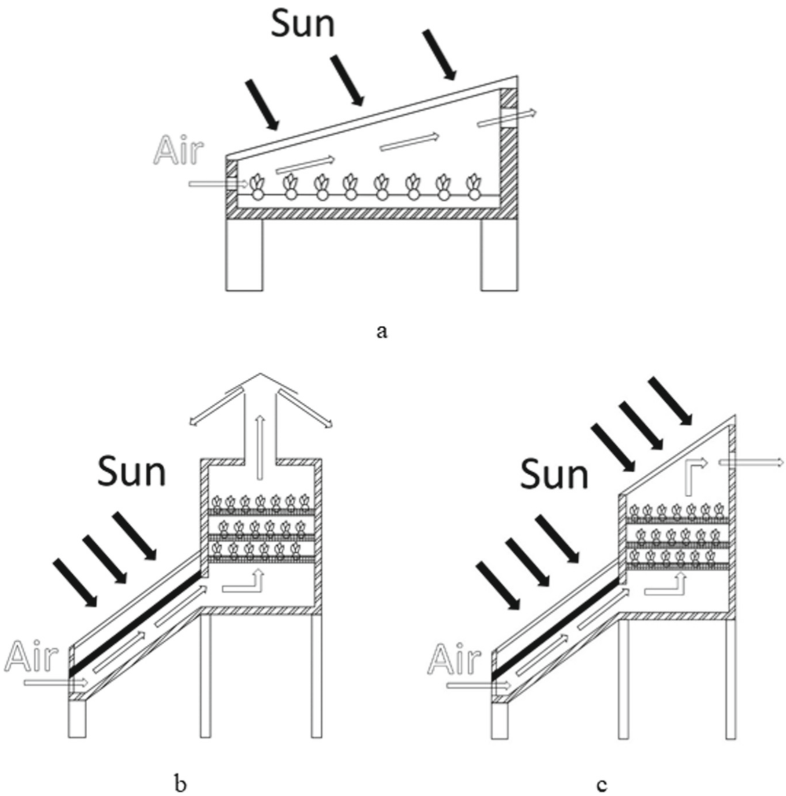

Fig. 7. a: Direct solar dryer, b: Indirect solar dryer, c: Mixed dryer.

3.1 Collector

The collector is the first element in the airflow path, mainly aiming to capture heat from the sun and deliver it to the airflow. It is usually a rectangular hollow parallelepiped, where the upper surface is responsible for absorbing the heat. The air enters one of its lower laterals. It travels through the channel while absorbing heat and increasing its temperature until it leaves it through the opposite extremity, thus decreasing its relative humidity of the air as it expands its capacity to absorb humidity. The collector can have different transparent layers (covers) or thermal insulators on its lateral and inferior surfaces to diminish heat loss by convection.

Table 4. Product damage, the volume of product, and efficiency by type of solar dryer configuration: Direct (D), Indirect (I), Mixed (M).

	Low	Medium	High
Product damage	I	D/M	D/M
Volume of product	I/D	I/D/M	D/M
Efficient	I	D	M

Table 5. Quantity of solar collector layers against efficiency and investment. No layer (0); **one** layer (1); Two layers (2).

	Low	Medium	High
Efficiency	0	1/2	2
Investment	0	1	2

The cover fulfils the objective of reducing the losses of the collector through the greenhouse effect generated between it and the absorber plate. Although transparent plastic covers seem a good solution, they degrade from ultraviolet radiation exposure needing to be regularly replaced. Using a non-transparent cover reduces the collector's efficiency, thus, the dryer. However, it reduces the investment and maintenance costs if the cover is made of plastic. Using two or more covers can generate air tightness promoting the natural airflow, Table 5.

3.2 Chamber

The drying chamber is where the essential part of a solar dryer takes place as it receives the air already dried by the collector. This air circulates the product intending to heat it, evaporate its water content and then transport it to the chimney, conducting a continuous flow.

Although the homogeneity of the flow will depend too much on the final design of the dryer, in general, avoid arranging the trays to generate a parallel flow, as this can lead to uneven drying inside the chamber. This problem can be solved with a cross-arrangement, Table 6.

Table 6. Drying chamber layout and flow homogeneity.

	Serie	Parallel	Cross	Fixe
Even	x		x	x
Uneven		x		

3.3 Chimney

The chimney is the last element playing a vital role in passive dryers once there are no fans to promote the airflow. It works due to the temperature difference between the column of hot air that runs through it and the outside temperature, generating an upward force by pressure difference.

3.4 Instrumentation

The instrumentation of solar dryers to measure and control the operating parameters is often forgotten. However, efficient and controlled drying can be achieved when information about the various elements is available to monitor the process. Accessing these parameters to interpret what happens during drying continuously is crucial. Previous works converge into similar solutions as presented in the Table 7.

The fundamental parameter to measure and control is temperature. It is essential to know the temperature in the interior of the drying chamber for airflow regulation. Also, remember that some foods can not be exposed to high temperatures. It is essential to control that these values are not reached, so all projects generated from solar dryers are made the temperature measurement. Table 7.

The relative humidity is generally measured in Table 7; this allows us to obtain information if the air circulating through the dryer can absorb the moisture generated by the products.

The airflow measurement has a double objective, not only to control this same parameter that allows us to measure if it generates airtightness or not but also to measure the airflow that circulates, enabling calculations indirectly.

On the other hand, there is the measurement of solar irradiation or the weight of the products. Measuring radiation is unnecessary because it can be obtained through meteorological centres. The weight of the load generally serves to access the drying curve of specific products in a particular dryer and at an exact location. It also lets the operator know when the batch can be removed. The drying curve is generally obtained by removing the load and weighing it on an outside scale.

3.5 Parameterization

The collector's efficiency η is given by Eq. 1:

$$\eta = \frac{Q_u}{I \times t \times A_c} \tag{1}$$

where Q_u is the heat from the solar collector to be delivered to the airflow, the airflow temperature increase is due to the heat radiating from the sun I over the collector's surface A_c during drying time t. The total energy E required to evaporate the water contained in the product is given by Eq. 2, [1]:

$$E = \dot{m} \times (h_f - h_i) \times t \tag{2}$$

Table 7. Instrumentation used on reviewed articles.

Reference	Velocity	Temperature	Humidity	solar irradiation	weight
[4]	x	x	x		
[16]		x	x		
[6]		x	x		
[13]	x	x	x		x
[12]	x	x	x	x	x
[10]	x	x	x	x	
[5]	x	x			
[24]		x	x	x	
[2]		x			
[20]	x	x	x		
[18]	x	x		x	
[12]	x	x	x	x	
[23]	x	x			
[22]	x	x	x		
[21]	x	x	x		
[11]		x	x		
[19]		x	x		
[14]	x	x	x		
[17]		x	x		
[7]		x	x		

Being that $\dot{m}$ is the mass flow $[\frac{kg}{s}]$ and $(h_f - h_i)$ is the vaporisation entalpy. t is drying time $[s]$. To achieve complete drying, the heat supplied to the air by the collector must equal the energy required to evaporate the desired amount of water from the product. Introducing Eq. 2 in Eq. 1 and clearing A_c:

$$A_c = \frac{\dot{m} \times (h_f - h_i)}{\eta \times I} \tag{3}$$

where $\dot{m}$ is:

$$\dot{m} = \frac{m_w}{t \times (w_f - w_i)} \tag{4}$$

Introducing Eq. 4 in Eq. 3:

$$A_c = \frac{m_w \times (h_f - h_i)}{\eta \times I \times t \times (w_f - w_i)} \tag{5}$$

where m_w is:

$$m_w = \frac{m_p \times (m_i - m_f)}{(100 - m_f)} \tag{6}$$

Introducing Eq. 6 in Eq. 5:

$$A_c = \frac{m_p \times (m_i - m_f) \times (h_f - h_i)}{\eta \times i \times (w_f - w_i) \times (100 - m_f)} \tag{7}$$

Where i is $I \times t$.

Searching for a ratio between the collector's area and the product's weight to be dried m_p is suitable. By equating Eqs. 7 arrives at:

$$A_c = \frac{k \times m_p}{\eta \times i} \tag{8}$$

The Eq. (8) shows that the collector surface area $[m^2]$ has to be k times greater than the weight product $[kg]$ between solar radiation $[\frac{W}{m^2}]$ and collector efficiency.

Where:

$$k = \frac{(m_i - m_f) \times (h_f - h_i)}{(100 - m_f) \times (w_f - w_i)} \tag{9}$$

k depends on product moisture $(m_i - m_f)$, enthalpy of vaporization $(h_f - h_i)$, absolute humidity $(w_f - w_i)$.

The values of k were calculated from the construction parameters consulted in the bibliography. The articles with a concluded prototype were selected, and the parameters were compiled. Each value of k was calculated using Eq. 9, synthesized and depicted in Table 8. The mean value of k was 2428, and its standard deviation 438. The extreme values, k_{min} and k_{max} fluctuate close to $\pm 18\%$. Thus, the solar collector's surface standardisation by the drying capacity may be explored to evaluate if the proportions were respected within certain values for the constructed solar dryers presented in the literature.

The examples in Table 8 show that the surface of the collector from built solar driers is smaller than required for the quantity of produce in almost all cases. Sometimes, the collector size should be more than double, indicating a systematic underdesign. In such cases, the solar dryer will underperform, not delivering the product as expected. The exception is [9], where the area of the collector exceeds the model by a meagre 6%.

Table 8. Values of k, the calculated surface A_k, and the existing surface A_r as indicated in the references. ϵ is the error for k model as reference.

Ref	k $[\frac{kJ}{kg}]$	A_k $[m^2]$	A_r $[m^2]$	ϵ [%]
[8]	1965	5.68	2.00	–65
[1]	2877	19.99	18.90	–5
[3]	2261	106.81	–	–
[9]	1944	20.00	21.20	6
[6]	2583	59.79	5.80	–90
[10]	2939	4.45	4.00	–10

4 Conclusion

Food drying is a millenary practice. It evolved throughout history as technology advanced, leaving traditional drying techniques in oblivion due to the food industry's need for standardization. Machinery has become more complex and energy-hungry, inhibiting access to medium-sized companies or start-ups to drying technology due to its high acquisition and maintenance costs.

Solar technology for food drying in a medium volume can cover a need found in medium-volume producers, which production volumes do not justify the acquisition of industrial machinery. An indirect solar dryer would adequately fulfil the role of a medium-volume dryer. However, the dryer must be instrumented to monitor the process and ensure the product maintains its nutritional properties to obtain a correct and standard dried product. In other words, it is possible to retrofit an old technology that, although simple, can meet the technical requirements with a more sustainable solution.

The parametrization provided by the k model and the analysis of the different models described in the references highlighted a possible explanation for the underperformance of current traditional solar dryers. The collector's surface tends to be inferior to its intended purposes. In 80% of the examples, the collector surface was inferior to what was required. Furthermore, in 40% of the cases, the surface of the actual solar collector was less than half of what it should be for the type and quantity of the intended food. The dryers, in such cases, will underperform.

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