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Recent Advances in Solar Drying Technologies for Tomato Fruits: A Comprehensive Review

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***Abstract*—The world's popular and productive vegetable crop is the tomato fruit. The tomato is the second-most important vegetable crop in the world. Fresh tomatoes cannot be stored for a long time because they have a high moisture content (MC). The high MC acts as a suitable environment for the growth of fungi and molds, which leads to damage to stored tomatoes. So, MC must be decreased to a suitable level for storage and handling using a suitable drying method to maintain nutritional value and natural color properties. There are many drying methods that can be used for drying tomatoes. Throughout history, tomato drying methods have relied on direct sunlight, firewood, fossil fuels, and coal, leading to carbon emissions. These techniques are costly, unreliable, and unsanitary. There are now many modern methods, including solar drying, microwave drying, vacuum drying, infrared drying, freeze drying, oven drying, and various hybrid drying techniques. But hot air drying, solar drying (SD), sun tunnel drying (STD), microwave drying (MD), and freeze-drying (FD) are some of the popular methods of drying tomatoes for preservation. This paper aims to present the state-of-the-art solar energy technologies for tomato drying. The drying methods presented in the current paper are applicable to a wide range of vegetables and fruits.**

***Keywords*— solar dryer; tomato; open sun drying; mechanical drying; solar tracking.**

I. INTRODUCTION

The tomato is a summer vegetable crop. It is a self-pollinating annual herbaceous plant grown in warm and temperate regions, originating in Central and South America. Tomato cultivation moved to Europe in the middle of the sixteenth century and then spread to most countries in the world [1]. Food and vegetable preservation have been enduring practices aimed at maintaining flavor, appearance, and quality. Throughout history, food grain drying methods have relied on direct sunlight, firewood, fossil fuels, and coal, leading to carbon emissions. These existing techniques are costly, unreliable, and unsanitary. Therefore, the utilization of a solar dryer (SD), harnessing free and clean energy, offers a superior option for enhancing the value-added aspect of food preservation [2]. Kocabiyik et al. [3] mentioned that hot air drying (HAD), solar drying (SD), sun tunnel drying (STD), microwave drying (MD), and freeze-drying (FD) are some of the popular methods of drying tomatoes for preservation. One of the disadvantages of drying is that it requires high energy inputs, especially in industrial applications that depend on the use of energy and traditional fuels. The main reason is the low thermal conductivity of agricultural products, and the quality of the products is affected by high temperatures and long drying times (DT). Poor rehydration properties, and loss of nutrients due to the use of industrial drying systems. SD, a renewable and sustainable energy source, has attracted the attention of many researchers worldwide to engage in solar energy (SE) application research. In developing nations, SD has the potential to meet the escalating demand for wholesome, economical natural foods while addressing the need for sustainable income. SDs employed in the dehydration of agricultural products stand out as highly advantageous devices from an energy conservation perspective. These equality and conserve energy, but also save considerable time, occupy minimal space, enhance product quality, and elevate the overall quality of life. While a solar-based crop drying system doesn't exclusively rely on SE for operation, recent progress in the drying process has led to the integration of alternative heating methods with SE. This approach aligns with current trends aimed at diminishing fuel consumption [4]–[6]. Based on the above, the current paper aims to present the state-of-the-art of solar energy technologies for tomato drying.

II. LITERATURE REVIEW

The drying of tomatoes is a widespread practice around the world, and different drying methods are used. These methods include solar drying, microwave drying, vacuum drying, infrared drying, freeze drying, oven drying, and various hybrid drying techniques [7]–[10]. Figure 1 shows the classifications of drying methods of tomato fruit.

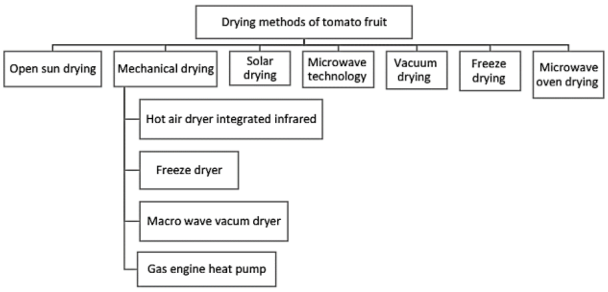

Figure 1. Classifications of drying methods of tomato fruit [11]-[15]-[16]-[17]-[18].

A. *Traditional drying or open sun drying (OSD)*

Open sun drying (OSD) is a traditional approach in which the product is directly exposed to sunlight and harnesses solar radiation for food preservation [11]. OSD is the most popular method for food preservation. In this method, the fresh product spreads on the ground, but there are a lot of problems associated with this method, like the low quality of the dried products and contamination by many sources like dust and insects. In addition, SDs have a good chance of improving the quality of the dried food products [12]. Andritsos et al. [13] stated that OSD requires a long time for drying, but it is very simple and requires small capital investments.

Opadotun et al. [14] make an experiment for drying tomato fruit by SD and OSD, where three different varieties of tomato fruit were used in the experiments. They found that dehydrated tomatoes retained slightly more nutrients than oven-dried tomatoes but took longer than the oven-dried sample. On the other hand, they found that dried tomato samples under an OD, that is, OD gave a better result compared to SD, because of factors of control.

B. *Mechanical drying*

A hot air dryer (HAD) was designed for drying tomato slices. The dryer was combined with infrared so that the operation variables could be adjusted. Three temperatures (60, 70, and 80°C), three tomato slice thicknesses (3, 5 and 7 mm), air velocity 1.1 m/s the thickness of the tomato slice ranged from 3 to 7 mm. The DT of the tomatoes decreased with the increase in temperature, while the electrical energy consumed increased [15]. Figure 2 illustrates the isometric view of the integrated infrared with HAD.

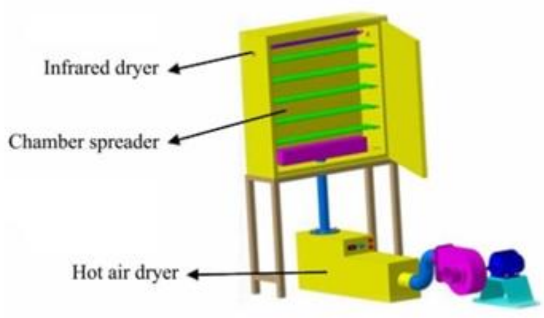

Figure 2. Isometric view of an integrated infrared with HAD [15].

Another approach to drying methods is Freeze drying based on [16]. It is one of the best methods of application in the dehydration of various plant-based foods, including fruits, vegetables, spices, and unconventional food items. It stands out as the preferred method for achieving exceptional final quality and preserving nutritional attributes, particularly when conducted in a vacuum environment. However, while freeze drying offers numerous advantages, it does come with the drawback of extended processing times and a relatively high cost associated with the drying process. This is partially due to its energy requirements, which are four to ten times greater than those of other drying methods. Also, some loss of vitamins and other valuable bioactive compounds can occur during freeze-drying. Figure 3 shows the main components of the freeze dryer.

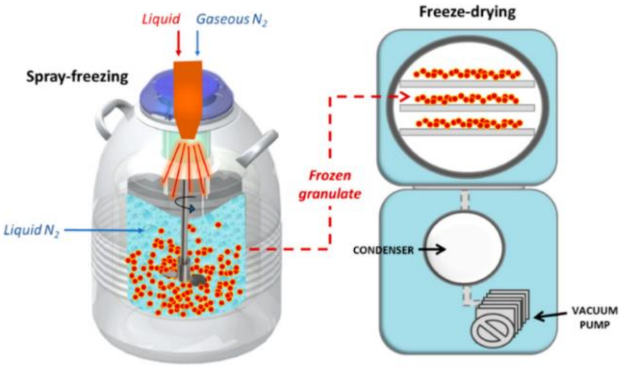

Figure 3. Main components of the freeze dryer [16].

A specialized microwave vacuum dryer was created by [17] to analyze the properties of button mushrooms (Agaricus bisporus). This innovative dryer is enhanced by incorporating a vacuum chamber into its structure. The study explored the effect of different drying parameters—microwave power, system pressure, and product thickness—on the drying kinetics and rehydration properties of mushrooms. The microwave vacuum drying system operates within a power range of 115-285 W, with pressure settings from 6.5 to 23.5 kPa, and uses mushroom slices between 6 and 14 mm thick. To measure its efficiency, the drying process was compared to conventional convection air drying, which was performed at different air temperatures (50, 60, and 70 °C). The results showed that microwave drying resulted in a significant 70–90% reduction in drying time. Furthermore, dried mushroom products showed superior rehydration properties compared to those dried using conventional convection air drying methods. Figure 4 demonstrates the main components of the microwave vacuum dryer.

A gas engine heat pump (GEHP) drying system was used to dry the food, and its performance, as well as each component part, was comprehensively evaluated by [18], as shown in Figure 5. The dryer consists of two main parts: (1) the heat pump system (HP system), which includes a compressor, condenser, expansion valve, and evaporator. (2) a gas engine (GE), which drives the system. The GEHP system heats the air efficiently, with precise temperature control through a dedicated controller. The airflow was regulated using a fan with a speed controller, and drying air was recirculated within the system. The dimensions of the drying chamber are 3.0 m in length, 1.0 m in width, and 1.0 m in height. Measurements were performed to evaluate the active efficiency of the system throughout the drying process. Experiments were performed u

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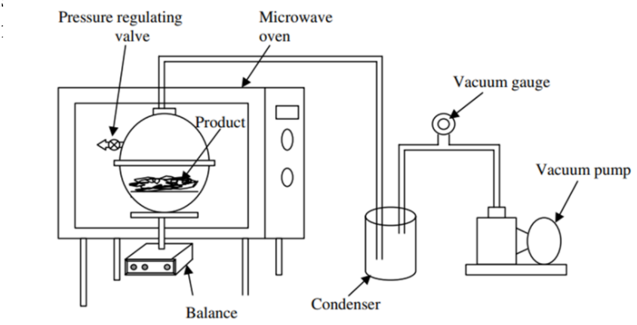

Figure 4. Main components of the microwave vacuum dryer [10], [17].

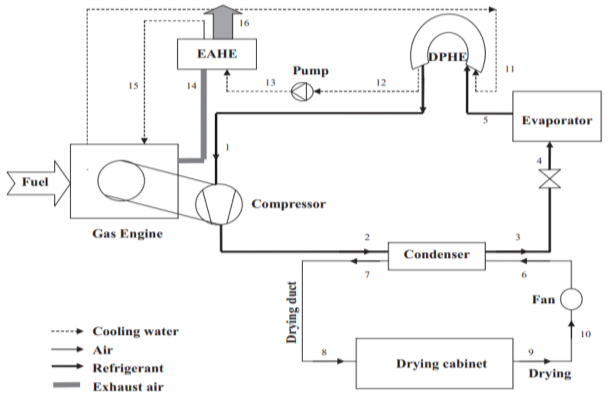

Figure 5. A schematic diagram illustration of the different components of the GEHP [18].

C. Solar drying

SD comes as an alternative method that can save time, energy, and cost and save the quality of products after drying, which is acceptable to national and international standards. The dried product is clean, with very low environmental impact [5].

Gutti et al. [19] studied a wide range of SDs and their effectiveness in drying agricultural products; they mentioned that developing efficient SDs for drying agricultural products using SE (SE) led to improved quality of dried products. Many systems use SE to dry various agricultural products and reduce production.

Mustayen et al. [6] reported that SD has emerged as a versatile and indispensable method for preserving and utilizing food and agricultural products. This environmentally friendly technique offers a myriad of benefits, making it a preferred choice in various applications. One of the first advantages of SD is its ability to simplify the preservation process. By harnessing the power of the sun, the drying procedure becomes more efficient and straightforward, effectively removing moisture from the products and hindering the growth of microorganisms, thus extending shelf life. Moreover, SD significantly enhances the quality of the final products. The controlled and gentle heat from the sun helps retain the natural flavors, colors, and nutritional value of the food items, resulting in dehydrated products that closely resemble their fresh counterparts, making them more appealing and nutritious. Additionally, SD contributes to improved storage capacity and transportation efficiency. The reduction in water content leads to lighter and more compact products, requiring less storage space and making transportation more cost-effective. Furthermore, embracing SD aligns with sustainable practices by utilizing renewable energy sources. As SE is harnessed to power the drying process, the dependence on non-renewable resources is minimized, resulting in reduced environmental impact and enhanced ecological benefits.

Kant et al. [20] reported that the SD technique serves as a valuable resource for both domestic and industrial sectors, benefiting various food and agricultural products in several ways: Firstly, SD simplifies the preservation process, allowing for the efficient removal of moisture from food items. By reducing MC, SD prevents microbial growth and enzymatic reactions that cause food spoilage, thereby extending the shelf life of the products. Secondly, this method enhances the usability of dried products. By removing water, the weight and volume of the food are significantly reduced, making it easier to handle and store. Moreover, the concentrated flavors and nutrients in the dried products enhance their taste and nutritional value, making them more appealing for consumption. Thirdly, SD increases storage capacity and enables cost-effective transportation. The reduced water content minimizes the need for bulky and expensive storage facilities, making it feasible to store larger quantities of dried products in a smaller space. Additionally, the lightweight and compact nature of dehydrated items reduces transportation costs, making them more economically viable for distribution and trade. Lastly, SD not only offers economic benefits but also harnesses direct or indirect ecological advantages. By utilizing renewable SE, the drying process reduces the reliance on fossil fuels and mitigates greenhouse gas emissions, contributing to environmental sustainability. Furthermore, SD can promote the consumption of locally grown and preserved food, supporting the local economy and reducing the environmental impact of long-distance food transportation.

Rashidi et al. [21] stated that SDs find extensive application in the agricultural sector, particularly in regions with abundant solar radiation, as they capitalize on cost-free and environmentally friendly energy sources. The utilization of SE for agricultural product drying is on the rise. In areas characterized by substantial agricultural output, particularly during the summer season, the reduction of MC in harvested produce holds significant importance. This reduction directly contributes to a noteworthy decrease in waste and product losses.

1) Solar dryer Technologies

Many types of SD can be used for drying agricultural products [22]. As well, much research has been done on SD for drying various vegetables and fruits [23].

2) Classification of solar dryers

Many studies dealt with the classification of SDs. Behera et al. [2] reported that SDs are classified in many ways. They can be classified based on:

- ✓ With hot air circulation, the dryers may have natural convection or forced convection.
- ✓ Exposure to solar irradiation, the dryers may be direct type, indirect type, mixed-mode type, or hybrid type.
- ✓ Temperature range, dryers may operate at high temperatures (fossil fuel as a heating source) or at low temperatures (se as a heating source).

Phadke et al. [24] stated that there are many types of SDs that can be classified based on air circulation mode (i.e., natural circulation SD and forced circulation SD), in addition to drying type (i.e., direct SD, indirect SD, and mixed-mode SD), material to be dried, and finally operation type (i.e., batch SD or continuous SD). Leon et al., [25] investigated that there is another classification of SDs depending on the design of SD components and the utilization mode of SE (i.e., passive SD and active SD).

Kumar et al. [4] analyzed three classes of SDs: direct SD, indirect SD, and hybrid SD. The study included the condition of the dryers, aspects of design and development, and performance evaluations. The classification is used as direct type SDs when the solar radiation directly affects the drying products, while they are classified as indirect if the solar radiation is received by a separate solar collector (SC). The collected heat is then transferred to the ambient air inside the collector, which then reaches the drying chamber to dry the product. Hybrid SDs are a subtype that incorporates complementary energy sources, such as biomass, electricity, thermal storage, or mechanical heat pumps, to enhance the drying process. The research results indicated that the indirect forced convection SDs showed remarkable performance, especially in terms of drying speed and output quality. The study also made recommendations aimed at improving the solar air collection unit to enhance drying efficiency in general. Another classification of SDs by El Hage et al. [26]. According to the method of airflow, mode of transferring heat from the sun to the product, and type of drying chamber, as shown in Figure 6.

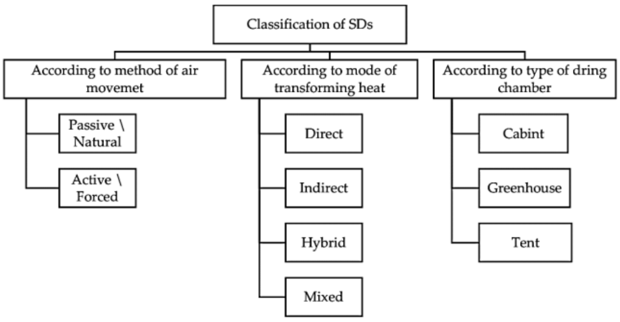

Figure 6. Classifications of SDs [10], [26].

3) *Drying of tomato by SDs*

Nabnean et al. [27] designed a SD for drying cherry tomatoes, where three batches of cherry tomatoes were dried in this SD during May–June 2014. For each batch, 100 kg of cherry tomatoes were dried. There was a considerable reduction in DT in the new SD as compared to OSD. The efficiency of the SC ranged between 21 and 69%, and the DT was 4 days. Figure 7 illustrates the main components of the SD integrated with SC and water tank storage.

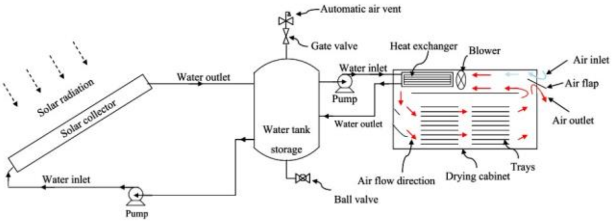

Figure 7. Main components of the SD integrated with SC and water tank storage [27].

Ghoniem et al. [28] designed and tested two direct SDs. The solar heat storage unit is integrated with one of the drying chambers to enhance drying rates after sunset. They found that in a dryer equipped with a heat storage unit, overnight internal temperatures were consistently about 5°C higher than in a standard dryer. The booster dryer showed a significant increase in the drying rate, resulting in a significant reduction of 33.3% to 36% in the total time required to reach the desired final MC. Figure 8 demonstrates the main parts of the SD integrated with the SC and heat storage unit.

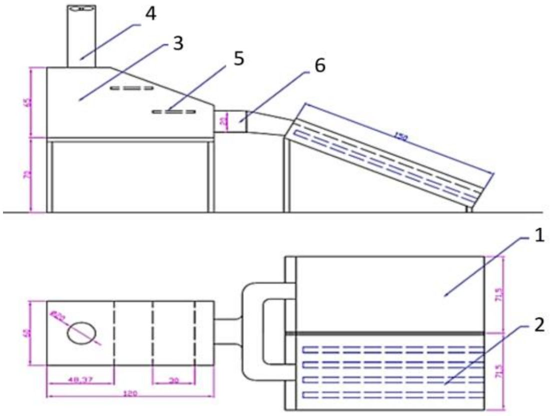

Figure 8. Detailed drawing of the mixed SD, 1. SC, 2. heat storage unit, 3. drying chamber, 4. chimney, 5. drying trays, 6. Duct [28].

Badaoui et al. [29] designed and installed a greenhouse-type SD for small-scale dried food industries. Figure 8 shows the main components of the designed SD, which has a drying capacity of about 1 ton of agricultural products. The SD is integrated with a gas burner for continuous drying during the day and night. Evaluation results showed that the hot air temperature inside the SD ranged between 35 and 65 °C. As well, the DT ranged between 2 and 3 days. Figure 9 demonstrates the main parts of the greenhouse-type SD integrated with the PV system and LPG burner.

Chouikhi et al. [30] designed and evaluated an indirect and forced SD that was equipped with a PV/T air collector to dry tomato slices. PV/T air collectors were used to generate both heated air and electrical energy. Throughout the experiment, Temperature, humidity, and mass of dried samples were meticulously recorded over a two-day period. A thorough thermal analysis of the SD arrangement was conducted. The resulting analysis revealed that the average daily efficiencies of the collector, dryer, and PV panel were calculated to be 30.9, 15.2, and 8.7%, respectively. The dryer is shown in Figure 10.

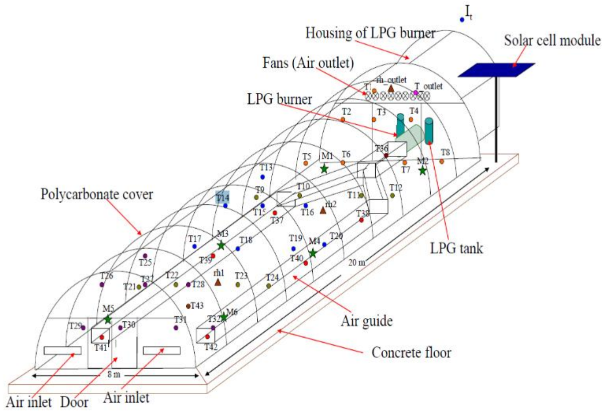

Figure 9. Main parts of the greenhouse-type SD integrated with PV system an LPG burner [29].

Figure 10. Main parts of the SD, 1. drying chamber, 2. PV/T SC, 3. solar charger, 4. battery, 5. controller, 6. Suction fan, 8. DHT22 sensors [30].

Ebadi et al. [31] developed and evaluated an indirect SD by integrating a concentrator SC with an electric auxiliary heater, aiming to advance sustainable tomato drying processes. This dryer was specifically designed to function in a dual mode, primarily relying on SE as its main power source. The auxiliary unit only came into play when solar radiation was absent or when the generated solar power was limited. He mentioned that the performance of dryers can be improved by integrating auxiliary units to increase the thermal efficiency of the dryers. The dryer is shown in Figure 11.

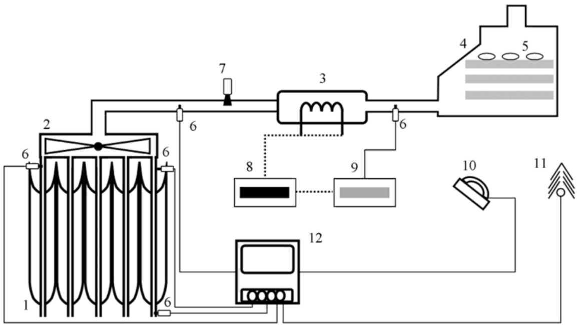

Figure 11. Detailed drawing of the developed SD, 1. SC, 2. suction fan, 3. auxiliary heater, 4. drying chamber, 5. drying product, 6. temperature sensors; 7. anemometer; 8. power controller; 9. temperature controller; 10. pyranometer; 11. ambient temperature sensor [31].

4) *Tracking SD*

Solar tracking systems (STS) could be a promising approach not only for their role in accelerating the SD process and reducing the DT but also for applying advanced technologies in industrial applications [32]. To achieve high system efficiency, it is essential to use an automated system, specifically a solar tracker, which constantly aligns the system with the optimal position as the sun moves across the sky. STS serve various commercial purposes, including enhancing the output of solar systems, optimizing thermal efficiency, and generating output power per unit surface area [33].

ElGamal et al. [33] developed a SD featuring an STS to enhance the performance of a SD constructed from aluminum cans drying apple fruit. The results show a substantial improvement in the thermal efficiency of the SD when equipped with the STS, with an increase of approximately 45% compared to the traditional fixed SD across all tested airflow rates. The highest thermal efficiency of 87.1% was attained by the SD equipped with the STS, operating at the highest airflow rate of 44 m³/h, as shown in Figure 12.

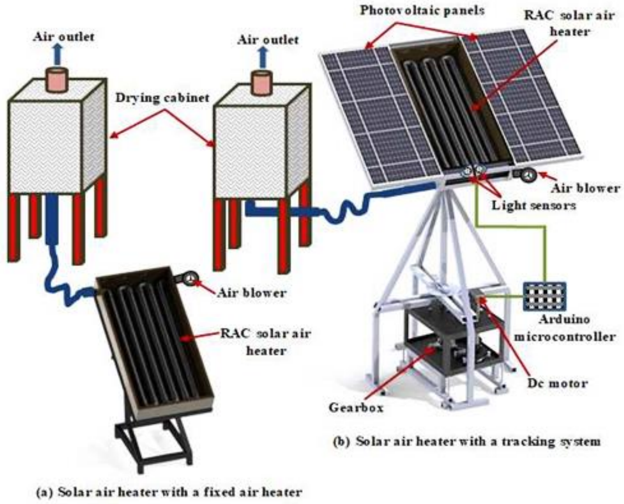

Figure 12. Detailed view of the SDs integrated with STS [33].

Das and Akpinar [34] constructed two SDs, one with a movable design and the other fixed, to investigate the impact of a STS on the performance of the SD on drying pear fruit. The findings revealed that the SD's thermal efficiency reached its peak at 91% when equipped with solar tracking, while the lowest solar air collector thermal efficiency was 34% in the non-tracking solar air collector. Furthermore, the STS-enabled SC exhibited an average drying efficiency of 66%, whereas the fixed solar air collector achieved only a 32% average drying efficiency. These results highlight the significant role played by the programmable logic controller STS in enhancing the average thermal efficiency by 42% and doubling the average drying efficiency in solar air collector dryer systems.

2.4. Other drying methods

Microwave technology, which exploits electromagnetic radiation, plays a pivotal role in drying fruits and vegetables quickly, both inside and outside the product [35], [36]. On the other hand, vacuum drying is well suited for highly perishable and heat-sensitive goods [37], [38]. Freeze drying, enhanced by infrared curing and acid dipping, and has dramatically reduced drying time for products such as banana chips while maintaining their color and creating a delicious crunch [39]. Notably, berries subjected to freeze-drying retain more phytochemicals, including antioxidants, ascorbic acid, and phenolic contents, compared to traditional air-drying methods, which lead to poorer quality results [40]. Infrared has gained prominence as the preferred drying method for a wide range of agricultural products due to its efficiency and effectiveness [41]. Similarly, microwave oven drying has proven to be a time-efficient process, especially for onion slices, as it retains phenols and minerals even at a moderate temperature of 70°C [42]. Moreover, oven drying not only maintains the rehydration ability of the dried samples but also maintains their structural and mechanical properties, as observed in strawberries [43]. Finally, hybrid drying systems have emerged as energy-efficient, cost-effective, and easy-to-use alternatives, effectively reducing processing time and costs [44].

Eventually, performance comparisons based on the literature are summarized in Table 1. It presents an overview of performances among different drying technologies for tomato fruit by using open sun drying, mechanical dryers, and solar dryers, which could give the reader a general understanding of the tomato drying field.

TABLE 1. SELECTED STUDIES ON DRYING SYSTEM FOR TOMATO FRUITS.

Drying method	**Research finding**	**Ref.**
Indirect solar dryer	The moisture content of tomato decreased from 15.667 to 0.803 kg/kg of dry basis (db). Mass transfer coefficient was in the range of 0.82×10^{-4} to 2.85×10^{-3} m/s for tomato. The average thermal efficiency of the collector and dryer was 59.05% and 31.4% during tomato drying and 58.42%. The average thermal efficiency of the SAC was 59.05%and 58.42% during tomato.	45
Hybrid solar dryer integrated with liquid petroleum gas	Drying times of 15 h, 28 h and 18 h are noted for liquid petroleum gas, solar and hybrid mode respectively.	46
Hybrid solar dryer integrated with solar-water storage	Time savings of 56.25% is for the hybrid solar dryer when compared to sun-drying compared with commercially available dried tomato available in the market, better quality is obtained especially in terms of ascorbic acid, lycopene and flavonoids contents.	47
Hybrid solar dryer integrated with solar-electric heater	Use of solar energy results in 6.6–12.5% energy savings non-enzymatic browning, Maillard reaction and lycopene degradation are observed in the dried tomato	48
Hybrid solar dryer with thermal storage natural convection	The temperature in drying chamber was observed 6 °C higher than the ambient temperature after sunshine hours till the mid night during the month of June.	49
solar dryer integrated with sun tracking system	The sun tracking system profoundly shortened the drying time about 16.6% to 36.6%. Application of the system substantially increased the effective moisture diffusivity in the ranges of 9.1–64.6% and the activation energy without any negative effect on the quality parameters of dried samples, i.e., color, rehydration ratio, and shrinkage.	50
Freeze drying	The moisture content was decreased from 91.37 % to 7.95 % after 48 hr	51
Vacuum pump	The energy cost was 3.2 USD for drying 1 kg of tomato fruits	52
Microwave oven	The energy cost was 1.6 USD for drying 1 kg of tomato fruits	52
Open sun drying	Drying times were determined as 26 and 22 h for natural and pretreated, respectively, Pre-treatment yielded good results in terms of drying time and color	53

III. CONCLUSION AND FUTURE WORK

Fresh tomatoes contain a high moisture content after harvesting that must be reduced to a safe level for storage and handling. Farmers used open-sun drying methods for drying tomatoes, where open-sun drying has some drawbacks in terms of quality, capacity, accuracy, and process efficiency. This causes product loss during drying, which is estimated to be 30–40% of the total production in developing countries. To overcome the above-mentioned problems of the open-sun drying method, it is necessary to develop solar dryers. In this article, the state-of-the-art of solar energy technologies for tomato drying has been presented as follows:

- ❖ There are different types of drying methods, such as open-sun drying, hot air drying integrated with infrared, vacuum drying, microwave drying, freeze drying, and solar drying.
- ❖ The present status of solar dryers with respect to developing countries is reviewed.
- ❖ A comprehensive review of the design, development, and performance evaluation of various types of solar dryers has been presented.
- ❖ Various types of solar dryers, such as natural convection and forced convection dryers, cabinet dryers, mixed mode dryers, direct and indirect type dryers, hybrid and integral dryers, have been depicted.

Many researchers around the world designed, developed, and constructed many types of dryers and devices for drying tomatoes, where the use of solar energy for drying tomatoes increased product quality, decreased drying costs, and decreased the environmental impact by decreasing the carbon footprint. Among the various types of solar dryers, indirect mode forced convection dryers have been reported to be superior in drying speed and quality. Due to their high drying rates and energy effectiveness, they have been observed to be suitable for low solar insolation and high humidity climate zones. Since the solar air collector unit is the most important part of indirect solar dryers, a significant improvement in it could lead to better drying performance for the system. Recently, some investigations in this direction have been made, such as the incorporation of double passes, recirculation of heated air, and v-corrugated and finned plates within the solar air collector unit. Furthermore, pretreatment of the product using chemicals before drying is also assumed to improve the product's drying efficiency. As well, we concluded that there are many parameters affecting the time required for the drying process by solar energy, like solar radiation intensity, wind speed, hot air velocity, ambient temperature, slice thickness, type of solar dryer, and quality of insulation materials used in manufacturing the solar dryer.

The current study is considered the cornerstone of the future design of a smart, automatic solar dryer for drying tomato fruits in order to obtain the best quality characteristics, reduce losses, and reduce the time required for drying at the highest operating efficiency. Where the drying methods presented in the current paper are applicable to a wide range of vegetables and fruits.

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