RESEARCH ARTICLE | NOVEMBER 27 2024

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AIP Conf. Proc. 3244, 060005 (2024)
https://doi.org/10.1063/5.0241450

Experimental Research on Greenhouse-Type Solar Dryer with Forced Convection

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Abstract: This work presents the results of experimental research on tomato drying in modified Quonset greenhouse type solar dryers operating in direct heat transfer mode with different transparent coatings. Traditional ordinary polyethylene and functional ceramic composite polyethylene specially produced for solar dryers were used as a transparent coating. Forced convection is provided by an air fan in solar dryers. The experiments were considered for cases where the surface of air-inlet slits is equal to S=0,2 m^2 and S=0,04 m^2. The results of the experiment showed that in both cases, the final mass of the product dried in the functional ceramic composite polyethylene coated dryer was less compared to the ordinary polyethylene coated dryer. The pulsating radiation created in the dryer with functional ceramic composite polyethylene coating made it possible to remove more water from the deep layers of the tomato and speed up the drying process.
Keywords: Ceramic composite polyethylene, convection, dryers, direct mode heat transfer, modified Quonset, mass, tomato, temperature.

INTRODUCTION

Tomatoes are one of the agricultural products in high demand by consumers worldwide and can be used as tomato paste, salads, preserves and spices [1]. Tomatoes are low in fat and cholesterol-free, and are rich in B vitamins, essential amino acids, carbohydrates, carotenoids (especially lycopene), ascorbic acid (vitamin C), vitamin E, folic acid, flavonoids, and potassium [2]. Tomatoes are a rich source of lycopene, and to a lesser extent beta-carotene, gamma-carotene, and phytoene, making it a rich source of antioxidant activity [3]. According to the analysis of medical researchers, lycopene may be useful in the treatment of cancer, cardiovascular diseases and other chronic diseases [4]. Tomato market size has been growing quite strongly in recent years and it is predicted to grow from USD 174,7 Billion in 2023 to USD 186.46 Billion in 2024 at a Compound Annual Growth Rate (CAGR) of 6,7% [5]. According to 2021 estimates, China (64,768 million tons), India (20,573 million tons), Turkey (13,204 million tons), America (12,227 million tons), Egypt (6,731 million tons), Italy (6,247 million tons), Iran (5,787 million tons), Spain (4,312 million tons), Mexico (4,137 million tons), Brazil (3,753 million tons) and Nigeria (3,693 million tons) are the countries that grow the most tomatoes in the world [6].

Despite the increase in the world's population and the high level of tomato consumption, tomatoes spoil very quickly when fresh and cause a certain part of the harvest to be wasted [7]. Due to the high humidity (almost 93-95%) of the tomato, it is quickly damaged when fresh, making it very difficult to store and transport [8]. Processing and storing the product in seasons when the demand for the product exceeds the demand in the market prevents large losses of the crop and makes it possible to use them in the non-seasonal period at a relatively low price [9]. Drying has become one of the most common ways to preserve tomatoes and process them into powders that can be added to foods, tomato pastes, and sauces [10].

According to various studies, drying methods such as microwave drying [11-12], heat pump drying [13-15], electrohydrodynamic [16], infrared drying [17-18] and freeze drying are used for tomato drying [19]. But as the demand for energy increases day by day, solar drying is also developing as an alternative to these additional energy-

International Scientific Conference on Modern Problems of Applied Science and Engineering
AIP Conf. Proc. 3244, 060005-1–060005-7; https://doi.org/10.1063/5.0241450

intensive drying methods [20]. For example, A. Gupta et al. dried 5 kg tomatoes cut into 5 mm thickness in a solar photovoltaic thermal dryer [21]. W. Saadeh et al dried 0.350 kg tomatoes cut into 15 mm thickness in Modified Indirect Air Solar Heater [22]. L.T. Dufera et al. dried Galilea tomatoes cut into 5 mm thickness in a Twin Layer Solar Tunnel dryer [23]. A.J. Tambe et al. dried 0.7 kg tomatoes cut into 4 and 8 mm in an Intelligent Solar-Photovoltaic Hybrid Tunnel Dryer for Tomatoes with Automatic Temperature Control and Air Recirculation [24]. M. Dorouzi and others dried 0.5 kg tomatoes cut into 5 mm in a liquid desiccant-assisted solar dryer coupled with a photovoltaic-thermal regeneration system [25]. In addition, scientific research in this field continues.

In 2021, Uzbekistan (2.2 million tons) took the 14th place in the list of countries that grow the most tomatoes in the world, and it is estimated that tomato production will increase by 0.6% per year and reach 2.3 thousand tons by 2026 [26]. The total land area occupied by greenhouses in Uzbekistan is more than 6 thousand hectares, of which 3.5 thousand hectares are heated by natural gas, 1.5 thousand hectares by coal, and the remaining 1000 hectares by other types of alternative fuels [27]. Due to the sharp increase in the demand for fossil fuels and limited resources, it is difficult to grow products in greenhouses, which also causes the price of products to increase. According to the FAO (Food and Agriculture Organization) and EAST-FRUIT reports, in 2021-2023, we can see that the price of tomatoes in Uzbekistan has increased sharply due to the ongoing problems in supplying gas to greenhouses in the winter season (Figs. 1-2). Data for Fig.1. have gotten from open source [28] and for Fig.2. from [29]. In addition, due to the carbon dioxide gases released in these greenhouses, great damage is being done to the environment. For these reasons, drying and processing of this product during the seasonal period of tomato production in Uzbekistan remains one of the urgent issues. This article presents the experimental results of tomato product drying in solar dryers with ordinary polyethylene and ceramic composite polyethylene coating.

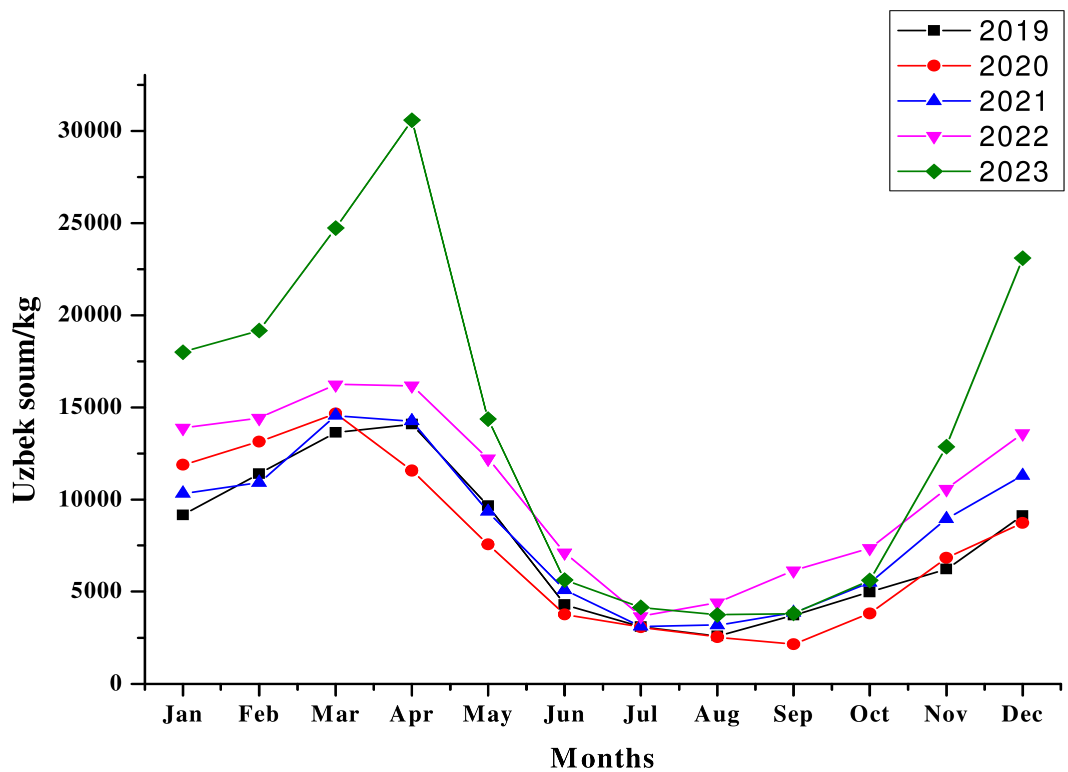

FIGURE 1. According to FAO statistics, the graph of tomato prices in Uzbekistan between 2019-2023.

METHODOLOGY

In this study, the product in dryers is dried by direct exposure to sunlight in direct heat transfer mode. The steam-air mixture formed inside the dryer is removed by forced convection. Drying of the product takes place at temperatures lower than 60-70 °C, otherwise excessive temperature in quick-dried products leads to the formation of a hardened crust, moisture remains inside the product, which in turn leads to a shortening of its shelf life due to the development of microbes and fungi

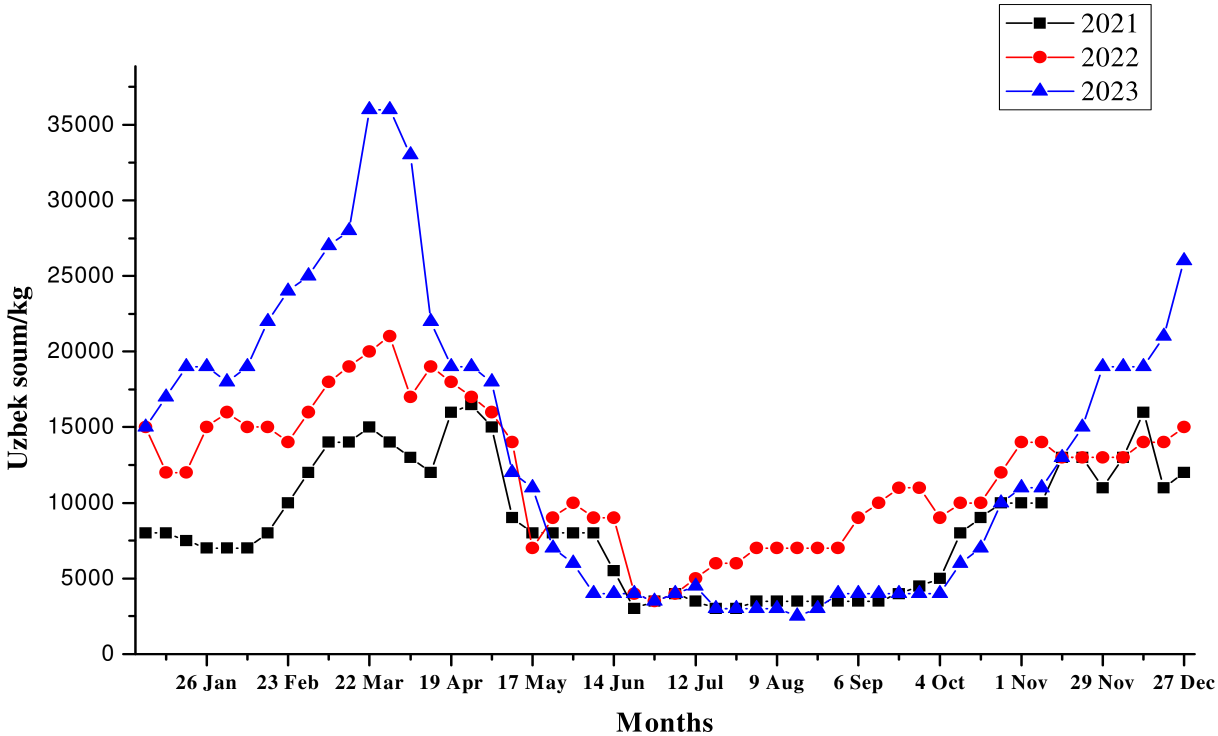

FIGURE 2. According to EAST-FRUIT statistics, the graph of changes in the price of red tomatoes in Uzbekistan between 2021-2023.

EXPERIMENTAL SET UP

The frame of two modified Quonset-shaped greenhouse-type solar dryers of the same size is made of local produced plastic pipe, which is covered with 0,1 mm thick functional ceramic composite and traditional ordinary polyethylene. The floor area of the dryer is 1,2×0,8 m^2, the central height is 0.6 m, and the height of the side walls is 0,4 m. The dimensions of the drying mat are 0,3×0,3 m^2. The dryer is placed on two identical tables with a height of 1,2 m in the east-west direction. Experiments were conducted for natural and forced convection cases. Forced convection flow was provided by a fan with dimensions of 0.15×0.15 m, power equal to 48.4 W (U=220 V, I=0.22 A, 1500 revolutions/minute). The north wall and floor of the dryers are not insulated. Functional ceramic composite polyethylene designed for solar dryers that converts sunlight into infrared pulses was created by adding alloy additives (0.1 - 20% of mass) to functional ceramics based on mullite $Al_6Si_2O_{13}$ (80 - 99.9% by mass): magnesium chromite $MgCrO_4$ 1÷15, lanthanum aluminate $LaAlO_3$ 0,5÷10, trichromate $YCrO_3$ 0.5÷3, zirconium dioxide ZrO_2 0.5÷5, cerium dioxide CeO_2 0.1÷1 (mass of these additives, in percent).

Ceramic composite polyethylene consists of 3 layers. Each layer is 30 microns and changes the rays of the falling sun. The first layer consists of polyethylene with additives that convert the ultraviolet rays contained in the incident sunlight into visible rays. The second layer is polyethylene without additives, which reduces the back radiation of pulsating infrared radiation, which is amplified and modified by the third layer. The third layer consists of a ceramic composite that absorbs solar energy on a large scale and produces maximum infrared rays for drying. Also, the ceramic composite polyethylene allows creating 10-20 photons from one high-energy photon in the ultraviolet and visible light regions. The resulting pulsating radiation allows drying of water from deep layers of the product and accelerates the drying process and improves the quality of the product [30].

MEASURING INSTRUMENTS

RS PRO TA298 Digital Hygrometer Hygrometer (wide temperature measurement range of 0 to 50°C (indoor) and -40 to 70°C (outdoors), ±5 %RH Accuracy, 99%RH Max) and Digital Panel Thermometer Hygrometers (wide temperature measurement range of -20 °C to 70 °C, humidity 10-99 RH, battery) were used to determine the temperature of the outside environment and the air inside the dryer. A TEJ-1000B laboratory scale (Max: 1000 g; d: 0.5 g) was used to measure the mass of the product. Solar radiation, wind speed and outdoor humidity were obtained from https://data.meteo.uz/.

SAMPLE PROCUREMENT AND PREPARATION

Locally grown tomatoes of the "MADERA" variety were selected for drying in solar dryers. Freshly picked tomatoes with no defects on the surface were sorted and washed with cold water to remove external dust and parasites. Tomatoes were cut to a thickness of 5 mm. Tomato slices with a net weight of 300 g were placed on each tray, weighed with high precision on a scale. The product trays were placed in both dryers at the same time and the experiment started at 8:00 a.m.

EXPERIMENTAL PROCEDURE

The experiments were conducted in September 2022. Drying of tomato slices was carried out in dryers for the following cases: (i) air inlet slot surface A_{in}=0,2 m^2 (air enters through 0,05 m slots on all sides of the dryer); (ii) air inlet slot surface A_{in}=0,04 m^2 (air only enters through the 0,05 m slot on the west side of the dryer). Figure 3-4 show the schematic and experimental image of the solar dryer.

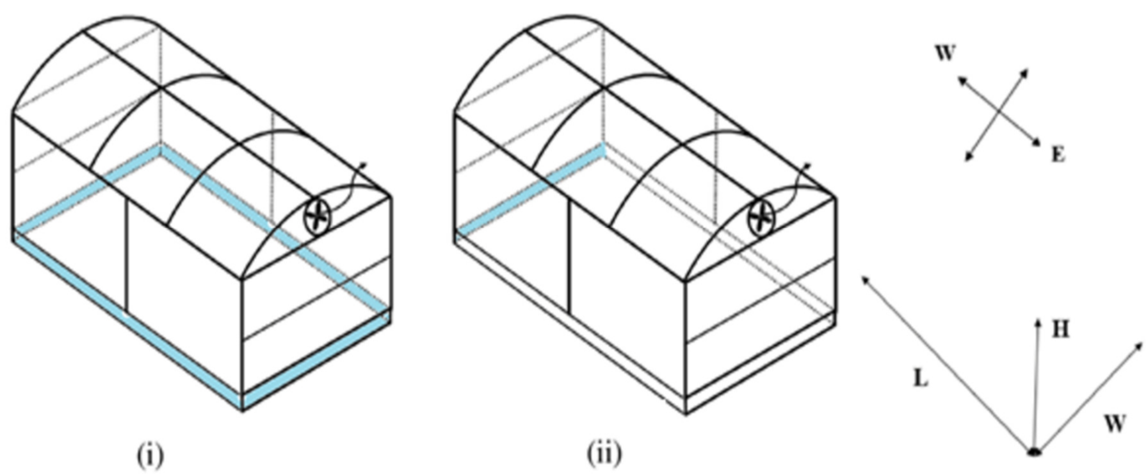

FIGURE 3. Schematic view of solar dryers in the conducted experiments: (i) air inlet slot surface A_{in}=0,2 m^2; (ii) air inlet slot surface A_{in}=0,04 m^2 (air inlet slot surface is marked in blue).

RESULTS AND ANALYSIS

In case (i): the drying process was carried out on the basis of forced convection. The inlet slots are open from 4 sides of the dryer, and the steam-air mixture is expelled using a fan located on the eastern upper side of the device. The total surface of air inlet slots is equal to A_{in}=0,2 m^2. The experiment was conducted on September 3-4. At 8 a.m. tomato products of the same mass were placed in the dryers. On September 3, the maximum solar radiation was 790,2 W/m^2 at 13:00, and the maximum ambient temperature was 34,6 °C at 16:00. The maximum air temperature inside the dryers at 15:00 was 49,3 ºC and 49,1 ºC in the ordinary and ceramic composite polyethylene coated dryers, respectively. The experiment lasted until 15:00 on September 4, and the maximum solar radiation at 13:00 was 772,6 W/m^2, and the ambient temperature was 34,4 ºC at 15:00. The maximum air temperature inside the dryers at 15:00 was 49 ºC and 49,6 ºC in the ordinary and ceramic composite polyethylene coated dryers, respectively. The mass of dried product was 21 and 18 g in ordinary and ceramic composite polyethylene dryers, respectively. The hourly mass change in dryers can be seen in Figure 5.

In case (ii): the drying process was carried out on the basis of forced convection. Only the air inlet slot on the western side of the dryer is open, and the total surface is equal to A_{in}=0,04 m^2. The experiment was held on September 8-9. At 8 a.m. tomato products of the same mass were placed in the dryers. On September 8, the maximum solar radiation was 711.6 W/m^2 at 13:00, and the maximum ambient temperature was 30.2 ºC at 16:00. The maximum air temperature inside the dryers at 15:00 was 42.9 ºC and 48.1 ºC in the ordinary and ceramic composite polyethylene coated dryers, respectively. The experiment lasted until 14:00 on September 11, and the maximum solar radiation at 13:00 was 687.5 W/m^2, and the ambient temperature was 30.9 ºC at 14:00. The maximum air temperature inside the dryers at 14:00 was 45.3 ºC and 46.4 ºC in the ordinary and ceramic composite polyethylene coated dryers, respectively. The mass of dried product was 24 and 18 g in ordinary and ceramic composite polyethylene dryers, respectively. The hourly mass change in dryers can be seen in Figure 6. Figures 7-8 show hourly change graphs of solar radiation, wind speed, ambient temperature and humidity for experiments (i) and (ii).

a) b)

FIGURE 4. The appearance of solar dryers during the experiment: a) with a traditional ordinary polyethylene coating; b) solar dryer with functional ceramic composite polyethylene coating.

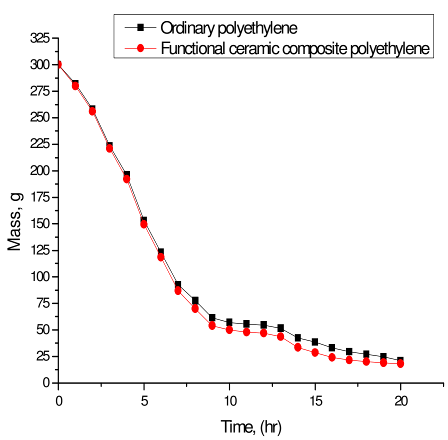

FIGURE 5. Graph of tomato mass change in case (i).

(September 3-4, 2022)

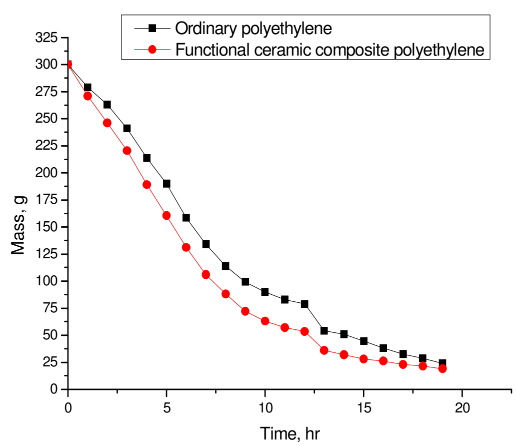

FIGURE 6. Graph of tomato mass change in case (ii).

(September 8-9, 2022)

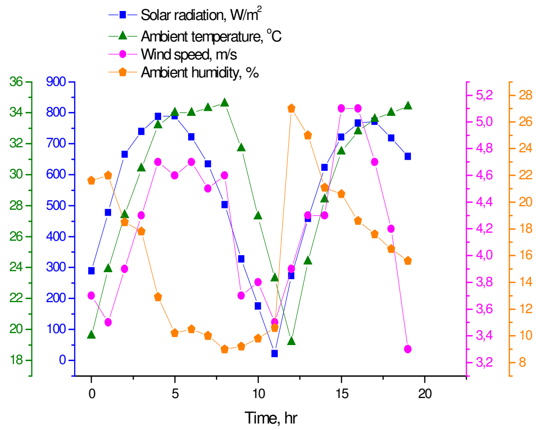

FIGURE 7. Hourly changes in solar radiation, wind speed, ambient temperature and humidity on September 3-4

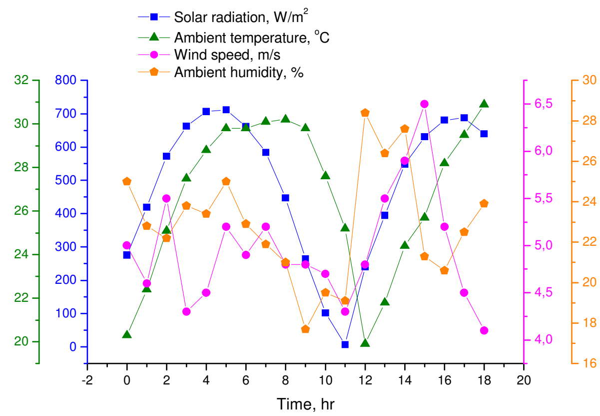

FIGURE 8. Hourly changes in solar radiation, wind speed, ambient temperature and humidity on September 8-9

CONCLUSION

According to the results of the experiment, in both cases, the final mass of the product dried in the functional ceramic composite polyethylene coated dryer was less compared to the ordinary polyethylene coated dryer. The pulsating radiation created in the dryer with functional ceramic composite polyethylene coating allows to remove more water from the deep layers of tomatoes and accelerates the drying process. In case (ii), the reduction of the air inlet surface caused the acceleration of the drying process in the functional ceramic composite polyethylene solar dryer. In further studies, it is recommended to focus on determining the optimal incoming air flow surface for the drying process, as well as improving the thermal efficiency of the dryers. Insulating, heat stored and phase-changing materials can be used to save the heat energy lost from the dryers through the floor and the north wall.

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