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DEVELOPMENT AND IMPROVEMENT OF DRYING TECHNOLOGIES IN A SOLAR DRYER

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Abstract: In this article, a comprehensive study examined the drying efficiency and capabilities of a new generation solar dryer equipped with a specially developed transparent film based on innovative functional ceramics. During the preliminary experiments, significant advantages of this device over traditional open-air drying methods were identified, in the solar dryer, the residual mass of the product was dried to 13% within 4 hours, which ensured that this is a more efficient process than open-air drying. In the second stage of the study, in order to assess the internal capabilities of the device and the drying dynamics in different layers, pieces of carrots of the same thickness 3 mm were placed in each layer, and it was found that in the first 3 hours, the residual mass in the 1st and 2nd layers was dried uniformly up to 47%. On the 3rd floor, drying was observed up to 44%, which indicates a slight difference in drying rate compared to the upper floors. The third and final stage of experiments is devoted to the study of the real capabilities of a solar dryer for drying various carrot products with a thickness of 3 mm, 5 mm, 8 mm, and 10 mm. The results confirmed that a 3 mm thick product can be completely dried in one sunny day.

Keywords: Solar dryer, functional ceramics, transparent film, drying efficiency, infrared radiation, moisture reduction, energy saving, mass, temperature, humidity, product.

Introduction. The use of energy- and resource-saving devices and technologies for the processing and drying of fruits and vegetables is of great importance, and according to the international statistical portal for 2024, taking into account the production of about 3.13 million tons of dried fruits and the consumption of energy from 2.700 kJ to 3.060 kJ per kilogram of freshly picked products, it is necessary to implement solar installations based on renewable energy sources. In this regard, the use of energy-efficient solar dryers in agricultural vegetable drying systems is of great importance.

Drying is a method of processing agricultural products and various industrial materials for long-term high-quality storage or service by removing moisture from the product being dried to a safe limit. Removing excess moisture from the product is an energy-intensive process, and the energy required for this process is mainly obtained from fossil fuels that have a negative impact on the environment. Due to the limited availability of such fuels, their prices are increasing day by day. [1]. It should be noted that currently, the improper organization of the drying method used for storing food and other types of products, or the lack of processes, leads to the loss of most products [2].

Solar dryers can be studied as three separate subclasses of direct, indirect type, and mixed mode solar dryers. It is also possible to give a brief description of direct, indirect, and combined mode of sun drying of food products [3].

Several existing technologies are used for drying vegetables in solar dryers. These technologies are the main approaches aimed at increasing drying efficiency, improving product quality, and accelerating the drying process.

The operating principle of direct solar dryers is very simple and is based on the direct use of solar energy. In this case, the dried vegetables are spread outdoors in direct sunlight or arranged on special shelves, and the surface of the product absorbs solar energy. The absorbed solar energy is converted into thermal energy inside the vegetables. As a result, increasing the product temperature increases the kinetic energy of water molecules in its composition, and water molecules begin to separate from the surface of vegetables in the form of vapor. The air around the vegetables is also saturated with heated water vapor. If this moist air is not removed, the drying process slows down. Therefore, through forced or natural convection (heat rise), moist air is removed from the vegetable surface and replaced by dry air. This process continues until the required amount of moisture in the vegetables is lost**.** [4].

The advantages of direct solar dryers are their low cost and ease of operation. However, their shortcomings can also be cited sufficiently. Including: When there is sun, drying is good, on cloudy or rainy days the process slows down or stops completely, If vegetables are outdoors, they may be exposed to dust, insects and other pollutants, If the sun is very strong, the outer part of the vegetable may dry quickly while the inside remains moist [5, 6]

Figure 1. Direct drying of products.
a-drying in open sun, b-drying in special drying equipment

Methodology & empirical analysis. Processing vegetables before drying in the sun improves product quality, reduces drying time, and extends shelf life. Sorting and washing - removing damaged, rotted parts of vegetables and cleaning vegetables from dust and dirt.

Figure 2. Product sorting and washing

a-washing process, b-sorting process

Cleaning and cutting - peeling vegetables, removing seeds, and cutting them into pieces of equal thickness, including slices, cubes, and rings, ensuring uniform drying of the vegetable.

Blanching, that is, steaming or dipping in hot water, is an important process for many vegetables. This process is carried out by brief immersion in hot water for several minutes or by evaporation. The goal is to inactivate enzymes, which helps preserve color, taste, and nutrients. It also softens tissues, accelerates drying, and destroys some microorganisms.

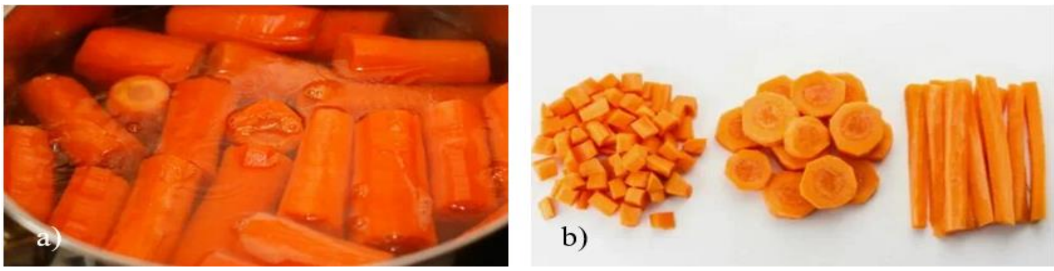

Figure 3. Evaporation or immersion of the product in hot water

Sulfiting - treating with sulfur dioxide SO2 or immersing in sulfite solutions while preserving the color of vegetables, usually in light-colored vegetables, slows down the development of microorganisms and the breakdown of certain vitamins, such as vitamins C and A.

Treatment with saline or acidic solutions - citric acid, ascorbic acid, or saline solutions can be used for some vegetables to retain color and have antimicrobial effects.

Figure 4. Dried carrots cut in different shapes
a-circular, b-cubic, c-pencil-shaped

For high-quality drying of vegetables, it is important to control the following parameters:

Temperature - the optimal temperature depends on the type of vegetable, but usually ranges from 40°C to 70°C. Excessively high temperatures can harden the outer part of vegetables, forming a crust, preventing the release of internal moisture, and break down nutrients. Low temperatures slow down drying and increase the risk of mold formation. In indirect and mixed mode dryers, it is possible to control the temperature to a certain extent.

Air circulation - good air circulation is necessary to remove moist air from the drying chamber and bring in dry air. This increases the drying speed and prevents mold formation. In natural convection dryers, this is provided through chimneys and openings, while in forced convection (fan) dryers, air flow is controlled more effectively.

Relative humidity - the relative humidity of the air in the drying chamber should be low, which increases the evaporation of moisture from vegetables. Good ventilation helps to reduce relative humidity.

Drying time depends on the type of vegetable, the thickness of the pieces, pre-treatment methods, the type of dryer, and weather conditions. Vegetables are dried until brittle or until their moisture content reaches the required level, usually 10-20%.

The choice of vegetable drying technology in solar dryers depends on local climatic conditions, available resources, the type and volume of vegetables to be dried, as well as the quality requirements for the finished product. By applying the correct technology, it is possible to store vegetables for a long time while preserving their nutritional value.

Transparent materials that are more commonly used in the development of direct solar dryers.

Polycarbonate has high impact resistance, good optical conductivity, and a wide temperature range. UV-resistant;

Traditional polyethylene film has high optical conductivity and low UV resistance, as well as low strength.

The proposed transparent film based on functional ceramics, developed for special drying, the method of drying under this film ensures complete preservation of proteins, biologically active substances, as well as vitamins, enzymes. Energy consumption and drying time are significantly reduced.

The results of the study of the temperature characteristics of this composite film for a three-layer cascade composition are presented - the first layer is polyethylene film with additives that make the UV range visible. This not only allows for more efficient use of solar energy, but also protects the film itself from photodegradation, which significantly extends its service life. The second layer is a frame made of the same film to increase mechanical strength, the third, lower layer contains nanostructured functional ceramics. The total amount of ceramics in the composite is 1.25% (by weight) of polyethylene. The functional ceramics added to the third layer absorb solar energy in a wide range and convert it into a maximum of 6-8 microns of infrared radiation [7-13].

The angle of inclination of the shelf in direct solar dryers is usually

From 0° to 15°. Often, a horizontal 0° position is the most common and practical. To determine the optimal angle, it is necessary to consider the exact design of the dryer, the characteristics of the product being dried, and the required airflow. In some cases, it is possible to determine the best angle through small experiments.

Figure 5. Experimental design
a-side view, b-front view, c-shelf view

Results: Conducting experimental tests on the developed model of the experimental solar dryer is crucial for determining how effectively its theoretical parameters work under practical conditions. This process involves several key stages, and each stage requires precise measurements and observations. Experimental studies were conducted on 1 floor of a solar dryer and in open sunlight. The results obtained on the solar installation are presented in Table 1 below.

Table 1. Results obtained on a solar installation

Time, clock	Product thickness, mm	Initial mass, g	Residual mass, g	In-camera humidity, %	In-camera temperature, °C	External temperature, °C
10:^{00}		90	61	17	31.4	33.1
11:^{00}		61	35	19	32.3	35.3
12:^{00}		35	16	18	36.4	36.8
13:^{00}	3.0	16	12	17	38.8	40.3
14:^{00}		12	10	16	42.4	43.8
15:^{00}		10	10	17	43.3	44.1
16:^{00}		10	10	15	42.4	44.7
17:^{00}		10	10	16	41.8	42.3

The results of studying the possibilities of open-air drying in parallel with the above-mentioned drying process are presented in Table 2. In this case, for each drying method, carrots were placed in the same thickness and mass for drying, and the change in mass was recorded every hour.

Table 2. Results obtained in the open sun

Time, clock	Product thickness, mm	Initial mass, g	Residual mass, g	External humidity %	External temperature, °C
10:^{00}		90	68	17	33.1
11:^{00}		68	39	18	35.3
12:^{00}		39	17	17	36.8
13:^{00}		17	11	15	40.3
14:^{00}	3.0	11	9	17	43.8
15:^{00}		9	9	17	44.1
16:^{00}		9	9	17	44.7
17:^{00}		9	9	17	42.3

At the next stage of the experimental study, the construction process of the product on the 1st, 2nd, and 3rd floors of the solar panel was analyzed, and the difference in the results of construction between the floors was determined.

Table 3. Results obtained on a solar installation

Time, clock	Product thickness, mm	Initial mass, g	Residual mass, g	In-camera humidity, %	In-camera temperature, ºC	External temperature, ºC
Floor 1						
$09:^{00}$	3.0	90	70	29	32.2	33.1
$10:^{00}$		70	55	20	33.6	35.3
$11:^{00}$		55	43	20	35.4	36.8
$12:^{00}$		43	19	20	39.8	40.3
$13:^{00}$		19	11	16	41.7	43.8
$14:^{00}$		11	10	17	41.8	44.1
$15:^{00}$		10	10	16	42.3	44.7
Floor 2						
$09:^{00}$	3.0	90	70	32	32.2	33.1
$10:^{00}$		70	55	19	33.6	35.3
$11:^{00}$		55	43	17	35.4	36.8
$12:^{00}$		43	18	17	39.8	40.3
$13:^{00}$		18	12	17	41.7	43.8
$14:^{00}$		12	11	17	41.8	44.1
$15:^{00}$		11	11	16	42.3	44.7
Floor 3						
$09:^{00}$	3.0	90	68	29	32.2	33.1
$10:^{00}$		68	52	19	33.6	35.3
$11:^{00}$		52	40	18	35.4	36.8
$12:^{00}$		40	17	17	39.8	40.3
$13:^{00}$		17	11	17	41.7	43.8
$14:^{00}$		11	10	17	41.8	44.1
$15:^{00}$		10	10	17	42.3	44.7

In the next stage of your experiment, the drying dynamics of carrot pieces with a thickness of 5 mm, 8 mm, and 10 mm were studied, which reflects a very important and in-depth scientific approach. These experiments help to understand not only the capabilities of the solar dryer, but also the laws of mass and heat exchange during the drying process. The results of the experiment are presented in Table 3 below.

Figure 6. Experimental process

Table 4. Results obtained on a solar installation

Time, clock	Product thickness, mm	Initial mass, g	Residual mass, g	In-camera humidity, %	In-camera temperature, °C	External temperature, °C
Floor 1						
08:00	5.0	134	112	31	28.2	30.8
09:00			90	19	31.6	34.7
10:00			78	19	34.4	36.5
11:00			41	17	35.8	37.6
13:00			28	16	36.7	39.8
15:00			25	17	40.8	42.1
16:00			23	17	33.3	36.7
17:00			22	17	32.2	35.7
18:00			22	16	30.8	32.9
Floor 2						
08:00	8.0	230	207	30	28.2	30.8
09:00			182	18	31.6	34.7
10:00			166	16	34.4	36.5
11:00			118	16	35.8	37.6
13:00			92	15	36.7	39.8
15:00			83	16	40.8	42.1
16:00			72	16	33.3	36.7
17:00			64	16	32.2	35.7
18:00			64	16	30.8	32.9
Floor 3						
08:00	10.0	275	250	30	28.2	30.8
09:00			223	16	31.6	34.7
10:00			209	17	34.4	36.5
11:00			158	17	35.8	37.6
13:00			128	17	36.7	39.8
15:00			118	16	40.8	42.1
16:00			115	16	33.3	36.7
17:00			94	16	32.2	35.7
18:00			94	16	30.8	32.9

Discussion: The experimental results obtained from the proposed solar dryer using an innovative transparent film based on functional ceramics demonstrate its potential for efficient and gentle drying of sensitive biological materials. A comparative analysis between in-solar drying and outdoor solar drying demonstrates the clear advantages of innovative design.

As can be seen from Table 1, the proposed solar dryer achieved a significant reduction in the mass of the product during the drying period. The product, having a thickness of 3 mm and an initial mass of 90 g, fell to 10 g within 6 hours (by 15:00). Nanostructured functional ceramics in the lower layer play an important role, effectively absorbing a wide spectrum of solar energy and converting it into infrared radiation with a maximum of 6-8 microns. This targeted infrared radiation effectively heats the product from the inside, facilitating the removal of soft and quick moisture without excessive high temperatures that can break down proteins, biologically active substances, vitamins, and enzymes.

The temperature and humidity inside the solar dryer (shown in Table 1) once again confirm its effectiveness. The internal temperature of the dryer constantly remained in a favorable range for storing sensitive materials, starting from 31.4°C at 10:00 and reaching 43.3°C at 15:00. At the same time, the humidity inside the chamber decreased from 17% to 15% by 16:00, which indicates the effective removal of moisture from the dried product. This controlled environment inside the solar dryer is drastically different from outdoor sun drying, where environmental changes can lead to unpredictable drying conditions and potential product damage.

Comparison of the results obtained in experimental studies with the results obtained in the open sun

Table 2 presents the results of experiments on open-air drying in parallel with a solar installation. Although open-air drying also showed a decrease in mass from 90 g to 9 g within 5 hours (by 2:00 PM), several key differences indicated the superiority of the proposed solar dryer. The external temperature during open solar drying (Table 2) is similar to the temperature inside the solar dryer, but factors such as direct UV radiation and unpredictable air currents lead to surface hardening, nutrient breakdown, and a non-uniform drying process. On the contrary, the innovative film of the solar dryer provides protection and an optimized drying environment, guaranteeing the complete preservation of valuable components. The ability of the functional ceramic layer to convert solar energy into specific infrared wavelengths provides more controlled and efficient internal heating, which ensures deep drying without excessive processing.

This experiment is aimed at a deeper understanding of the laws of mass and heat exchange during the drying process, and the capabilities of the solar dryer in drying carrot pieces of different thicknesses were determined. The main goal of the experiment is to assess the uniform drying of the product in different layers of the device and determine the possibility of effectively drying carrot of what thickness during one solar day. The data in Table 3 show the drying dynamics of carrot pieces with a thickness of 5 mm, 8 mm, and 10 mm.

Floor drying efficiency

The results of the experiment show that the mass of carrot pieces decreased significantly in all three layers of the solar dryer. In the first layer (carrot 5mm thick), a decrease from the initial mass of 134g to 22g was observed by 18:00. This demonstrates quick and efficient drying, as the finest pieces require less time to dry. In the second layer (carrot with a thickness of 8 mm), a decrease in mass from 230 g to 64 g was noted, and in the third layer (carrot with a thickness of 10 mm) from 275 g to 94 g.Kamera ichidagi harorat ertalabki 28.2°C dan kunning oʻrtalarida 40.8°C ga koʻtarilgan va keyinroq bu ko'rsatgich pasaygan. Namlik esa aksincha, jarayon davomida doimiy ravishda pasayib borgan, bu mahsulotdagi namlikning samarali chiqarilishini koʻrsatadi. Bu esa, oldingi tajribalarda ta’kidlanganidek, funksional keramika asosidagi plyonkaning infraqizil nurlanishga aylantirish xususiyati tufayli erishilgan.

Effect of product thickness on drying

According to the experimental results, the thickness of the carrot pieces directly affects the drying rate. Although carrots with a thickness of 5 mm were partially dried the next day, pieces with a thickness of 8 mm and 10 mm also had a significant residual mass at the end of the day. This is a natural phenomenon, and it takes more time and energy to remove moisture from thicker products. In particular, carrots with a thickness of 10 mm after one day of drying constituted less than a third of their initial mass. This shows that the proposed solar dryer is very effective for preliminary drying of relatively thicker products or partial drying for one day. For complete drying, further drying may be required, especially in the early morning or the following days.

Conclusion. It was found that in the first 4 hours of the solar installation, the residual mass dries up to 67%, 38%, 17%, and 13%. In direct sunlight, it has been determined to dry up to 75%, 43%, 18%, and 12%. These results substantiated the ability of the solar dryer to ensure an efficient drying process compared to traditional open solar drying methods.

In the second stage of the experiment, products of the same mass were placed in 3 mm for each layer. As a result, it was found that in the first 3 hours, the residual mass on the 1st and 2nd floors was dried equally to 77%, 61%, and 47%, and on the 3rd floor - to 75%, 57%, and 44%. This indicates that the possibility of drying products on the 3rd floor is uneven compared to the 1st and 2nd floors.

In the third stage of the experiment, a carrot product with a thickness of 3 mm, 5 mm, 8 mm, and 10 mm was dried during one sunny day. As a result, the possibility of drying products with a thickness of 3 mm during any sunny day of the drying season was determined.

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