

Experimental Study of Apricot Drying Using Direct and Indirect Solar Dryers with Natural Convection

Jobir Kodirov¹, Shavkat Mirzaev^{1,*}, Laziz Yuldoshov¹, Ikhtiyor Barakayev¹, Tolibjon Jumayev¹, Sardor Khamrayev²

¹Bukhara State University, 11, M. Ikbol, Bukhara, Republic of Uzbekistan

²Karshi State Technical University, 180100, Karshi, Uzbekistan

Abstract. This study investigated the drying performance of apricots using direct and indirect solar dryers operating under natural convection. Experimental trials were conducted under field conditions to compare drying time, product surface temperature, moisture reduction, and quality indicators. For reference, open-air sun-drying was used as a control. The results showed that apricots dried in the indirect dryer reached equilibrium moisture content in 6 d, compared to 8 d in the direct dryer and 10 d in open-air drying. The product surface temperature in the indirect system was, on average, 12 °C lower than in the direct dryer, thereby preserving the structural integrity of the product. Chemical analysis revealed lower concentrations of toxic elements (0.13 mg/kg vs. 0.22 mg/kg) and nitrate ions (8.5 mg/kg vs. 9.3 mg/kg) in apricots dried in the indirect system compared with open-air drying, resulting in a 10–12% improvement in quality. The findings confirm that indirect solar dryers provide better quality retention and shorter drying times than traditional methods.

1 Introduction

As the world seeks ways to manage energy sustainably, thorough research on the use of solar energy in the management of thermal energy, water conservation, and the food industry is being undertaken [1-2].

Apricot fruit is a single-seeded product of yellow-red color, round in shape, with longitudinal grooves, elliptical, or ovoid in shape. The apricot kernel is thick-walled, smooth or lumpy [3]. The average weight of wild apricot fruit is 3-18 grams, and that of cultivated varieties is up to 80 g. The weight of 1000 seeds was approximately 1800-2100 grams. One hundred grams of the apricot product contained an average of 44 kcal of energy. It mainly consists of two parts: the wall of the fresh fruit and the wet fruit pod. The wall of the wet fruit has pulp and is divided into three layers: outer, middle, and inner layers. The wet fruit pit is also divided into three parts: the skin, embryo, and endosperm. The outer layer of apricot fruit contains proteins 0.9 g, fats 0.1 g and carbohydrates 9 g, and the pulp contains 2.1 g of dietary fiber and 86.2 g of water, as well as a number of vitamins: PP 0.8 mg, B1 0, 03. mg, V2 0.06 mg, A 0.267 mg, C 10 mg, YE 1.1 mg and niacin 0.7 mg, beta-carotene 1.6 mg. The outer and middle layers of the apricots contained the following chemical elements: glucose, 2200 mg; fructose, 800 mg; phosphorus, 26 mg; magnesium, 8 mg; potassium, 305 mg; calcium, 28 mg, iron 0.7 mg and sodium 3 mg.

Drying is a process used to extend the shelf life and quality of agricultural products. In many countries, agricultural products are dried in open sun using traditional methods. However, this drying method

negatively affects the quality of the dried product owing to exposure to direct sunlight and the influence of external contaminants, uneven drying speed, and other influences (dust, insects, birds, etc.). Solar dryers are considered to be very useful devices in terms of energy saving and avoiding some of the major disadvantages of traditional drying [4]. Closed-system solar dryers use solar energy as the only source of heat needed and rely on natural convection to flow air. If the solar drying process is performed correctly, not only can food be preserved, but the nutritional and biological value of dried food can also be preserved [5].

Currently, scientists worldwide are conducting scientific research on the creation of modernized devices, research, and widespread introduction into industry to improve the design of solar dryer models. Many scientists believe that solar dryers are closed systems that contain food, and when used effectively, they should be a system of devices that produces dried food that meets hygienic and quality requirements in the most suitable operating mode. Among them are Nicholas Musembi Maundu [6], S. Udeynya [7], Abhay Lingayat [8], and Phadke [9], who recommended the use of indirect solar natural convection dryers that can dry apricot products relatively easily and economically.

The main problem of drying apricot products and the reason for solving this problem in solar devices is that the internal structure of the apricot fruit consists of a complex composition with an average water content of 86.2%, which is located mainly in the outer and middle layers of the apricot, that is, it is present in the pulp. To evaporate the water in the middle and inner layers of the apricot product, the biological fibers in the dried outer

* Corresponding author: murotbekoskarov@gmail.com

layers lose their properties during the heating process, which leads to deterioration in the quality of the product.

The required drying time to ensure the production of a product with a final (equilibrium) moisture content can be calculated according to the kinetic laws of the drying process [10]. To prevent such ineffective measures during the drying process, it is necessary to dry different types of apricot fruits in solar devices with natural air convection. This article discusses the problems in analyzing the experimental results of drying apricot products in direct and indirect solar dryers with natural air convection. The issue of using drying technology in solar installations with maximum preservation of the quality of dried products (color, taste structure, aroma, nutritional properties, drying cost, payback period, etc.) was considered. Drying is a widely used method for extending the shelf life of agricultural products by reducing their moisture content while preserving their nutritional and sensory qualities. Traditionally, apricots and other fruits have been dried in the open sun; however, this method has major disadvantages, including exposure to contaminants (dust, insects, and birds), uneven drying, excessive heating, and degradation of the product quality. To address these issues, solar dryers provide a cost-effective and energy-efficient alternative that offers protection from external factors, while ensuring more controlled drying conditions.

Recent research has focused on improving solar dryer design to achieve higher efficiency and product quality. Among the proposed solutions, indirect solar dryers with natural convection have gained attention because of their simple construction, low cost, and ability to provide more uniform drying than direct sun drying. Nevertheless, further improvements are needed to optimize the thermal performance and ensure that the quality of sensitive products, such as apricots, is maintained. Apricots are particularly challenging to dry because of their high initial water content (~86%) and the layered structure of their pulp, which makes moisture migration from the inner to the outer layers difficult. Excessive heating during drying can damage the biological fibers in the peel, leading to undesirable changes in texture and color. Therefore, the design of drying systems must balance efficient moisture removal with minimal thermal degradation. The main research question of this study is as follows: How do direct, indirect, and upgraded indirect solar dryers with natural convection perform in terms of drying performance, energy efficiency, and preservation of apricot quality?

The objectives of this work are to:

1. Develop and test experimental setups of direct and indirect solar dryers with natural convection, including an upgraded design with a solar collector and a storage unit.
2. The drying time, product temperature, moisture content, and quality indicators were evaluated under different drying modes.
3. Assess the impact of using silica gel in a storage cabinet on the drying conditions and final product quality.
4. Recommendations for practical applications of solar drying technologies for fruit processing.

2 Materials and Methods

2.1 Experimental Materials

Fresh apricots (Navoi variety) (32.209 kg) were selected for the experiments. The fruits had an average size of 36 mm × 33 mm × 31 mm and a weight of 24–27 g. Their initial moisture content was approximately 86%, as measured using a laboratory moisture analyzer (AND MX-50, Japan, ±0.1% accuracy). Before drying, the apricots were washed and halved, and the pits were removed. During the drying process, water evaporated from the outer layers of the pulp. The evaporation of water vapor from the middle and inner layers is difficult because the temperature of the parts of the water that evaporate before transferring heat to the middle and inner layers increases, which leads to the rupture of biological fibers in the outer layer and the loss of their previous properties. To fully preserve the quality of the dried products, they should be stored in drying devices with direct solar radiation and natural air convection until the water in the outer layer evaporates. In indirect solar dryers with natural air convection, the dryer may be suitable for this target until equilibrium moisture content is achieved.

2.2 Drying Systems

Two solar drying systems were evaluated: (1) a direct solar dryer with natural convection, and (2) an indirect solar dryer with natural convection. For comparison, open-air sun-drying was used as a control group. The indirect dryer included a storage cabinet containing silica gel to control the humidity. To solve such problems, it is necessary to conduct an experimental study on the stages and timing of the drying process of apricot products in a direct solar dryer with natural air convection. Selected apricot products were processed using traditional methods before being placed in a solar dryer. The dimensions of the elements of the structural model of the direct-acting solar dryer with natural convection were selected primarily based on the following method proposed by the authors of [11]:

$$\alpha = \frac{F_t}{F_g} = \frac{2,06}{4,94 + 2,06 \frac{H}{L}} \quad (1)$$

The efficiency coefficient of the lower part of the device is $\alpha = \frac{F_t}{F_g} = 0,36$ and the angles of inclination of the sides from which solar radiation directly falls on the device relative to the horizon $\beta_1 = 38^\circ$, $\beta_2 = 52^\circ$ (considering the geographical width region). The total length of the device is $L=2,5\text{m}$, width $M=1,55\text{m}$, height of the I-chamber $H=0,75\text{m}$, and height of the II-chamber $h=0,4\text{m}$. A general view of a direct solar dryer with natural convection is shown in Figure 1.

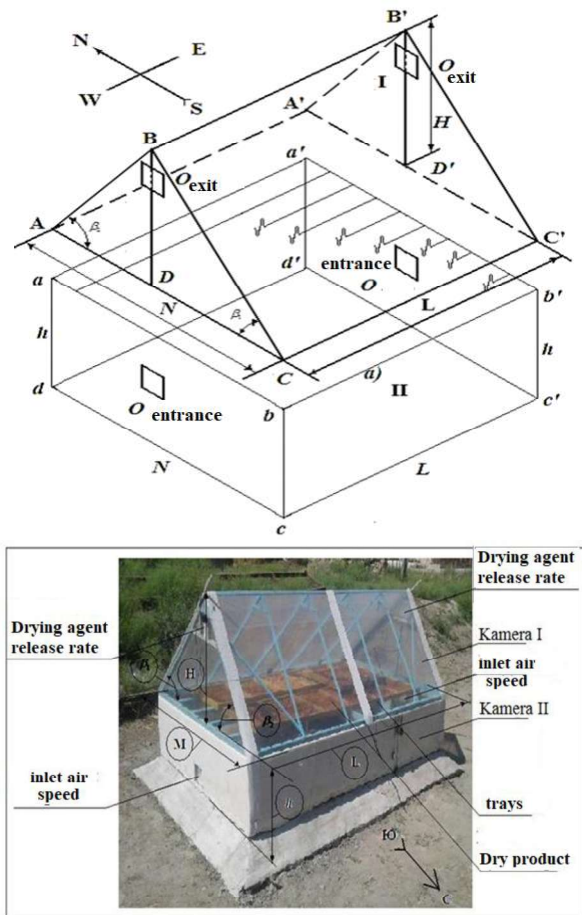


Fig. 1. Schematic and general view of a direct solar dryer with natural convection.

A solar dryer with direct natural convection consists of two chambers: a solar heating chamber II heated air supply chamber. The device was covered with a polyethylene film. Chamber I was designed as a triangular parallelepiped with unequal sides, whereas Chamber II was designed as a parallelepiped with a square base. The frame of each 30 × 20 mm cell was made of wooden blocks (bars) of a certain size. Both chambers were connected to each other by a wooden tray-bar on which trays with dried apricots were placed. On each side of chamber I, slits (windows) were designed to release the drying agent from inside the chamber into the environment. On the side walls of chamber II, slits were designed to allow air to enter from the environment (Figure 1).

In the field of drying agricultural products, indirect natural convection solar dryers are preferred over other solar dryers because they are simple in structure, cheap, portable, and do not require traditional power sources. Such devices mainly consist of two parts: a solar collector (air heating) and a cabinet for drying the products [12]. The principle of operation of such devices is as follows: part of the solar radiation falling on the chamber of the solar collector is absorbed by the transparent surface of the collector, the rest is absorbed by the air inside it, and the heated air is convectively transferred to the chamber of the drying cabinet, and then, due to the action of a thermosyphon, is dried through the air outlet and discharged from the closet into the environment [10]. As a result of the uniform

distribution of air flow in the drying cabinet over the surface of the product subjected to natural drying, the quality of the dried product increases, and the preservation of its uniform color is ensured [13, 6-9].

2.3 Experimental Setup

Each experiment was conducted in triplicates to ensure repeatability. Approximately 10 kg of apricot was loaded per trial. In the case of open-air drying, the fruits were spread on trays under direct sunlight and protected from insects and dust with a mesh cover. Based on the analysis of scientific research carried out by scientists around the world using methods for determining the linear dimensions of a solar dryer, an indirect solar dryer with natural convection was developed. A general schematic view of the developed indirect solar dryer with natural convection is shown in Figure 2.

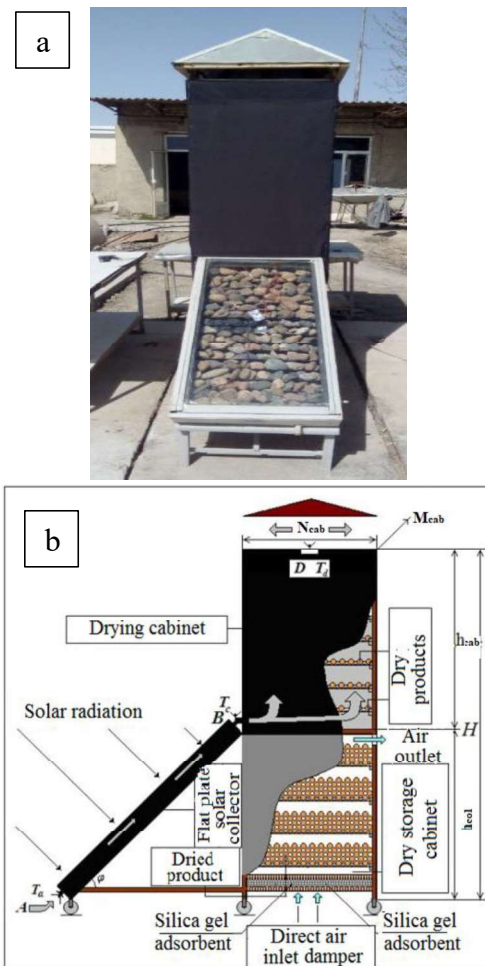


Figure 2. Indirect solar dryer with natural convection: a) general view of the device; b) schematic diagram.

The developed indirect solar dryer with natural convection did not differ significantly in appearance from the prototype. However, the linear dimensions of the elements of the structural model of the device were chosen based on semi-empirical formulas calculated based on thermodynamics and the laws of free fall of bodies. These include the length of the drying cabinet, the linear dimensions and areas of the air intake and exhaust openings, and the mass of the product to be

dried. In addition, during experimental studies on drying apricot products under natural conditions in an apparatus, values characterizing the thermal properties of the apparatus were calculated and determined based on semi-empirical formulas [14]. The advantage of this method is that heat losses in the elements of the solar dryer are not considered when determining parameters reflecting thermal properties based on the proposed semi-empirical formulas. To determine the main parameters characterizing the thermal properties of the device, the temperatures of the mixture of air and steam entering and exiting it at given points and their partial pressures (relative humidity) should be recorded using special instruments.

Based on the proposed semi-empirical formulas using the specified parameters, the height of the drying cabinet, efficiency of the drying installation, drying speed, thermal efficiency, and heat capacity of the solar dryer with a flat-plate collector were determined. To improve the thermal and operating efficiency of the indirect solar dryer with natural convection compared with prototype devices, the device has been upgraded, that is, to fully meet the requirements of farmers to store the product in the device for temporary storage and dry the finished product under the necessary conditions in the field itself without excessive costs, for which an additional cabinet was installed (Figure 2).

The drying cabinet is located at the bottom of the drying cabinet. The internal structure of the storage cabinet and the thermal insulation of the sides and parts of the roof are identical to those of the drying cabinet. Only it has its own air intake and exhaust slots built into its own cabinet, the supply slot is installed at the bottom of the storage cabinet, and the exhaust slot is directed to the south and towards the bottom of the collector. Holes at the bottom of the storage cabinet were cut from the inner and outer plywood. The internal parts of these plywoods were covered with mesh. Between the two layers of plywood, silica gel was placed from a mixture of supersaturated silicic acid ($n \text{ SiO}_2 \cdot m \text{ H}_2\text{O}$) with a round shape. The main function of silica gel is to absorb moisture from the air entering the storage cabinet from the environment (Figure 2).

To distinguish the indirect natural convection solar dryer from the prototypes, we refer to it as an upgraded indirect natural convection solar dryer. The modernized indirect natural convection solar dryer consists of two main parts: a solar collector (heat source) and a cabinet for drying and storing food (Figure 2). To store solar energy in a solar collector, gravel stones weighing approximately 40 kg were installed as heat accumulators in the lower part of the collector. To dry the products, 6-8 shelves and mesh trays were placed in a drying cabinet. The distance between trays was 15-20 cm. The grid of trays is made of reeds, the surface of the tray is selected according to the width and height of the drying cabinet, the surface area of each tray is $34 \text{ sm} \times 44 \text{ sm} = 1500 \text{ sm}^2 \approx 0,150 \text{ m}^2$ for this device is the same.

The solar collector and drying cabinets were prepared in parallel. The collector and frames of the drying cabinets were composed of transverse wooden beams measuring $4 \text{ sm} \times 3 \text{ sm}$ and $3 \text{ sm} \times 2 \text{ sm}$. The internal and external surfaces of the sidewalls and bottom of the

collector were covered with 3 mm thick plywood. The center of the internal and external surfaces, covered with plywood, was filled with 2 cm thick thermal insulation foam. The surface of the collector facing the sun is covered with glass. There are openings on the bottom and top sides of the collector to remove air from the environment and transfer heated air to the drying cabinet. All sides, bottom, and top of the drying cabinet were similar to the manifold, lined with 3 mm thick plywood.

The middle of the internal and external surfaces, sheathed with plywood, was filled with heat-insulating foam 2 cm thick. At the bottom of the southern side of the cabinet and at the top of the cabinet (roof), holes exist for the entry of hot air from the collector and exit of the steam-air mixture into the environment. The collector power Q is determined without considering the heat loss from the sidewalls and bottom. The A term of the semi-empirical formula in Equation (3) can be considered as the useful work done by the collector:

$$A_{col} = A_{air} + A_{battery} = c_p^{air} \cdot m' \cdot (T_c - T_a) + c_p^{battery} \cdot m_{battery} \cdot (T_{i+1} - T_i) \quad (2)$$

$$Q_{col} = \frac{A_{col}}{3600} = \frac{c_p^{air} \cdot m' \cdot (T_c - T_a) + c_p^{battery} \cdot m_{battery} \cdot (T_{i+1} - T_i)}{3600}, \quad (3)$$

2.4 Instrumentation and Measurements

temperatures of the drying air, product surface, and exhaust air were measured using calibrated thermocouples (Type K, Omega Engineering, USA, $\pm 0.5 \text{ }^\circ\text{C}$) connected to a data logger (Testo 176T4). Relative humidity was recorded using a digital hygrometer (Testo 608-H2, $\pm 2\% \text{ RH}$). Data were collected every 15 min during the daylight hours. The instruments were calibrated before the experiments following the manufacturer's recommendations.

2.5 Quality Assessment

Dried apricots were analyzed for toxic element and nitrate concentrations using atomic absorption spectroscopy (PerkinElmer Analyst 200) and ion-selective electrode analysis, respectively. The influence of silica gel in the storage cabinet was evaluated by comparing the residual moisture content and product color of the samples dried without silica gel.

3 Results and discussions

3.1 Drying Time and Temperature Profiles

Apricots in the direct solar dryer required eight days to reach equilibrium moisture content, while the indirect dryer reduced the time to six days. In contrast, open-air drying required 10 days and showed higher variability owing to fluctuating weather conditions. The product surface temperature in the direct dryer reached up to $56 \text{ }^\circ\text{C}$, which caused noticeable hardening of the outer layers. In the indirect dryer, maximum surface

temperature was limited to 44 °C, preserving fiber structure and improving product quality.

The drying of the apricot products was carried out in a direct solar dryer with natural convection, and the results are presented in Figure 3. Curves 1 and 2 in Graph 3 show the temperature and humidity on the surface of the dried apricots, curves 3 and 4 show the temperature and humidity of the steam-air mixture, and curve 5 shows the change in drying speed over time.

According to the lines in Figure 3, the drying process of apricot products is carried out in the first and second stages in a direct solar dryer with natural convection [8]. The first stage of the drying process (A) is conventionally divided into two periods according to the change in drying rate (Figure 3): growth (I) and decline (II).

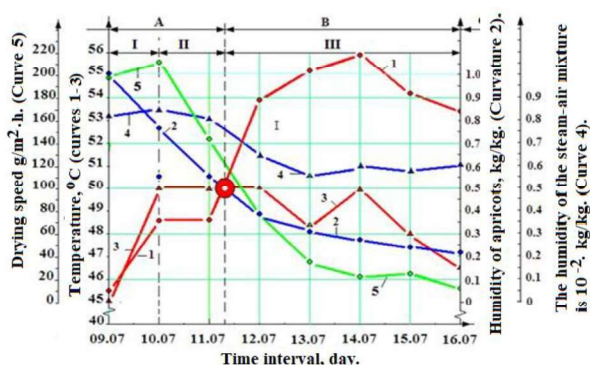


Figure 3. Stages and cycles of the process of drying apricots in a solar dryer with natural convection: A, B and C - stages of the wet, hygroscopic and equilibrium state of apricot; I, II, III – drying speed cycles; 1 and 2 - change in temperature and humidity on the surface of dried apricots; 3 and 4 - change in temperature and humidity of the drying agent; 5-speed drying.

In the first period (I), there was a sharp increase in temperature and decrease in humidity on the surface of the apricot product compared to the initial state. During this period, the product temperature and drying rate slightly increased with little change. In this case, the temperature of the surface of the apricot product did not change. In the second period (II), the drying rate decreased and the temperature on the surface of the product remained constant, while there was a thermal equilibrium between the amount of heat change on the surface of the apricot and the amount of heat entering the surface of the apricot. converts moisture into steam, or the heat expended in converting moisture into steam is equal to the amount of heat change on the surface of the apricot. This process continued until the moisture content of the dried apricot product reached 50%. In this experiment, this situation occurred within two days of 22-23 hour exposure to solar radiation. In this case, the surface of the apricot product becomes dry, and moisture is transferred from the middle layers of the pulp to its surface through capillaries formed between the biological fibers. The second stage of the drying process corresponds exactly to the period of falling drying speed (Figure 3).

In the second (B) and third (III) stages of drying, a slow decrease in the drying rate and a sharp increase in

the surface temperature of the apricot were observed. In this case, there is a thermal imbalance between the amount of heat transferred to the surface of the apricot (56°C) and the amount of heat required to convert the moisture into steam (50°C). Violation of the thermal balance destroys the quality of biological fibers located on the surface of the apricot. The third drying period begins from point “0,” marked in the graph of Figure 3. The first stage of the drying process (A) can be divided into two periods according to the change in speed: slow decrease (I) and slow decrease (II).

3.2 Moisture Reduction and Drying Kinetics

The drying process followed the typical stages of constant rate and falling rate periods. During the constant rate period, rapid evaporation occurred from the outer fruit layers, whereas during the falling rate period, the internal diffusion of moisture limited the drying rate. The indirect dryer maintained more stable drying conditions, reducing thermal stress and minimizing shrinkage. In the process of drying apricot products in a solar natural convection dryer, a difference in heat occurs between the sudden increase in temperature of the surfaces of the apricots and the amount of heat falling on the surface of the apricots and the amount of heat required to convert the moisture contained in it into steam, an imbalance occurs, resulting in the quality of the product deteriorates. The temperature of the steam-air mixture changes as a result of the absorption and additional radiation of rays of a certain infrared wavelength of solar radiation (according to the law of thermal radiation in gases). It has been established that this phenomenon negatively affects the quality of dried products, and based on the results of the experiment, it is recommended that products be dried in indirect solar dryers with natural air convection.

The experimental results obtained using a modernized indirect and direct solar dryer with natural convection were analyzed. Based on the results of the analysis, we compared the processes of drying apricots in modernized indirect and direct apparatuses with natural convection, and compared the characteristics of the curve graphs in Figure 3 with the graph in Figure 4.

- The process of drying wet fruit products in a direct solar dryer with natural convection to an equilibrium state takes 8 days for apricots. In a modernized indirect solar dryer with natural convection, the duration of this process for the apricots was five days.

- In the direct solar dryer with natural convection, the temperature on the surface of the dried products increased to 56 °C, and in the modernized indirect dryer with natural convection, this temperature was 44° C. The temperature on the surface of the direct device product increased by 12° C compared to the temperature indirect device, which led to a deterioration in the quality of biological fibers in the peel and outer layer of the apricot product.

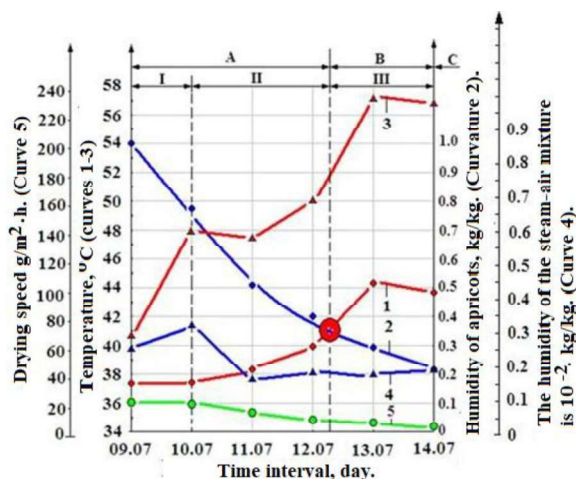


Figure 4. Stages and cycles of the apricot drying process in a modernized indirect solar dryer with natural convection: A, B and C - stages of the wet, hygroscopic and equilibrium state of apricot; I, II, III – periods of drying speed; 1 and 2 – temperature and humidity on the surface of dried apricots; 3 and 4 – temperature and humidity of the drying agent; 5 – speed drying.

3.3 Effect of Silica Gel Storage Cabinet

In the indirect dryer, the silica gel storage cabinet reduced the relative humidity in the drying environment by 5–7% compared with open-air drying. This resulted in a slightly faster drying in the final stages and improved the preservation of color and texture. The samples dried with silica gel also showed lower residual moisture variability.

3.4 Quality Analysis

Chemical analysis revealed that apricots dried in the indirect dryer contained lower concentrations of toxic elements (0.13 mg/kg) and nitrate ions (8.5 mg/kg) compared with open-air drying (0.22 mg/kg and 9.3 mg/kg, respectively). The overall product quality, assessed in terms of color, aroma, and texture, improved by approximately 10–12% compared to traditional sun drying.

4 Conclusions

The drying speed of apricot products in the direct solar dryer with natural convection decreased sharply (from $200 \cdot 10^{-3}$ to $20 \cdot 10^{-3}$) at stages A and B, while the drying speed in the modernized solar indirect dryer with natural convection decreased relatively slowly (from $20 \cdot 10^{-3} \frac{kg}{m^2 \cdot soat}$ to $3,5 \cdot 10^{-3} \frac{kg}{m^2 \cdot soat}$). It is known that the slow drying of agricultural products has a positive effect on their quality.

The classification of the botanical characteristics of apricots for drying in an indirect solar dryer with natural convection and an air collector was studied, and changes in the humidity of apricots were also studied. An indirect solar dryer with natural convection was experimentally installed and preliminary experimental studies were conducted. In the course of experimental studies, drying

curves were determined, reflecting the process of drying apricots, according to which the temperature of the air entering and exiting the dryer changes to 40–50°C, humidity 16–35%. In order to determine the level of quality of the dried product when conducting an experiment in an indirect solar dryer with natural convection and a solar air collector, when drying apricot products in the device and in the open air at the same time, the amount of toxic elements was 0.13 mg/kg and 0.22 mg/kg, the amount of nitrate ions is 8.5 mg/kg and 9.3 mg/kg, as a result of which the quality of apricot products has improved by an average of 10...12%. This study demonstrated that the performance of solar dryers varies significantly depending on their design. The upgraded indirect solar dryer with natural convection provided the shortest drying time (5 d), lowest product surface temperature (44 °C), and best preservation of apricot quality compared to direct and open-air drying. The integration of silica gel into the storage cabinet further enhanced the drying efficiency by lowering the humidity and stabilizing the quality of the final product. They offer a reduced drying time, improved product safety, and better nutritional retention. Future research should focus on scaling the technology for larger applications and conducting detailed energy efficiency analyses.

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