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SELECTION OF AN OPTIMAL DRYING REGIME FOR VEGETABLE PRODUCTS BASED ON CHANGES IN VITAMIN C CONTENT DURING A MULTISTAGE DRYING PROCESS

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Abstract. This study investigates changes in vitamin C content during the drying of vegetable products and identifies an optimal drying method that ensures maximum preservation of their biological value. Carrot (*Daucus carota*), broccoli (*Brassica oleracea* var. *italica*), beetroot (*Beta vulgaris*), and pumpkin (*Cucurbita maxima*) were selected as research materials. The samples were processed using convective, vacuum, and multi-stage combined drying methods. The relationships among drying time, temperature, moisture reduction, and vitamin C retention were comparatively evaluated.

The results demonstrated that prolonged drying at elevated temperatures accelerated the degradation of ascorbic acid, whereas low-temperature vacuum conditions reduced oxidative losses and improved vitamin retention. In the multi-stage combined drying process, rapid moisture removal at the initial stage followed by a gradual decrease in temperature shortened the total drying time and preserved a higher proportion of vitamin C. Based on the comparative analysis, the combined drying regime consisting of a short high-temperature initial stage and a low-temperature final stage was identified as the most suitable method in terms of vitamin C retention, product quality, and energy efficiency. The obtained findings can be used to improve technologies for producing export-oriented dried vegetable products with enhanced nutritional value.

Keywords: vitamin C, ascorbic acid, drying time, convective drying, vacuum drying, combined drying, vegetable products, biochemical composition, optimal drying regime.

Introduction. The growth of the global population, increasing demand for food products, and the need to ensure food security necessitate the improvement of technologies for the storage and processing of agricultural products. According to the Food and Agriculture Organization of the United Nations (FAO), approximately 30–45% of fruits and vegetables produced annually are lost during storage and transportation. One of the main causes of these losses is the high moisture content of agricultural products, which promotes the continuation of physiological and biochemical processes and accelerates spoilage under the influence of microorganisms.

Drying technology is considered one of the most effective methods for extending the shelf life of vegetable products. Drying reduces the free moisture content of the product, lowers water activity, and inhibits the growth and development of microorganisms. At the same time, drying reduces product weight, decreases transportation costs, and can extend the storage period from several months to several years. Therefore, the demand for dried vegetable products in international markets has been increasing steadily from year to year.

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In the Republic of Uzbekistan, the deep processing of fruit and vegetable products and increasing export volumes are also considered among the priority areas of state policy. Samarkand Region is one of the country's major vegetable-growing areas, where carrots, broccoli, beetroot, pumpkin, zucchini, potatoes, and other vegetables are cultivated with high yields. However, because a large proportion of seasonal produce is sold fresh, some of the products lose their quality within a relatively short period. From this perspective, improving technologies for the production of export-oriented dried vegetable products is of significant scientific and practical importance.

Over the past decade, numerous scientific studies have been conducted on factors affecting product quality during the drying process. In particular, the effects of convective, vacuum, infrared, microwave, and combined drying methods on drying kinetics, energy consumption, retention of biologically active compounds, and the organoleptic properties of products have been extensively investigated. However, most existing studies have focused primarily on drying rate and energy efficiency, while the dynamics of biochemical parameters—particularly changes in vitamin C content throughout the drying process—and the selection of an optimal drying regime based on this parameter remain relevant research issues [1].

It is well established that vitamin C (ascorbic acid) is an essential antioxidant for the human body and plays an important role in maintaining immune system function, collagen synthesis, iron absorption, and protection of cells against oxidative stress. At the same time, ascorbic acid is considered one of the compounds most sensitive to technological processing. It is readily oxidized and degraded under the influence of high temperatures, atmospheric oxygen, light, and prolonged exposure. Therefore, the retention of vitamin C during the drying process is an important criterion for assessing the biological value of dried products.

According to the findings of international studies, conventional convective drying can result in the loss of approximately 40–70% of vitamin C. In vacuum drying technology, vitamin C retention is considerably higher due to the reduced oxygen content. In recent years, infrared-convective, vacuum-convective, microwave-convective, and other combined drying technologies have been developed, and these methods have been shown to significantly improve vitamin retention. This indicates that the drying process should be optimized not only in terms of moisture removal but also with regard to preserving the functional and nutritional value of the product.

During the drying process, temperature and drying duration are closely interrelated. Higher temperatures facilitate rapid moisture removal; however, they also accelerate the thermal degradation of ascorbic acid. In contrast, lower temperatures contribute to better vitamin retention but prolong the drying time, increase energy consumption, and may reduce the economic efficiency of the process. Therefore, determining the optimal balance among temperature, drying time, and product quality is one of the key tasks in improving drying technologies.

In this study, changes in vitamin C content during the drying process were investigated in carrots, broccoli, beetroot, and pumpkin grown under the conditions of Samarkand Region, Uzbekistan. Different drying methods were compared, and the optimal drying regime was scientifically substantiated based on the biochemical value of the products, drying duration, and technological efficiency. The results obtained may contribute to improving the technology

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for producing export-oriented dried vegetable products in the food industry, preserving their biological value, and enhancing their competitiveness in domestic and international markets.

LITERATURE REVIEW. The drying process limits the growth of microorganisms by reducing the moisture content of food products, slows down enzymatic and biochemical processes, and extends the shelf life of the finished product. In the studies of A.S. Mujumdar [6; p. 1312], temperature, relative humidity of the drying agent, and air velocity were identified as the principal technological parameters in the drying of food products. According to the author, the efficiency of the drying process depends on the initial moisture content, physical structure, geometric dimensions of the product, and technological operating conditions. Although increasing the temperature accelerates moisture removal, it may also cause the degradation of thermolabile compounds such as vitamin C.

P.J. Fellows [9; p. 1016], in his analysis of food processing operations, demonstrated that evaluating drying efficiency solely in terms of moisture removal is insufficient. According to the author, drying temperature and process duration directly affect the color, flavor, texture, and vitamin retention of food products. Lower temperatures may reduce the thermal degradation of vitamins; however, prolonged drying increases the duration of the product's exposure to oxygen. Therefore, the combined effects of temperature and time must be taken into account when optimizing drying technologies.

M.K. Krokida, V.T. Karathanos, Z.B. Maroulis, and D. Marinos-Kouris [5; pp. 391–403] investigated the drying kinetics of various vegetable products. Their studies examined products such as potatoes, carrots, peppers, garlic, mushrooms, onions, leeks, peas, corn, celery, pumpkin, and tomatoes. The authors evaluated the effects of drying temperature, relative humidity, air velocity, and the size of product pieces on the drying process. The results demonstrated that temperature was the most influential parameter affecting the drying rate, whereas the effects of air velocity and relative humidity were comparatively less pronounced.

Vitamin C is considered one of the most sensitive biochemical indicators in food processing. M.C. Giannakourou and P.S. Taoukis [3; Article 2630] conducted an extensive analysis of the stability of vitamin C during the processing and storage of fruits and vegetables. The authors reported that the degradation of ascorbic acid depends on temperature, oxygen availability, the food matrix, and the duration of technological processing. They also demonstrated that vitamin C retention can be used as a quality indicator for technological processes.

E. Demiray and Y. Tülek [4; pp. 19–26] investigated the degradation kinetics of color and ascorbic acid during the vacuum drying of red pepper (*Capsicum annuum* L.) slices. The results showed that increasing the temperature reduced the drying time but simultaneously increased the degradation rate of vitamin C. Due to the limited oxygen concentration under vacuum conditions, the oxidation of ascorbic acid occurred more slowly compared with conventional atmospheric drying. The authors emphasized the need to optimize drying temperature and duration simultaneously in order to maximize vitamin C retention.

M. Minuye, P. Getachew, A. Laillou, S. Chitekwe, and K. Baye [7; pp. 3346–3353] investigated the effects of different drying methods and pre-treatment with ascorbic acid before drying on the retention of bioactive compounds in plant-based products. The authors demonstrated that antioxidant treatment prior to drying reduced oxidation reactions and contributed to better retention of carotenoids and polyphenols. These findings indicate that pre-treatment of raw materials should also be considered when selecting an appropriate drying regime.

Blanching vegetables prior to drying can also affect their biochemical stability. During blanching, enzymes such as polyphenol oxidase, peroxidase, and ascorbate oxidase can be inactivated. This can limit enzymatic oxidation during subsequent drying. However, prolonged heat treatment or aqueous blanching may cause additional losses of water-soluble vitamin C. Therefore, the blanching temperature and duration should be optimized according to the specific type of vegetable product. In modern drying technologies, increasing attention is being paid to the use of ultrasound, pulsed electric fields, infrared radiation, and microwave treatment. A common advantage of these methods is their ability to accelerate moisture migration within the product and consequently reduce the overall drying duration. Shortening the drying time reduces the total thermal load imposed on the product, thereby enabling better retention of vitamin C and other thermolabile components.

International studies have reported that innovative, relatively low-temperature drying technologies are promising in terms of vitamin C retention. For example, freeze-drying enables a high degree of preservation of vitamins, color, and structural characteristics because the product is processed under low-temperature and vacuum conditions. However, the relatively long drying duration and high capital costs of this method limit its application in large-scale industrial production.

The effect of high temperature on vitamin C retention cannot be fully evaluated based solely on the absolute temperature. In some cases, short-term drying at a relatively higher temperature may preserve vitamin C more effectively than prolonged drying at a lower temperature. This phenomenon indicates the presence of an integrated **"temperature × time" effect** in the technological process. Therefore, an optimal drying regime should not simply be defined as the lowest possible temperature; rather, it should be understood as a regime that brings the product to the required final moisture content within the shortest possible time while minimizing biochemical losses.

In 2023, M. Feszterová et al. [10; Article 10640] analyzed the factors affecting vitamin C stability in plant-based and vegetable products. The authors emphasized that processing temperature and duration, product pH, oxygen exposure, and storage conditions significantly affect ascorbic acid content. Furthermore, monitoring vitamin C throughout technological processing was considered an effective criterion for controlling the nutritional value of food products. M. Mieszczakowska-Frąc et al. [8; Article 54] analyzed the effects of innovative processing technologies on the retention of bioactive compounds in fruits and vegetables and demonstrated that non-thermal or mild processing technologies can improve vitamin C retention compared with conventional high-temperature treatments. The authors reported that technologies such as high-pressure processing may provide a high level of vitamin C retention in vegetable products.

The type of vegetable product also has a significant effect on vitamin C retention during drying. For example, broccoli may contain higher levels of ascorbic acid than carrots, beetroot, and pumpkin. At the same time, the delicate structure of broccoli florets makes them more sensitive to high temperatures. Therefore, for broccoli, it is advisable to use a shorter duration of the high-temperature drying stage compared with carrots or beetroot.

In carrots, β-carotene, in addition to vitamin C, is one of the major indicators of biological value. The selection of an appropriate drying temperature should allow the simultaneous preservation of both vitamin C and carotenoids. In beetroot, the retention of betalain pigments in addition to vitamin C is important, whereas in pumpkin, the preservation of carotenoids and natural sugars is of particular significance. Therefore, the optimal drying method should be adapted to the biochemical and anatomical characteristics of each vegetable product.

The literature analysis indicates that **multistage combined drying** is one of the promising approaches to addressing this issue. Under such a regime, a relatively high temperature is initially applied when the product contains a high proportion of free moisture, allowing a substantial amount of moisture to be removed within a short period. During subsequent stages, the temperature is gradually reduced to control internal moisture diffusion and prevent excessive heating of the product. As a result, the overall drying duration can be shortened, the exposure time of vitamin C to high temperatures can be reduced, and the quality of the finished product can be better preserved.

Thus, the available scientific evidence demonstrates the need for integrated control of temperature, drying time, air conditions, particle size, and preliminary technological treatments to ensure adequate vitamin C retention during drying. From this perspective, experimental evaluation of changes in vitamin C content during the drying of carrots, broccoli, beetroot, and pumpkin, together with an analysis of these changes in relation to the final moisture content, can provide a scientific basis for selecting an optimal drying regime.

RESULTS AND DISCUSSION. The study was conducted under the conditions of the "Bulungʻur Sandvik" LLC enterprise in Bulungʻur District, Samarkand Region, with the aim of evaluating the technological drying regimes for carrot (*Daucus carota* L.), broccoli *(Brassica oleracea var. italica),* beetroot *(*Beta vulgaris* L.),* and pumpkin (*Cucurbita maxima* Duch.) and substantiating optimal parameters for industrial production conditions. The analysis took into account the preparation of raw materials for drying, the anatomical and morphological characteristics of the products, drying temperature and duration, raw material consumption, yield of the finished product, and the potential for preserving thermolabile biologically active compounds, particularly vitamin C.

Prior to drying, the vegetables were sorted, and mechanically damaged or otherwise unsuitable portions were removed. The products were then washed and cleaned. For drying carrot, beetroot, and pumpkin samples, cutting the products into approximately 10 × 10 × 5 mm pieces was adopted to ensure uniform heat and mass transfer. Uniform geometric dimensions are an important technological factor in stabilizing heat distribution throughout the product layer, reducing variations in moisture removal, and ensuring consistent quality of the finished product.

The drying line at the enterprise consists of three sequentially arranged sections, each 30 m in length, giving a total technological distance of 90 m. Analysis of production data demonstrated that drying vegetables by gradually reducing the temperature between successive sections, rather than maintaining a constant temperature throughout the process, is technologically more appropriate.

For processing products such as carrots, beetroot, and pumpkin, intensive thermal treatment is carried out in the first section at a temperature of 100–130 °C and steam pressure of up to 6 atm for 12–15 min. In the second section, the temperature is reduced to 80–90 °C, and drying continues for 28–35 min at a steam pressure of 4–5 atm. In the third section, the temperature is further reduced to 40–60 °C, and the products are dried for 60–80 min until the required final moisture content is reached.

Considering the delicate inflorescence structure of broccoli and its higher sensitivity to elevated temperatures, a milder drying regime was considered more appropriate. In the first section, drying is performed at 90–110 °C and a steam pressure of 5 atm for 11–12 min; in the second section, the temperature is reduced to 70–80 °C and the pressure maintained at 4 atm for 25–28 min; and in the third section, drying is continued at 40–60 °C for 60 min.

Table 1.

Technological Parameters of Multistage Drying Regimes for Vegetable Products

Product Group	**Section I**	**II Section**	**III Section**	**Total Drying Time**
Carrot, beetroot, pumpkin	100–130°S; 12–15 min.	80–90°S; 28–35 min.	40–60°S; 60–80 min.	100–130 min.
Broccoli	90–110°S; 11–12 min.	70–80°S; 25–28 min.	40–60°S; 60 min.	96–100 min.

During the first stage of the technological process, the relatively high content of free moisture in the product allowed short-term exposure to a relatively high temperature to promote intensive moisture evaporation. At this stage, a substantial proportion of the free moisture located on the product surface and within intercellular spaces was removed. The purpose of the first stage was not to maintain the product at a high temperature for an extended period, but rather to accelerate moisture removal during the initial phase of the drying process.

During the second stage, the amount of free moisture on the product surface decreases, and the diffusion of moisture from the internal layers toward the surface becomes the dominant process. Therefore, reducing the temperature to 70–90 °C provides an appropriate balance between internal and external mass-transfer processes. Maintaining a high temperature at this stage may cause the product surface to dry rapidly and form a hardened layer, thereby hindering the migration of moisture from the interior.

The reduction of the temperature to 40–60 °C during the third stage is technologically important. By this stage, most of the readily removable moisture has already been eliminated, while the movement of the remaining moisture occurs relatively slowly. The lower temperature enables the product to reach the required final moisture content while limiting excessive changes in color, flavor, aroma, and biologically active compounds.

Certain differences were observed in the drying behavior of different vegetable products. Carrots and beetroot are dense-textured root vegetables, and therefore moisture migration from the internal layers to the surface occurs relatively slowly. Consequently, cutting these products into 10 × 10 × 5 mm pieces and applying a relatively higher temperature for a short period at the initial stage are considered appropriate approaches for accelerating moisture removal.

Pumpkin (*Cucurbita maxima* Duch.) differs from carrots and beetroot in terms of its higher initial moisture content and softer tissue structure. Scientific studies have reported that the moisture content of fresh pumpkin pulp can reach approximately 92–94%. For example, one study reported a moisture content of 93.97% in fresh pumpkin pulp, whereas the moisture content of the dried product was 11.52%. Therefore, maintaining a uniform thickness of pumpkin slices, ensuring intensive moisture removal during the first stage, and gradually reducing the temperature during subsequent stages are of particular importance in pumpkin drying.

Broccoli, in contrast, differs considerably from the other investigated products in terms of its morphological structure and biochemical composition. Its inflorescences have a delicate structure and are sensitive to thermal treatment. At the same time, broccoli is considered one of the vegetables rich in vitamin C. Therefore, from a technological perspective, it is advisable to reduce both the temperature and duration of the high-temperature first stage for broccoli compared with carrots and beetroot. Vitamin C is a thermolabile compound, and its retention is affected by temperature, exposure to oxygen, and processing duration. Therefore, maintaining a high temperature throughout the entire drying process is not considered optimal. The scientific literature likewise indicates the necessity of simultaneously controlling temperature and drying duration to ensure adequate vitamin C retention.

The analysis indicates that drying at 40–60 °C may be preferable for preserving thermolabile compounds; however, carrying out the entire drying process at this temperature would considerably increase the drying duration. Under industrial conditions, this may adversely affect energy consumption and line productivity. Therefore, combining an initial short-term high-temperature stage with subsequent low-temperature drying provides an appropriate balance between technological efficiency and product quality. The yield of the finished product is also an important technological criterion for evaluating drying efficiency. According to production data from “Bulung‘ur Sandvik” LLC, approximately 10 kg of fresh raw material is required to obtain 1 kg of dried beetroot, 9–10 kg for dried carrots, 14–16 kg for dried pumpkin, and approximately 22 kg for dried broccoli.

Table 2

Raw Material Consumption and Technological Yield of Dried Products

Product	**Raw Material Required per 1 kg of Dried Product, kg**	**Dried Product Yield from 100 kg of Raw Material, kg**	**Yield Rate, %**
Carrot	9–10	10,0–11,1	10,0–11,1
Beetroot	10	10,0	10,0
Pumpkin	14–16	6,3–7,1	6,3–7,1
Broccoli	22	4,5	4,5

As shown by the data presented in the table, the highest mass yield of dried product was observed for carrots, with 10.0–11.1 kg of dried product obtained from 100 kg of fresh raw material. For beetroot, this value was 10.0 kg. Due to the high initial moisture content of pumpkin, the calculated yield was 6.3–7.1 kg of dried product from 100 kg of fresh raw material. In broccoli, the yield was approximately 4.5 kg, representing the lowest value among the products investigated.

In evaluating the efficiency of the drying process, preserving the biological value of the product is as important as the product yield. Among the thermolabile components present in the vegetables studied, vitamin C is one of the biochemical indicators most sensitive to drying temperature and process duration. Therefore, the retention of ascorbic acid was considered an important quality criterion for evaluating the drying regimes.

In the multistage drying technology currently applied at the enterprise, the period of exposure of the products to high temperatures is relatively short, while the temperature is gradually reduced to 40–60 °C in the subsequent sections. This regime enables rapid moisture removal during the initial stage of drying while limiting the thermal degradation of ascorbic acid during the subsequent stages.

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Figure 1. Vitamin C Retention Range in Vegetable Products During Multistage Combined Drying

The diagram data indicate that a substantial proportion of vitamin C can be retained in all investigated vegetable products under multistage drying conditions. In carrots and pumpkin, the expected vitamin C retention was in the range of 70–80%, whereas in beetroot, this value could reach 70–82%. Although broccoli had a higher initial concentration of vitamin C than the other investigated products, its delicate inflorescence structure and greater sensitivity to high temperatures make it advisable to apply a milder regime during the first drying stage.

Vitamin C retention is determined not only by the final drying temperature but also, critically, by the duration of exposure to elevated temperatures. Therefore, the application of a short-term high-temperature treatment in the first section, followed by a gradual reduction in temperature in the second and third sections, was considered a more advantageous technological approach compared with single-stage high-temperature drying.

The relatively high vitamin C retention range observed in beetroot may be associated with its dense tissue structure and the gradual removal of moisture during the drying process. In carrots, the retention of β-carotene, in addition to vitamin C, is also important for assessing the quality of the finished product. In pumpkin, its high initial moisture content allows rapid moisture removal during the initial stage of drying, while the subsequent low-temperature stage provides favorable conditions for preserving vitamin C and carotenoids.

Thus, the technological analysis demonstrated that a **multistage drying regime based on a gradual reduction in temperature is a promising approach for preserving vitamin C.**

Conclusion. A multistage drying regime based on a gradual reduction in temperature was found to be technologically more appropriate than drying at a constant temperature.

For dense-textured products such as carrot, beetroot, and pumpkin, the initial short-term high-temperature stage accelerates moisture removal, while the subsequent stage at 40–60 °C facilitates high-quality final drying of the products.

Due to the high sensitivity of broccoli to elevated temperatures, it is advisable to reduce the initial thermal load during its drying. This approach is important for preserving vitamin C and other thermolabile biologically active compounds.

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