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The mathematical model of drying melon pulp by the convective method

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ABSTRACT

Melon is a dessert loved by many, captivating with its thick aroma and delicate honey taste. The juicy, fragrant pulp is not only delicious but also very useful for dietary purposes, with a therapeutic effect on diseases of the liver and kidneys, anaemia, rheumatism and cardiovascular disorders. This storehouse of vitamins is especially rich in potassium and iron salts, pectins, fibre, easily digestible sugars, proteins, starch and other elements necessary for health. This article presents the results of a study of the Myrzachulskaya melon variety and establishes the optimal parameters for drying the pulp, pre-treating melons with 99.5% ethanol before drying. Twenty drying experiments were carried out, in which the parameters of the operating variables, namely temperature, air velocity and sample size, were varied according to the compiled mathematical processing planning matrix. Drying caused a decrease in biologically active compounds, affecting some antioxidant properties (vitamin C content, total phenol content and antioxidant capacity) of melon pulp. As a result, the optimal parameters were established, at which samples of dried melon pulp showed insignificant losses (up to 1%) in the total content of phenolic compounds, carotenoids and ascorbic acid. The optimal parameters for drying melon fruits are a temperature of 55 °C, a drying time of 11 h and a slice thickness of not more than 0.5 cm.

Keywords: drying, melon, convective drying, phenols, mathematical modelling

INTRODUCTION

Consumer demand for high-quality food products is growing, driving the food industry to look for new food processing technologies. New food products must meet consumer demands for healthy and nutritious food. Thus, the food industry is looking for ways to preserve and increase the nutritional value of foods, which can be achieved in several ways, such as adding functional compounds and vitamins to the product, as well as improving food processing to avoid the loss of nutritional qualities. New industrial processes may need to fulfil some of these requirements. As such, techniques that can preserve as much of the natural vitamins as possible or even increase their availability and minimize the appearance of unwanted degradation products are of great industrial interest **[1]**. Natural antioxidants are essential, especially in fruits and vegetables, because of their proven ability to prevent the effects of oxidative stress. Redox imbalances in the body can cause severe damage to tissues, proteins, enzymes and genetic material such as DNA and RNA **[2]**. The antioxidant capacity of food is related to vitamins or phenolic compounds **[3]**. Melon is high in antioxidants, including choline, zeaxanthin and beta-carotene. The carotenoid zeaxanthin is a natural pigment. Under the rays of the sun in any living organism, including in the human retina, free radicals are formed. These particles damage the structures of the eye. The function of carotenoids is to protect the eyes from such damage. Thus, they play a protective role concerning the eyes and reduce the damage from macular degeneration. Melon flavonoids protect against breast and colon cancer **[4]**. Vitamins are particularly important because they play an important role in many important reactions, and any lack of vitamins can lead to serious illness **[5]**. Melons are high in vitamin C, an antioxidant with strong anti-inflammatory properties. Vitamin C strengthens the immune system, increases resistance to infectious and viral diseases, accelerates recovery processes, prevents cell damage during oxidation and activates the production of interferon and antibodies **[6]**. The shelf life of melons is considered short after harvest, not exceeding 1 or 2 weeks under normal conditions, or special cooling equipment such as cold stores is needed, leading to an increase in marketing costs **[7]**. Fresh food can be considered a matrix consisting of carbohydrates, proteins, fats, water and components dissolved in water. In fresh products, the molecular mobility of the compounds in the aqueous phase is high and therefore, they are susceptible to chemical, enzymatic, microbiological and physical degradation **[8]**. This way, the melon can be dried to preserve a portion of the product that will be easily consumed or exported, providing extended shelf life, lighter shipping weight and less storage space **[9]**. Drying fresh food reduces the water content and, therefore, the concentration of dissolved components such as sugars **[8]**. Drying is a process widely used to increase the shelf life of melons by reducing the moisture content and has many benefits such as higher concentration of nutrients due to water loss; higher stability at room temperature; inhibition of the action of microorganisms; protection against enzymatic and oxidative degradation; ease of transportation and storage; and the reduction of post-harvest losses to obtain new forms of consumption and reduce the cost of transportation and storage. Removing water from fruits and vegetables by drying is one of the oldest forms of food preservation known to humans and is the most important process for maintaining nutritional value **[10]**, **[11]**. Therefore, consumers demand processed products that retain their original characteristics to a greater extent. From an industry perspective, this requires the development of operations that minimize the adverse effects of the process **[12]**.

Modelling of the air-drying process is well known and has been presented in most of the studies on drying fruit with warm air **[13]**, **[14]**, **[15]**, and there is little data on mass transfer coefficients that are required for the optimization of the industrial dehydration process. Optimization is selecting the best alternative from a given group of alternatives for a particular process. This requires a relation describing the potential alternatives of the process and a criterion for determining which of the alternatives is the best. An appropriate experimental design is fundamental to allow the researcher to explore the process under investigation and successfully lead to its optimization, obtaining a maximum or minimum, if they exist, or to determine the area in the general space of factors in which certain desirable operating conditions are satisfied **[16]**, **[17]**.

However, a decrease in the quality of dried products is often observed since most traditional technologies use high temperatures in the drying process. Processing may also result in undesirable changes in appearance and a change in the natural flavour and colour.

Appearance and a complete colour change are important physical properties of dehydrated fruits. It is important to visually evaluate dehydrated fruits because consumers primarily judge the quality of a product by its appearance and colour. An incorrect colour or a significant change in appearance will cause the consumer to reject the product **[18]**. The colour change after dehydration occurs because fruits contain high amounts of reducing sugars such as glucose, sucrose, fructose and carbohydrates. These reducing sugars can undergo a Maillard reaction through the intervention of amino compounds during drying **[19]**. The Maillard reaction is reported to occur after air drying at a high temperature and with a long duration **[20]**. In addition, an enzymatic reaction can cause dehydrated fruits to turn brown or darker due to the oxidation of phenols to o-quinones (brown pigment or melanins) **[21]**.

Colour is a sensory parameter widely used to justify consumer acceptance of dehydrated fruit. Fruit subjected to the convection drying process suffers from loss of quality in terms of colour, taste (taste and aroma) and texture, while rehydration is often poor. The main problems are hull hardening (formation of a hard outer shell) and shrinkage. In recent years, the main goal of the research has been to improve the quality retention of dried products (rehydration capacity, etc.) by changing the process conditions and pre-treatment **[22]**. Therefore, dehydration technology should focus on producing dried products with little or no loss of flavour characteristics. Research is encouraged to optimize process conditions and apply pre-treatment to minimize the above changes **[23]**.

In recent years, many studies have been published on using ultrasound as a pre-treatment for drying **[24]**. They reported changes in the structure of melon cells caused by ultrasound. However, unlike osmotic dehydration, cell destruction was not observed, and microscopic channels appeared in the cell structure, which could be the reason for the increase in the water diffusion coefficient. When studying the use of ultrasonic or vacuum pre-treatment with sucrose solutions and distilled water concerning the drying efficiency of melon slices, a reduction in drying time was observed when pre-treating samples. Dried melon pre-treated using ultrasound and vacuum showed a lower total carotenoid loss, softer texture, better colour retention and good sensory acceptance **[25]**. However, we note that it is still necessary to understand, describe and improve the mechanisms for using ultrasound, which also depends on the processing conditions used. The authors emphasized the importance of evaluating its effect on food components to decide if its use is an advantage **[26]**.

Another little-explored alternative is to use an ethanol solution pre-treatment before convective drying. Several papers have reported an increase in drying speed in this case. In this sense, pre-treatment with ethanol gave interesting results. A balance of structural and compositional changes, such as changes in cell wall thickness and removal of air from intercellular spaces, may be responsible for improving process and product properties **[27]**. Alcohol is harmless to humans and leaves no residue after drying. It can replace water as the ultrasonic propagation medium, which will greatly improve the final food product's drying process and quality **[28]**.

In addition, during pre-treatment, a mixture with water is formed when ethanol is introduced into the sample. Then, during drying, the efficient evaporation of ethanol contributes to mechanisms that speed up the drying process, such as the Marangoni effect **[29]**. The use of ethanol pre-treatment during convection drying has also shown very positive results in terms of reduced drying time and improved product properties such as rehydration, texture, nutrient retention and availability **[30]**, **[31]**, **[32]**.

The use of ethanol as a drying pre-treatment and its effect on the quality of dried melon has never been studied. Therefore, the present study was aimed at evaluating the effect of using ethanol solutions at various concentrations as a pre-treatment, whether or not associated with the use of ultrasound and vacuum pulse, in the drying of melons, and also to test the effect of pre-treatment on several quality parameters, such as ascorbic acid content, total phenol content, total carotenoid content and colour. The results will be important for understanding drying processes and useful for developing appropriate drying and pre-treatment conditions.

Scientific Hypothesis

Improving the quality of dried melon will depend on the mode and technology of drying. The drying temperature will have a significant effect on the vitamin C content in drying melon pulp.

MATERIAL AND METHODOLOGY

Samples

For the study, melons of the Myrzachulskaya (Torpedo) variety were taken. Melons harvested in summer 2021 were provided by a farm (Shymkent, Kazakhstan) for research. The tests were carried out with melons with a soluble solids content of 10 to 12 °Brix (measured with a PAL-α refractometer). The average initial humidity was 9.61 ±0.08 kg water/kg dry matter.

Chemicals

All reagents were of analytical grade and were purchased from Laborfarm (Kazakhstan) and Sigma Aldrich (USA).

Animals and Biological Material

Animal and biological materials were not used in this study.

Instruments

We used an electric multi-cutter Moulinex DJ-905832 (Moulinex, France), an electric dryer Kitfort KT-1921 (Kitfort, China).

Laboratory Methods

The following indicators of raw materials and the resulting product were studied in work: the content of ascorbic acid (vitamin C) according to GOST 24556-89, the content of carotenoids according to GOST 54058-2010, organoleptic indicators according to GOST 1750-86. For the study of raw materials and finished products, standard conventional chemical and organoleptic methods were used.

Description of the Experiment

Preparation of raw material

The melons were cleaned on apparatus developed for cleaning gourds (developed in the Astana branch of the Kazakh Research Institute of Processing and Food Industry LLP, Nur-Sultan, Republic of Kazakhstan) **[33]**. Further, the peeled melons were subjected to deseeding by cutting the fruit in half with a knife. For drying, the pulp was cut into slices of various thicknesses (Table 1) on a Moulinex DJ-905832 electric multi-cutter. After that, the sliced melon pulp segments were soaked in absolute ethanol (99.5%) **[34]**.

Drying process

Drying was carried out in a Kitfort KT-1921 electric dryer (Figure 1). The operating principle of the dryer is based on the principle of convective drying **[35]**. The KT-1921 dryer has a temperature range from 35 to 75 °C and is equipped with a timer for up to 24 h. Slices of melon fruits were laid out on a mesh baking sheet, avoiding contact with each other to avoid sticking due to the release of sugars during the drying process.

Figure 1 Kitfort KT-1921 dryer for vegetables and fruits.

Drying (xeroanabiosis) of products is one of the oldest preservation methods. It limits the growth and development of microorganisms with minimum moisture content in dried products. Microorganisms do not develop in products with a moisture content of 4 – 30%. For products with a large mass fraction of sugars and other water-soluble substances, in which the concentration in solutions during drying increases significantly and the osmotic pressure increases, dehydration can be carried out up to 13 – 20% of moisture.

Drawing up plans for full-factor drying experiments and building a model

The primary stage in constructing a mathematical model is coding intervals and levels of parameter variation. The coding of intervals and levels of variation of input factors is compiled for the characteristics of the origin of raw materials. To obtain a mathematical model of the process of drying melon pulp, which is a regression equation, a second-order rotatable plan (Box plan) was used; the number of factors x was 3, the number of experiments was more than 20, the number of experiments at the zero point was 6, and the number of equation coefficients was 10. As a mathematical apparatus, we used mathematical and statistical methods; the resulting system of regression equations models the relationship of the most preferred optimality criterion with the rest. The main criterion for the process of drying melon fruits is the moisture content of the finished product (y), influenced by the following factors: drying temperature (T, °C), drying time (t, min) and slice thickness (L, cm); the above factors determine specific production terms. Therefore, it is advisable to adjust the system of regression equations following these factors.

The regression equation has the form (1):

$$y_1 = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 \quad (1)$$

Coding intervals and levels of variation of input factors for drying melon fruits are presented in Table 1. An experiment planning matrix is presented in Table 2.

Table 1 Coding of intervals and levels of variation of input factors.

Factors		Levels of variation					Variation intervals
Natural	Coding	−1.68	−1	0	+1	+1.68	
T, °C	x_1	51.6	55	60	65	68.4	5
t, min	x_2	9.3	10	11	12	12.6	1
L, cm	x_3	0.1	0.3	0.5	0.7	0.8	0.68

Table 2 Matrix for rotatable planning of experimental studies of the process of drying the melon pulp.

No.	Encoded values			Natural values		
	x_1	x_2	x_3	T, ˚C	t, min	L, cm
1	2	3	4	5	6	7
1	−	−	−	55	10	0.3
2	−	−	+	55	10	0.7
3	−	+	−	55	12	0.3
4	−	+	+	55	12	0.7
5	+	−	−	65	10	0.3
6	+	−	+	65	10	0.7
7	+	+	−	65	12	0.3
8	+	+	+	65	12	0.7
9	−1.68	0	0	51.6	11	0.5
10	+1.68	0	0	68.4	11	0.5
11	0	−1.68	0	50	9.3	0.5
12	0	+1.68	0	50	12.6	0.5
13	0	0	−1.68	50	11	0.1
14	0	0	+1.68	50	11	0.8
15	0	0	0	50	11	0.5
16	0	0	0	50	11	0.5
17	0	0	0	50	11	0.5
18	0	0	0	50	11	0.5
19	0	0	0	50	11	0.5
20	0	0	0	50	11	0.5

Quality research

All studies of the quality indicators of dried melon fruits were carried out in triplicate for fresh and processed samples: moisture content, ascorbic acid content, total phenol content, total carotenoid content and colour (to preserve the presentation).

Humidity was determined gravimetrically in an oven at 105 °C for 24 h **[36]**. The results are expressed as a percentage (%).

The ascorbic acid content was determined according to the AOAC method **[36]**, based on the reduction of 2,6-dichlorophenol-indophenol with ascorbic acid. The results are expressed as dry matter (mg ascorbic acid/100 g dry matter).

The total phenolic content of the extracts was measured based on the Folin–Ciocalteu reagent as described by Singleton et al. **[37]**. The reaction mixture contained 0.5 mL of the phenolic extract, 2.5 mL of the Folin–Ciocalteu reagent (Sigma-Aldrich, Germany) and 2 mL of sodium carbonate (4 g/100 g). Then the mixture was left in the dark for 2 h at room temperature. The absorbance of the sample was determined at 760 nm using an aqueous solution of gallic acid (5 – 100 µg/mL) as a standard. The results are expressed as mg gallic acid equivalents (EAA)/g sample (on a dry weight basis).

Total carotenoids were quantified based on the method described by Rodriguez-Amaya et al. **[38]**. Briefly, extraction was carried out with acetone, followed by separation and dilution in petroleum ether; finally, the absorbance was measured at 470 nm. Some precautions were taken against degradation or alteration of the pigment, such as protection from light and high temperatures and using a short analysis time. The results are expressed as µg carotenoids/g dry matter.

Organoleptic indicators determined the colour and presentation of dried melon fruits.

Number of samples analyzed: We analyzed 2 samples.

Number of repeated analyses: All tests were performed in triplicate.

Number of experiment replication: 2 times.

Statistical analysis

The data were analysed using MS Excel for Windows version 10 Pro, 2010, and a second-order rotatable plan (Box plan) was also used. In the analysis process, absolute and relative statistical indicators, and tabular and graphical methods for presenting the results were used.

RESULTS AND DISCUSSION

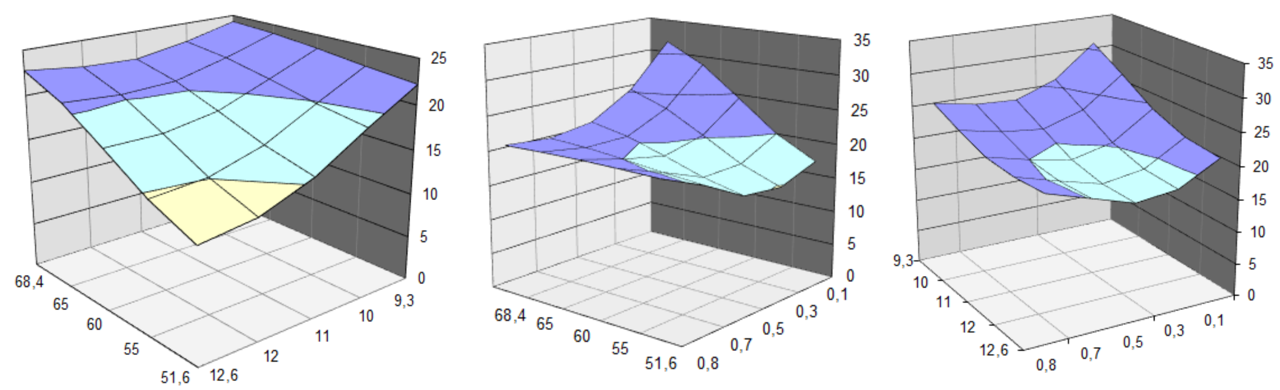
Studies were carried out to achieve the best values of melon pulp drying parameters. A number of experimental studies were carried out to determine *y* for indicators with different ratios of input parameters *x*. The results are shown in Table 3.

Table 3 Data from experimental studies of the process of drying the melon pulp.

No.	Encoded values			Natural values			Experimental values
	x_1	x_2	x_3	T, °C	t, min	L, cm	*y*, %
1	2	3	4	5	6	7	8
1	−	−	−	55	10	0.3	17
2	−	−	+	55	10	0.7	35
3	−	+	−	55	12	0.3	21
4	−	+	+	55	12	0.7	30
5	+	−	−	65	10	0.3	15
6	+	−	+	65	10	0.7	17
7	+	+	−	65	12	0.3	11
8	+	+	+	65	12	0.7	26
9	−1.68	0	0	51.6	11	0.5	15
10	+1.68	0	0	68.4	11	0.5	20
11	0	−1.68	0	50	9.3	0.5	14
12	0	+1.68	0	50	12.6	0.5	25
13	0	0	−1.68	50	11	0.1	34
14	0	0	+1.68	50	11	0.8	9
15	0	0	0	50	11	0.5	19
16	0	0	0	50	11	0.5	18
17	0	0	0	50	11	0.5	19
18	0	0	0	50	11	0.5	18
19	0	0	0	50	11	0.5	20
20	0	0	0	50	11	0.5	19

Table 3 shows that 20 experiments were carried out. The discrepancy between the results at the zero point was ±0.1.

The mathematical model of drying melon pulp is shown in Figure 2.



a b c

Figure 2 Dependence of input parameters: a – dependence of temperature and drying time; b – dependence of temperature and thickness of slices; c – dependence of drying time and slice thickness.

Figure 2 shows that drying proceeds correctly if the rate of evaporation of moisture from the surface of the product is equal to the rate of moisture transfer inside it. At a higher evaporation rate, that is, with an increase in temperature, a crust forms on the product's surface to be dried, slowing down the drying process; with slow evaporation, the product is steamed. The drying process was intensified by increasing the evaporation surface, for which the melon pulp was cut into slices with a thickness in the range of 0.1 to 0.8 cm.

Thus, when the temperature rose above 55 °C, the final product had a low moisture content; at a temperature below this value, pieces of melon pulp were not dried to the full extent, regardless of the thickness of the slices into which melon was cut.

The sample size, namely the surface to volume ratio, can also significantly impact the drying process: the drying time is significantly reduced as the size is reduced, which facilitates the processing of small products when possible.

It is easy to see that the planning matrix is orthogonal with linearly independent column vectors; hence the diagonality of the matrix and the system of equations is normal, and thus the mutual independence of the estimates of the coefficients of the regression equation. Then the regression equation for drying melon pulp with the optimal importance *y* has the form (2):

$$y = 16.0437 - 0.31097x_1 - 25.8639x_2 + 13.25491x_3 - 0.15x_1x_2 + 0.125x_3 - 2.50000x_2x_3 + 0.00283x_1^2 + 0.63492x_2^2 - 33.5131x_3^2 \quad (2)$$

Thus, the optimum drying parameters fall on a point with a temperature of 55 °C and a drying time of 11 h, and slices of melon pulp must be cut to a thickness of no more than 0.5 cm. At these parameters, a moisture content of 20% is achieved.

Melon samples were dried to a moisture content of 0.25 kg H_2O/kg dry weight (20%, wet basis) (Figure 3) and then subjected to quality analysis.

Figure 3 Dried samples of Myrzachulskaya (Torpeda) melon.

The average values of the assessed quality parameters are shown in Table 4. There was a significant decrease (total phenol up to 14.3%, carotenoids up to 24.9%, ascorbic acid up to 57.9%) in the values of these parameters for all dried samples compared to fresh melon, indicating a possible connection with thermal decomposition. The type of pre-treatment and the concentration of ethanol also influenced the results.

Table 4 Physico-chemical characteristics of fresh and dried melon samples.

No.	Melon samples	Total phenols (mg GAE/g DM)	Carotenoids (µg/g DM)	Ascorbic acid (mg/100 g DM)	Colour
1	Fresh	3.5	138.1	185.3	White
2	Dried	0.5	34.4	107.2	White with a yellowish tint

Table 4 shows that the total phenol content of the dried samples was significantly reduced (up to 14.3%) compared to the fresh melon samples, from 3.5 to 0.5 mg GAE/g DM, respectively. The amount of carotenoids in the formulation decreased from 138.1 to 34.4 µg/g DM. Ascorbic acid turned out to be the most resistant in a dried sample of melon pulp; its content decreased from 185.3 to 107.2 mg/100g DM.

Phenolic compounds. In the dried sample, a decrease in the concentration of total phenolic compounds (TPC) was observed. The decrease in these phytochemicals may be due to their being sensitive to high temperatures and thus may be affected by the drying process, resulting in a decrease in their content and antioxidant capacity **[39]**. Also, polyphenol oxidase's enzymatic oxidation occurs during the decomposition of phenol and convective drying **[40]**. Thus, the result was a lower phenol content in the pre-treated dried melon. In addition, morphological changes may occur.

Carotenoids. In total carotenoids, the decrease was due to exposure to a higher temperature (50 °C) and longer processing time, as these pigments are very unstable and subject to degradation or isomerization **[41]**. In addition, carotenoids are fat-soluble molecules (non-polar) and soluble in organic solvents such as ethanol but insoluble in water (polar), which may explain the lower retention of carotenoids when a 100% ethanol solution was used for pre-treatment compared to water-ethanol solution (50%) and untreated dried samples.

Vitamin C. A decrease in the content of ascorbic acid after drying was noted. Degradation is also strongly influenced by the characteristics of the drying process, most of the content being lost due to heat and the presence of oxygen **[42]**. Also, degradation is associated with the destruction of the internal structure and the release of nutrients during drying. Natural plant materials are often well organized into cellular compartments, where nutrients and other components (sugar, starch and protein) are located in natural cellular compartments. However, the cell wall also becomes a factor that controls nutrient bioavailability. The cell structure's physical state regulates the components' release, mass transfer, availability and biochemical stability.

Colour. There was no significant difference (up to 3 – 5%) in colour determination between dried and fresh samples. Fresh slices of melon pulp were white, while dried slices were white with a yellowish tint.

CONCLUSION

By constructing a mathematical model, the optimal parameters for drying the pulp of the Myrzachulskaya melon variety were determined. The optimization criterion was aimed at achieving an optimal moisture content of 20% (to achieve a solids content of 80%) without losing consumer properties, that is, maintaining the main nutrients and presentation. So, as a result of optimization, the optimal parameters for drying melon fruits were determined: temperature 55 °C, drying time 11 h and slice thickness not more than 0.5 cm. The qualitative indicators obtained for dried melon samples show that phenolic compounds and carotenoids are sensitive to high temperatures. In the convective drying of melon pulp, their content decreased significantly, phenols by 7 times and carotenoids by 4 times. However, the content of ascorbic acid underwent minor losses of only 1.7 times comparing fresh and dried samples. Ascorbic acid, in turn, prevents the harmful effects of free radicals and fights oxidative processes, which allows dried melon slices to be stored for even longer.

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