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**Leonid Chervinsky***
Doctor of Technical Sciences, Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0001-7215-2474

**Oleksandr Savoiskyi**
Senior Lecturer
Sumy National Agrarian University
40021, 160 Gerasim Kondratyev Str., Sumy, Ukraine
https://orcid.org/0000-0002-6459-4931

**Viktor Sirenko**
PhD in Technical Sciences, Associate Professor
Sumy National Agrarian University
40021, 160 Gerasim Kondratyev Str., Sumy, Ukraine
https://orcid.org/0000-0003-0831-6563

# The influence of ultrasonic processing on the structure and electrophysical properties of fruit in combined drying

**Abstract.** The intensification of ultrasonic vibrations for the processing of agricultural products is becoming increasingly important in the food industry, as it can reduce energy consumption for the dehydration of raw materials. The research aims to study the effect of sonication on the change of electrophysical parameters and structure of apple raw materials in the process of combined drying using direct electric heating. Using scanning electron microscopy, images of the surface structure of dried apple samples were obtained at different combinations of sonication duration and methods of heat supply to the raw material during the drying process. Based on the experimental studies, the dependences of the current flowing through the sample in the process of combined drying using direct electric heating on the duration of raw material processing in an ultrasonic bath were obtained. The influence of preliminary sonication on the maximum values of the current strength during direct electric heating was determined. The dependences of changes in the resistivity of apple samples during dehydration at different pretreatment durations were investigated. The effect of ultrasound on the initial resistivity of apples, the duration of electro-plasmolysis, and the resistivity values at which the maximum values of the direct electric heating current are observed were determined. The results of the experiments show that the pretreatment of raw materials in an ultrasonic bath can reduce the peak current values by up to 27%. The initial values of the resistivity of the raw material after sonication are reduced by 7.8-13.8% compared to the control samples. The obtained images of the dried fruit surfaces showed an increase in the porosity and roughness of the samples. The obtained results of experimental studies can become a prerequisite for the development of an energy-efficient technical means of ultrasonic processing of fruit and vegetable raw materials before drying and the selection of optimal operating modes

**Keywords**: raw apple; convective dehydration; direct electric heating; resistivity; scanning electron microscopy; roughness

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*Corresponding author

## INTRODUCTION

Vegetables and fruits are indispensable sources of useful vitamins and minerals necessary for the normal functioning of the human body. Due to their high moisture content (up to 90%), these products are very sensitive to temperature and spoil quickly, requiring them to be processed for long-term storage. According to V. Chandramohan (2020), drying is the easiest, cheapest, and least labour-intensive way to store fruits and vegetables.

The products obtained by this processing method are well stored, do not require special storage facilities and take up little space. In recent years, the development of technologies and equipment for the thermal dehydration of food products has focused on improving consumer properties by making production more complex, and high profitability is supported by marketing.

Drying units differ in the methods of heat supply to the dehydration object: convective (Carmeliet & Verboven, 2017), infrared (Huang *et al.*, 2021), high, ultra-high frequency currents (Zhou & Wang, 2019) and ultrasound (Fan *et al.*, 2017). A more innovative method of drying fruit and vegetable products is the freeze-drying method, which is described in S. Bhatta *et al.* (2020). All of these drying methods are based on the use of a clean form of energy – electricity. However, most of the proposed methods cannot provide an acceptable drying time for a given quality of the finished product. In addition, the specific energy consumption for the dehydration process is several times higher than the theoretical energy consumption for the evaporation of one kilogram of moisture.

Despite the numerous dehydration methods available today, drying remains the most energy-intensive stage of raw material processing. The quality and speed of the drying process largely determine the quality and cost of the final product. The research aims to reduce energy consumption for drying fruit and vegetable raw materials and improve the quality of the finished product.

The most common thermal method is the blanching of fresh raw materials in hot water. The authors (Guida *et al.*, 2013; Doymaz *et al.*, 2015) proved that immersion of products in hot water before drying reduces the duration of their dehydration, which is explained by an increase in the permeability of material cells as a result of high temperature. H. Xiao *et al.* (2017) found that thermal blanching also slightly improves the quality of the finished product by inactivating enzymes and microorganisms. At the same time, exposure to high temperatures can lead to discolouration of the finished product, loss of water-soluble and heat-sensitive vitamins and minerals.

An effective method of heat treatment is the preheating of raw materials by passing an alternating electric current through them. J. Moreno *et al.* (2013) and A. Isci *et al.* (2018) demonstrated the use of ohmic heating of raw materials before drying reduces the duration of dehydration by up to 30%. The reduction in drying time is caused by the damage and destruction of cell membranes as a result of electroplasmolysis. However, due to the significant heating of the raw material, the sample may boil. This leads to the destruction of the cell structure of the material and discolouration of the finished product.

According to J. Garcia-Noguera *et al.* (2012), due to the unique effects on agricultural products, low-frequency ultrasound waves are commonly used to intensify freezing, thawing, and drying processes.

J. Zubernik *et al.* (2018) noted that the use of ultrasound during the pretreatment of apples in an ethanol solution reduces the duration of convective dehydration by 18.3% compared to control samples. At the same time, an increase in the electrical conductivity of the solution was observed with an increase in the sonication time, which indicates the leakage of intracellular juice into the treated medium and a decrease in the number of nutrients in the finished product.

The research conducted by Z. Ren & Y. Bai (2018) showed the effectiveness of sonication of apple slices before vacuum freeze-drying. Pretreatment of the samples for 5 min in water at 25°C at an ultrasonic frequency of 100 kHz increased the drying rate by 25%. At the same time, increasing the processing time to 10 and 15 min did not improve the result or, on the contrary, worsened the rate of moisture removal from the samples. A.M. Jambrak *et al.* (2018) explained this behaviour by the possibility of closing surface pores during prolonged ultrasound application, which limits mass transfer. This situation can prevent the leakage of water-soluble solids from the intercellular space to the environment.

Studies of the electrophysical properties of raw materials after sonication show an ambiguous effect of ultrasound on the electrical conductivity of the material. Despite many studies on the preliminary sonication preceding the drying process, its effect on the electrophysical parameters and structure of dried raw materials is not well understood. The results of ultrasound exposure will vary depending on the type of raw material to be dried, methods of heat supply and technological parameters of the dehydration process.

The research primarily aims to obtain the dependences of changes in the electric current strength of direct electric heating and the resistivity of apple raw materials during dehydration, as well as to study the changes in the microstructure of dried apples under different processing modes in an ultrasonic bath.

## MATERIALS AND METHODS

The research was conducted at Sumy National Agrarian University (Sumy, Ukraine). The objects of research were apples of early summer and summer ripening of the varieties “Red Mac”, “Mantet” and “Helios” grown in the Sumy region (Ukraine) and harvested in 2022.

The pre-prepared apples were cut into discs of 0.005 m height and 0.028 m diameter. Ultrasonic (US) treatment of the sliced apples before drying was carried out in an ultrasonic bath DSA 50-JY2 (China) according to the procedure provided by O. Savoiskyi *et al.* (2023). Then, the treated samples were dried in a convection-type drying oven SNOL-2.5 (Ukraine) with additional heating by direct electric heating. The scheme of the drying unit and the drying methodology are given by O. Savoiskyi *et al.* (2021). During drying, the value of the electric current passing through the samples, their mass, and linear dimensions were recorded. Based on the measurements, the value of the current resistivity of the raw material during the drying process was calculated using the expression:

$$\rho = RS/l, \quad (1)$$

where $\rho$ – current resistivity, Ohm·m; $R$ – electrical resistance of the sample; Ohm, $l$ – current length (height) of the sample, m, $S$ – cross-sectional area, m$^2$. Statistica 12 (USA) was used to visualise the research results.

The methodology for studying the structure of dried fruit was as follows: samples pre-dried by various methods before sputtering the conductive film were dried in a drying oven to a constant weight at a temperature of 40°C. Complete removal of moisture from the samples before sputtering is a prerequisite, since, as a result of placing the latter in a working chamber with a high vacuum value, the moisture remaining in the sample begins to move from the inner layers to the surface and evaporate. This phenomenon negatively affects the quality of the sputtered conductive film, which further reduces the quality of the images obtained.

Subsequently, the dried samples were placed in the working chamber of the vacuum post-VUP-5 (VUP – vacuum universal post) (Ukraine), where an electrically conductive carbon film was sputtered onto their surface under a high vacuum ($10^{-5}$ mmHg) (Fig. 1).

a)

b)

**Figure 1.** The appearance of samples before and after carbon film deposition
**Note:** a – before sputtering; b – after sputtering

The electron microscopic examination of the surface of dried fruit samples was carried out using a REM-106I device (REM – scanning electron microscope, I – measuring) (Ukraine) (Fig. 2).


**Figure 2.** Scanning electron microscope REM-106I (Ukraine)

To create additional "bridges" of electrical conductivity, the sputtered samples were glued to the slide on carbon tape and placed in the working chamber of the microscope, where, after vacuum evacuation, the surface was scanned (Fig. 3).

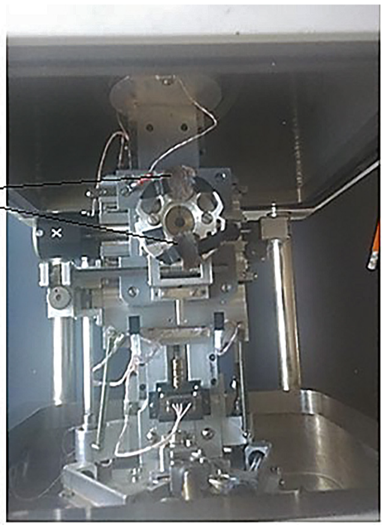


**Figure 3.** Vacuum chamber REM-106I (Ukraine) with the samples placed in it in action

The surface was scanned in the proprietary SELMI software environment, where the optimal scanning mode and magnification were selected.

The amount of heat energy supplied by direct electric heating during convective drying is primarily determined by the resistivity of the raw material and the amount of current flowing through the sample.

Direct electric heating dramatically changes the course of the dehydration process (Savoiskyi *et al.*, 2021). Drying by the proposed combined method can be divided into two main periods: a period of increasing and a period of decreasing drying rate. In this case, during the period of increasing drying rate, 30-35% of the moisture mass is removed, and the period of constant rate, which is characteristic of the convective dehydration process, is absent.

## RESULTS AND DISCUSSION

Figures 4 and 5 show the results of experimental studies of the effect of sonication on the electrophysical characteristics of fruit in the process of combined drying using direct electric heating.

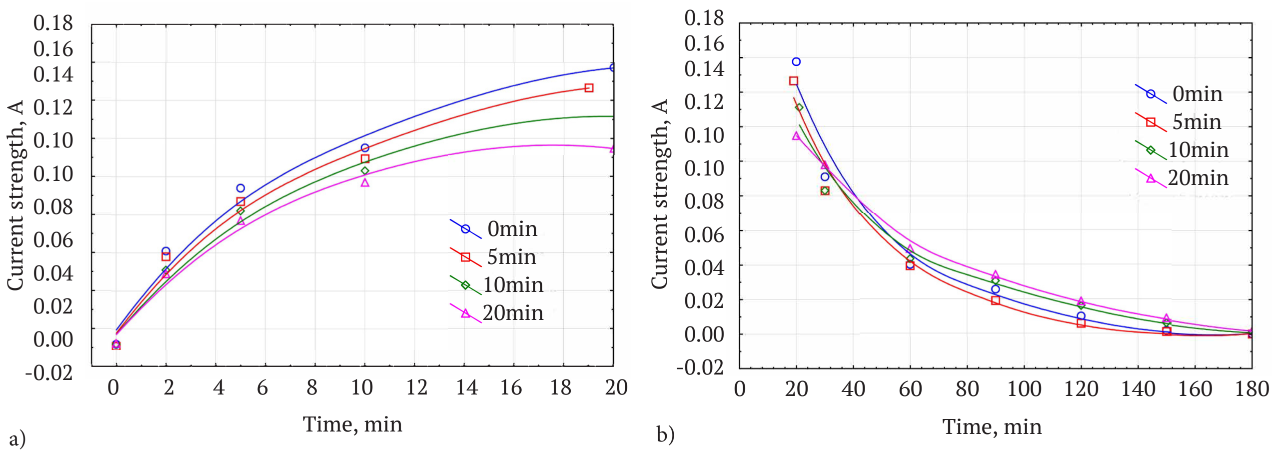


**Figure 4.** Dependences of the electric current strength passing through the sample during the drying process after sonication

**Note:** a – during the period of increasing drying rate, b – during the period of decreasing drying rate

**Source:** compiled by the authors

The main parameter that determines the quality of the finished product and the amount of energy consumed for moisture evaporation during drying by the proposed method is the magnitude of the electric current passing through the dried material. At the beginning of the drying process, when the fruit is heated by direct electric heating, the phenomenon of electro plasmolysis occurs, which is characterised by a constant increase in the strength of the electric current through the object (Fig. 4a). The increase in current is explained by a sharp decrease in the resistivity of the samples (Fig. 5a) due to irritation and destruction of cell membranes, resulting in the release of a significant amount of electrically conductive juice.

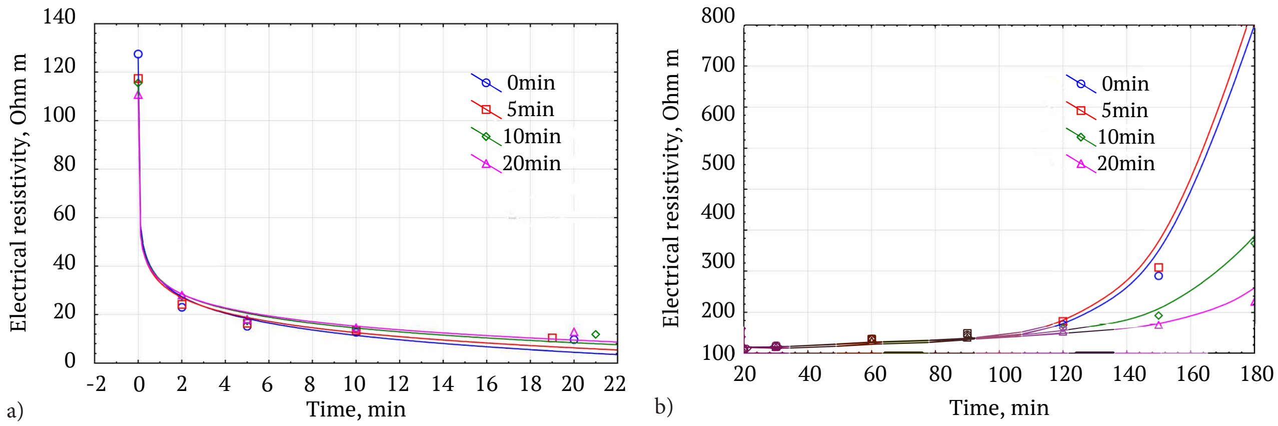


**Figure 5.** Dependences of the current fruit electric resistance during the drying process after sonication
**Note:** a – during the period of increasing drying rate; b – during the period of decreasing drying rate
**Source:** compiled by the authors

The obtained research results (Fig. 4) show that the pretreatment of raw materials in an ultrasonic bath before drying leads to a decrease in peak current values. The maximum value of the electric current that passed through the untreated samples during combined heating was 0.159 A. After sonication for 5 min, the maximum current during the drying process reached a value of 0.142 A.

Further increasing the sonication duration to 10 and 20 min reduced the maximum current values during the dehydration process to 0.131 and 0.116 A. Thus, increasing the sonication duration to 20 min reduced the maximum current through the sample by 27%.

The measurement of the resistivity of the raw material can be used to evaluate the efficiency of using direct electric heating during the drying process. The analysis of the results in Figure 5 shows that the sonication of fruit before drying leads to a reduction of its initial resistivity. The initial resistivity of the untreated fruit was about 127 Ohm-m (Fig. 5a). After treatment in an ultrasonic bath for 5 min, the initial resistance values decreased by 7.8% and amounted to 117 Ohm-m. Further increasing the duration of the ultrasonic treatment to 10 and 20 min reduced the initial resistivity values by 9.4 and 13.4% and amounted to 115 and 110 ohm-m, respectively. The obtained results confirm the data of A. Wiktor *et al.* (2016), showed that contact sonication for 5 min increased the electrical conductivity of the material by 57.7% compared to control samples. However, the effect of ultrasound on the electrical conductivity of tissues was ambiguous. Increasing the treatment duration to 20 min without changing the frequency reduced the electrical conductivity by 12% compared to the control samples. This can be explained by the phenomenon of pore closure in the material described by A.M. Jambrak *et al.* (2018).

The decrease in the electrical resistance of raw materials is explained by changes in the microstructure of fruit. Ultrasound causes leakage of the intracellular content of apple raw materials, which leads to an increase in free moisture in the samples and an improvement in the electrical conductivity of the material (Savoiskyi *et al.*, 2023). It should be noted that the decrease in electric current strength as a result of ultrasonic treatment has virtually no effect on the time of electro-plasticization of raw materials. In all cases, the duration of electroplasmolysis was up to 19-20 minutes. At the same time, the peak current values are reached at slightly higher values of the electrical resistance of the raw material, as can be seen in Figure 4a. This is due to the damage to the cell membranes by ultrasonic vibrations (ultrasonic cavitation), which reduces their current and thermal resistance.

After reaching the peak values, a gradual decrease in the strain force through the sample (Fig. 4b) is observed as a result of an increase in the specific electrical resistance of the raw material (Fig. 5b), which is explained by a decrease in the amount of moisture in the samples. When the critical moisture content is reached (140-150 min in Fig. 5b), there is a significant increase in the electrical resistance values, which may indicate the inappropriateness of using direct electric heating at this stage.

Figure 6 shows the results of the study of the surface structure of fruit at different processing times in an ultrasonic (US) bath, dried by different methods: convective (CK) and convective with direct electric heating (CK+ED).

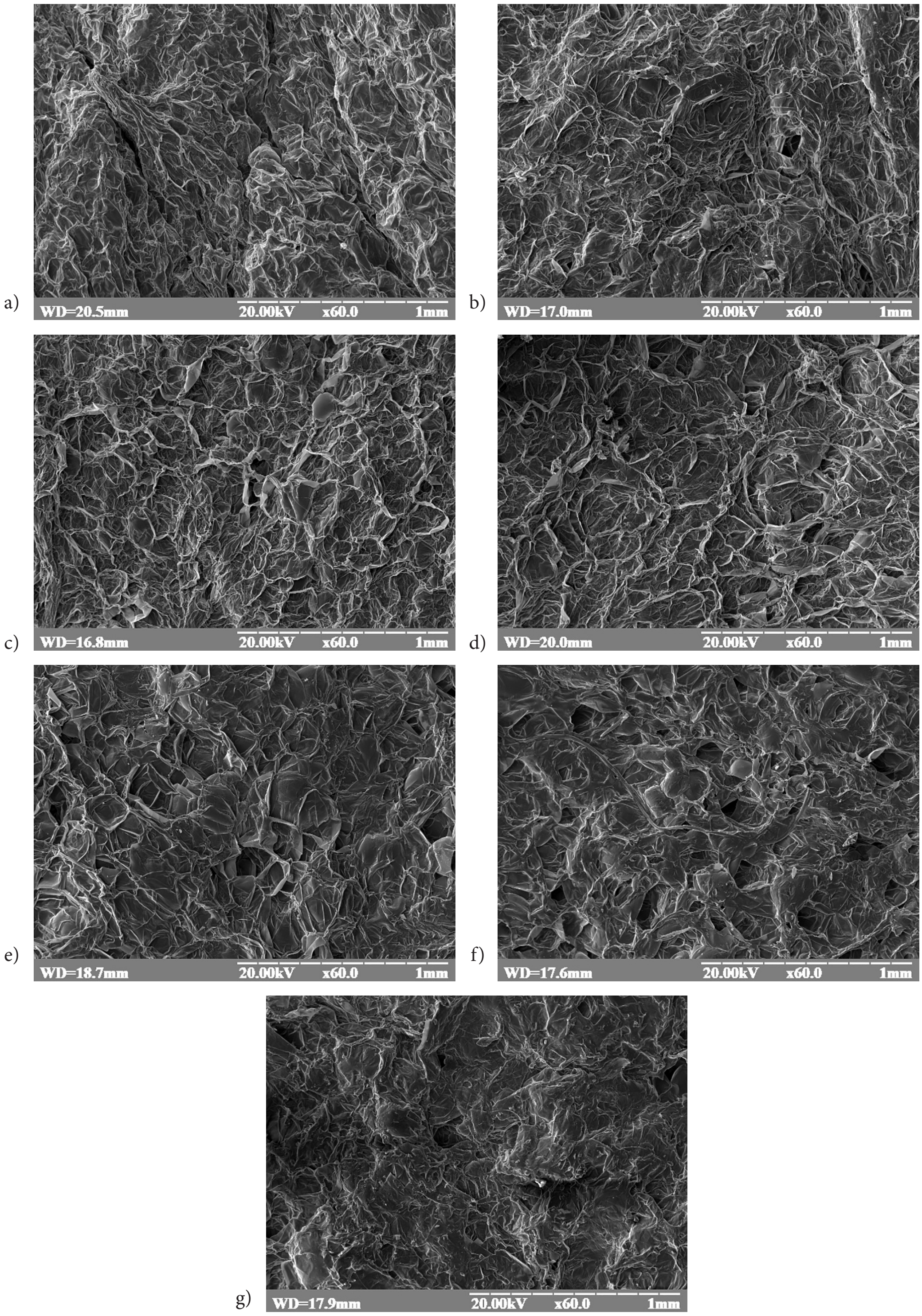


**Figure 6.** Images of dried fruit surfaces at different heat inputs and sonication duration

**Note:** a – CK; b – CK+US 5 m; c – CK+US 10 m; d – CK+US 20 m; e – CK+ED; f – CK+ED+US 5 m; g – CK+ED+US 20 m

**Source:** compiled by the authors

The use of ultrasonic treatment in the liquid before drying and direct electric heating during the dehydration process significantly reduces the final deformation of the finished product. The pieces produced in this way have a more regular shape and curl less during the drying process.

The sample, dried by the traditional convective method at a temperature of 55°C (Fig. 6a), has a rough surface with longitudinal cracks up to 1 mm long over the entire surface area, characteristic of this drying method. The roughness of the sample surface is created by the cell membranes deformed as a result of dehydration.

As a result of sonication before drying (Fig. 6b-Fig. 6d), the surface of convection-dried samples becomes rougher. This is due to the rupture and detachment of cell membranes (in the form of flakes in the photo) of the upper layers of the sample under the action of ultrasonic cavitation. With the increase of the ultrasonic treatment time from 5 (Fig. 6b) to 10 min (Fig. 6c), the surface roughness of the sample increases. However, the surface of the sample treated for 20 min (Fig. 6d) looks less rough compared to the one treated for 10 min. This is due to the significant destruction of the sample by ultrasonic cavitation, which leads to the removal of the top layer of destroyed cells from the surface. Consequently, the use of ultrasonic processing for more than 10 min can negatively affect the final weight of the finished product, resulting in significant losses of useful dry matter.

In addition to the change in surface roughness, the appearance of pores in the material is observed, which confirms the results obtained by M. Nowacka *et al.* (2022). The authors note that ultrasound has a significant effect on the structure of the dried raw material. As a result of ultrasonic vibrations, the shrinkage of the material during the drying process increased from 9 to 11%, the density of the product decreased by 6-20% and the porosity increased by 9-14% compared to untreated samples.

The use of direct electric heating during the convective drying process leads to an increase in the porosity of the sample (Fig. 6d). From the images obtained, it is possible to see the presence of micropores of a certain size throughout the surface. The surface roughness of the samples dried using direct electric heating does not visually differ from that of the conventionally dried sample.

The analysis of the surface structure of the samples shows that changes in apple raw materials caused by ultrasound differ from those caused by the use of direct electric heating in the process of combined drying. When apples are processed in an ultrasonic bath, almost no ruptures of tissue cell membranes are observed, or the damage is small and local. At the same time, the use of direct electric heating in the dehydration process has a more significant impact on the structure of the raw material. This is due to the destruction of the cell membranes of the samples as a result of electroplasmolysis.

The simultaneous use of ultrasonic treatment for 5 min and direct electric heating in the process of convective drying leads to both an increase in the porosity of the sample and an increase in the roughness of its surface (Fig. 6e). However, the structure of the samples during combined drying treated with ultrasound for 20 min (Fig. 6e) has a slightly lower roughness and porosity, which confirms the hypothesis of the possible closure of pores in the material under prolonged exposure to ultrasonic vibrations, as outlined in A.R. Jambrak *et al.* (2018). The increase in the roughness and porosity of the samples explains the intensification of the rate of moisture removal from the material. As the roughness of the samples increases, the useful area of their blowing increases, and as a result of the increase in the porosity of the material, additional channels for moisture removal appear, which facilitates its movement from the inner layers to the surface (Wiktor *et al.*, 2016; Fijalkowska *et al.*, 2017).

The decrease in the porosity of fruit raw materials as a result of prolonged sonication explains the decrease in the rate of moisture removal and the increase in the drying time during combined heating using direct electric heating and confirms the results of the study by O. Savoiskyi *et al.* (2023). Studies have shown that when samples are treated in an ultrasonic bath for 10 min, the time to reach the final moisture content increases by 17.2%, and when the treatment duration is increased to 20 min, it increases by 23.4% compared to control samples.

One of the simplest methods to intensify the dehydration process and reduce energy consumption is to pretreat the raw material immediately before drying. Pretreatment can be carried out by chemical and physical methods. All physical pretreatment methods can be divided into two types: thermal and non-thermal.

X. Cheng *et al*. (2015) found that in the food industry, ultrasonic waves of the low frequency of 20-100 kHz are commonly used, as the effect of ultrasonic cavitation in this wave range is the most optimal.

The studies conducted by O. Savoiskyi & V. Sirenko (2023) show that the use of pretreatment in an ultrasonic bath for 10 min at a frequency of 44 kHz can reduce the duration of convective dehydration by 27.8%. The obtained results are in line with the data reported by S. Tüfekçi & S.G. Özkal (2020), who found that sonication reduces the duration of dehydration by 25-40% and reduces energy consumption by 35-70%.

The use of ultrasonic treatment in combined drying with direct electric heating is ambiguous. Processing of raw materials in an ultrasonic bath before drying with a combined heating method for 5 min practically does not intensify the dehydration process, and for 10 and 20 min, on the contrary, reduces the efficiency of moisture removal, as established in the work of O. Savoiskyi & V. Sirenko (2023). This is caused by changes in the electrophysical parameters and structure of the raw material during sonication.

It should also be noted that as a result of the use of ultrasonic treatment and direct electric heating in the drying process, there is no cracking of the material, which is typical for convective heating. Thus, experimental studies confirm that the use of preliminary sonication of raw materials in the combined drying process with direct electric heating reduces the current strength of electric heating, which can avoid overheating of raw materials, improve the quality of finished products and contribute to an increase in biomethane yield.

## CONCLUSIONS

Experimental studies show the feasibility of using preliminary ultrasonic treatment of raw materials in the technological process of combined drying using direct electric heating.

An increase in the duration of the pretreatment reduces the maximum values of the direct electric heating current in the process of convective drying. Processing of apple raw materials for 20 min reduced the peak current values by 27% compared to untreated samples. Reducing the current intensity during the drying process will exclude possible overheating of apple raw materials during dehydration, which can positively affect the quality of finished products.

It has been determined that the longer the duration of sonication, the lower the value of the initial resistivity of the raw material. After sonication in an ultrasonic bath for 5 min, the initial resistivity values decreased by 7.8%, and further increasing the duration of sonication to 10 and 20 min reduced the initial resistivity values by 9.4 and 13.4% compared to the control samples. The duration of pretreatment does not affect the time of electro-plasmolysis of raw materials, and the destruction of the shells occurs at slightly higher values of resistivity.

The analysis of the obtained images of the sample surface structure shows that the ultrasonic treatment for 5 and 10 min during convective drying increases the roughness of the dried samples and increasing the treatment to 20 min can lead to the destruction of the sample surface and the loss of useful dry residue in the finished product. The simultaneous use of ultrasonic processing and direct electric heating in the process of convective drying significantly increases the roughness and porosity of apple raw materials, which can lead to easier release of moisture from the inner layers and intensification of the dehydration process.

Further research should focus on the development of technical means and methods for drying fruit and vegetable raw materials using efficient methods of heat supply and pretreatment, which will simultaneously reduce the energy intensity of the dehydration process and improve the quality of finished products.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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**Леонід Степанович Червінський**
Доктор технічних наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0001-7215-2474
**Олександр Юрійович Савойський**
Старший викладач
Сумський національний аграрний університет
40021, вул Герасима Кондратьєва, 160, м. Суми, Україна
https://orcid.org/0000-0002-6459-4931
**Віктор Федорович Сіренко**
Кандидат технічних наук, доцент
Сумський національний аграрний університет
40021, вул Герасима Кондратьєва, 160, м. Суми, Україна
https://orcid.org/0000-0003-0831-6563

## Аналіз впливу ультразвукової обробки на структуру та електрофізичні властивості фруктів при комбінованому сушінні

**Анотація.** Використання ультразвукових коливань для інтенсифікації технологічних процесів переробки сільськогосподарської продукції набуває актуальності в харчовій промисловості, оскільки може призвести до зниження енерговитрат на здійснення процесу зневоднення сировини. Метою роботи було дослідження впливу ультразвукової обробки на зміну електрофізичних параметрів та структуру яблучної сировини в процесі комбінованого сушіння з використанням прямого електричного нагріву. Ультразвукову обробку яблук перед сушінням проводили в ультразвуковій ванні, заповненій водою, протягом 5, 10 та 20 хв. За допомогою методів растрової електронної мікроскопії отримано знімки структури поверхонь висушених зразків яблук при різних комбінаціях тривалості обробки ультразвуком та способів підводу тепла до сировини в процесі сушіння. На основі проведених експериментальних досліджень отримано залежності величини сили струму, що перетікає через зразок в процесі комбінованого сушіння з використанням прямого електронагріву від тривалості обробки сировини в ультразвуковій ванні. Встановлено вплив попередньої ультразвукової обробки на максимальні значення сили струму при прямому електронагріві. Досліджено залежності зміни питомого електричного опору зразків яблук в процесі зневоднення при різній тривалості попередньої обробки. Визначено вплив ультразвуку на початковий питомий електричний опір яблук, тривалість електроплазмолізу та значення питомого електричного опору, при яких спостерігаються максимальні значення струму прямого електронагріву. Результати проведених експериментів показують, що попередня обробка сировини в ультразвуковій ванні дозволяє зменшити пікові значення струму до 27 %. Початкові значення питомого електричного опору сировини після обробки ультразвуком зменшуються на 7,8–13,8 % в порівнянні з контрольними зразками. Отримані знімки поверхонь висушених фруктів показали збільшення пористості та шорсткості зразків. Отримані результати експериментальних досліджень можуть стати передумовою для розробки енергоефективного технічного засобу ультразвукової обробки плодоовочевої сировини перед сушінням та вибору оптимальних режимів роботи

**Ключові слова**: яблучна сировина; конвективне зневоднення; прямий електронагрів; питомий електричний опір; растрова електронна мікроскопія; шорсткість