Thesis of Doctoral (PhD) Dissertation

INSPECTION OF THE TECHNOLOGICAL CHARACTERISTICS INFLUENCING THE QUALITY OF DRIED FRUITS AND VEGETABLES

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1. THE OBJECTIVES OF THE PHD THESIS

Drying is one of the possibilities of processing the vegetables and fruits produced. The most frequently applied method of this ancient preservation procedure is the artificial convective drying. This procedure became popular mainly as a result of its simple use and low operational costs; however, we should not forget about its disadvantages, either. These disadvantages concern the quality of the dried product: significant decrease in the nutritional value, shrinkage, formation of a hard, non-permeable layer, denaturation of proteins, etc.

Researches have been conducted for a long time for preserving the abundant gifts of nature, fruits and vegetables in such a way that they keep their original properties for the cold winter months as well. Nowadays, in the 21st century the requirements set out for dried fruits and vegetables include that they should be microbally stable, keep their physical, chemical and mechanical parameters and have excellent storing, packaging and transportation properties. In addition, they should have high nutrient contents suitable for producing functional foods and food supplements. Only a few drying methods are suitable for satisfying the above-mentioned demands on preservation. According to our actual knowledge, the most tolerant dehydrating method is the vacuum freeze-drying. Better quality of lyophilized products results from that the temperatures applied during lyophilization are much lower than during traditional drying and that the denaturation processes typical of the traditionally dried products does not occur. During lyophilization, no internal diffusion takes place because the sublimation starting from the surface gradually spreads to deeper layers; the ice directly passes into steam.

This is why in my thesis I laid emphasis on the inspection of such product-influencing factors the consideration of which is essential for the recognition of the phenomena and the processes as well as the relationships and the effects. In order to study my subject and answer my questions put, I have placed two drying methods (convective and vacuum freeze-drying) in the focus of my research analysis and synthesis. Accordingly, I set the following objectives during my research work:

- Know the technological characteristics influencing the quality of the dried products and develop its uniform approach evaluation.
- Inspect and characterize the dried fruits and vegetables during the process of heat and mass transport. I selected this objective since I think the

description of processes of heat and mass transport for lyophilized horticultural products is not complete in the literature.

- Define the change of nutrient contents under the effect of dehydration through analyses based on instrumental tests and using the possibilities of the drying tests.
- Conduct experiments concerning the rehydration of dried vegetables and fruits. Prepare a model uniform in its mathematical appearance and able to simulate the process of rehydration accurately.
- Define and analyse the surface strength for materials dehydrated with various methods.
- Through the textural inspection of the dried products, demonstrate the damage occurred in the texture of dried vegetable and fruit varieties as a result of dehydration.

2. RESEARCH METHODS

As the first step of the research work, I analysed the literature dealing with or connecting to the theme of drying. Although the research of this field is insufficient and the methods are missed in the Hungarian literature, numerous methods are published in the relevant foreign literature for the quality characterization of dried products and I described them without striving for completeness.

Based on the test methods and test results found in the literature, I developed the research methods and tools applied for the objectives set.

The model found on the next page (Figure 1) shows a well-arranged, overall picture about all the tests I conducted during my doctoral work and demonstrates their significance.

I dealt with the inspection of such properties which determinate and influence the quality of the dried product (typed in bold in the middle of the figure); these are as follows:

- Chemical properties, e.g. nutrient content.
- Mechanical properties, e.g. hardness.
- Physical properties e.g. heat and mass transport, rehydration.
- Biological properties, e.g. texture.

Without the inspection of these properties, we cannot speak of quality products keeping their values. Therefore the base material (vegetable and fruit varieties) must be subjected to such a treatment – in this case a dehydration process – which is controllable, measurable and influencable in order that we can preserve their original status as far as possible. Therefore we should consider such parameters and retroactions as well which have an effect on the characteristics influencing the quality such as the temperature and the speed of the drying air, the moisture content of the raw material, the drying time, the amount of nutrient contents and the chemical reactions influencing them, the internal resistance formed in the dried product under the effect of the dehydration, the hard layers formed on the surface, the composition of the material structure and the possibility of its being saturated with water, the damage of the tissues as a result of the drying and the condition of the cell wall.

My results show that these five characteristics are not only in close connection with each other but also have an effect on each other.

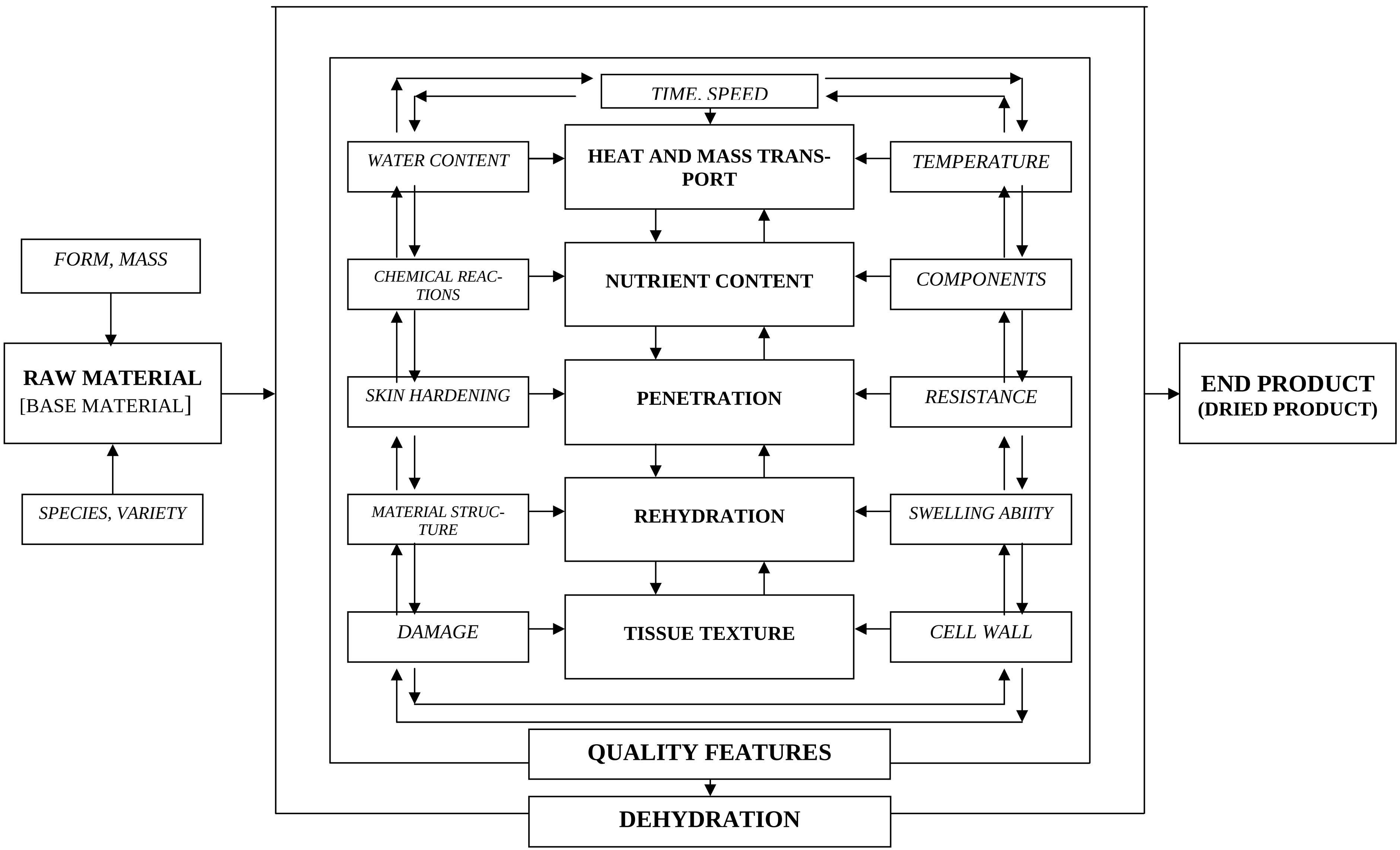

Figure 1. Systems approach summary of the characteristics determining the quality (Source: own drawing)

2.1. Description of the materials used in the experiments

The tests and data recording took place in five years from 2005 to 2009 at the College of Nyíregyháza. During the measurements I tested fruits and vegetables of exactly known origin purchased from local producers and traders (Nyíregyháza).

The raw materials used in the experiments are summarised in Figure 2.

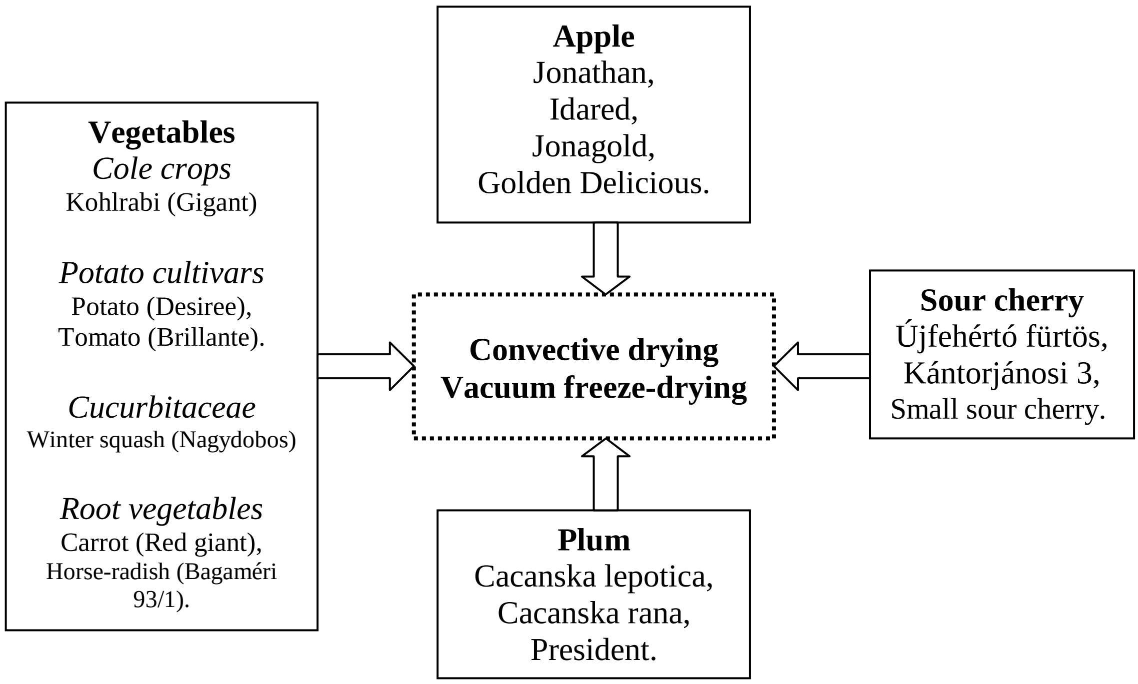

Figure 2. Description of test materials

(Source: own drawing)

2.2. Description of the dryers applied in the experiments

I made the dehydration of the horticultural products used in the experiments with the following dryers:

1. Convective drying - LP 302 laboratory cylindrical drying cabinet
2. Lyophilisation - Armfield FT33 laboratory vacuum freeze dryer,

   - factory sublimation dryer.

2.2.1. LP 302 laboratory cylindrical drying cabinet

I performed the convective drying of the fruits and vegetables in the cylindrical drying cabinet found in the laboratory of the Department of Vehicle and Agricultural Engineering, Faculty of Engineering and Agriculture of the College of Nyíregyháza.

The equipment is suitable for drying materials of small amount since its volume is 60 litres. The materials to be dried are placed on perforated trays in the interior made of aluminium. The electric heating unit found on the bottom of the dryer is used for the production of hot air (maximum 200 °C). The power input can reach even maximum 1 kW. The heating can be controlled by a thermostat, with an accuracy of ±0.3 °C. The air is circulated by a ventilator and the air speed is controlled by the restrictive found on the top of the dryer.

The exact measurement of air speed, air moisture content and air temperature can be done on the stud found on the top of the dryer. I measured the heat engineering parameters of the drying medium with an officially calibrated TESTO 4510-type apparatus.

I cleaned and sliced the materials to be dried and placed them on the perforated shelves of the drying cabinet in one layer. I performed the convective drying of the fruits and vegetables in accordance with the drying technology offered by *Burits (1992)*.

2.2.2. Armfield FT33 laboratory vacuum freeze-dryer

This apparatus is found in the laboratory of the Department of Vehicle and Agricultural Engineering.

The Armfield freeze-dryer is a compact unit consisting of two chambers. The interior of the chambers is made of corrosion-proof stainless steel and easy to sterilize. One chamber is of 300 mm diameter and 370 mm depth; this is the working chamber where the raw material to be dried is placed. The chamber has a transparent acryl cover in order that the process can be monitored. This chamber has four mobile heat probes, too, which are suitable for recording the temperature change of the material. In the close vicinity if the drying chamber, there is a condenser chamber of 200 mm diameter and 150 mm depth where the moisture abstracted by sublimation will be frozen. At the end of the drying process, the frozen part can be removed after defrosting through the discharge valve. The two chambers include also a built-in refrigerator system with compressor and a heating system with temperature regulation (electric heating unit).

The abstraction of moisture is done by two-stage rotary vacuum pump equipped with an oil mist filter so the process is fully environment-friendly. The pump and the chambers are connected by a special pipe, to which the vacuum sensor is coupled.

In order to analyse the processes taking place during the drying exactly, we equipped the laboratory freeze dryer with a data recording system.

I cleaned the material to be dried and cut it to size then placed it on the tray of the dryer in one layer. I performed the drying test of the varieties both simultaneously and separately.

The described apparatus with the data recording system (platform cell – scale instrument – DATPump software) can be seen in Figure 3.

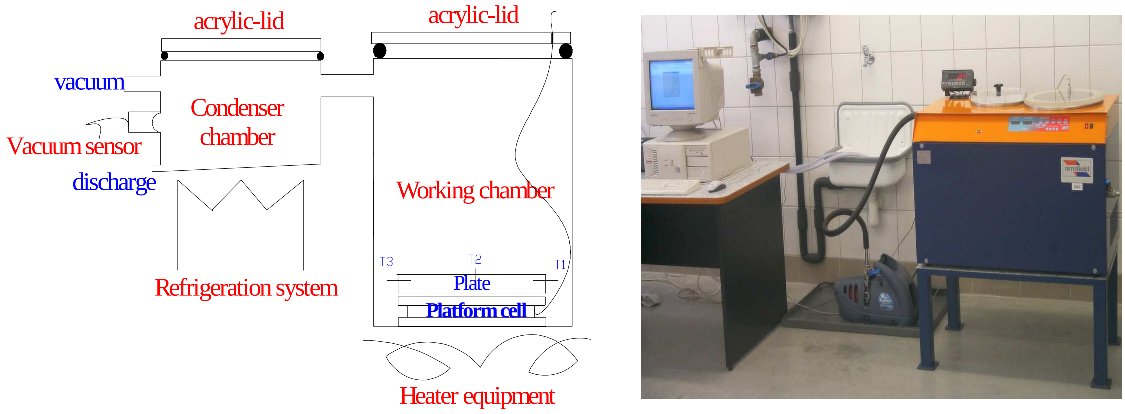

Figure 3. Armfield FT33 lyophilisation apparatus with data recording system

(Source: own drawing)

2.2.3. Factory vacuum freeze-dryer

On the other hand, I performed the experiments under factory conditions for comparison at a company seated in Debrecen. They perform researches for the production of functional, preventive, therapeutic food and food supplements by the application of the so-called sublimation dryer.

In order to operate the sublimation dryer, we need to apply two technical apparatuses simultaneously: the turbo air refrigerator meets the demand for cooling down to a range of minus 50-130 °C with atmospheric air and the sublimation equipment ensures the dehydration under vacuum.

Figure 4 shows the main parts of the lyophilisation equipment: sublimation dryer (a) and turbo air refrigerator (b).

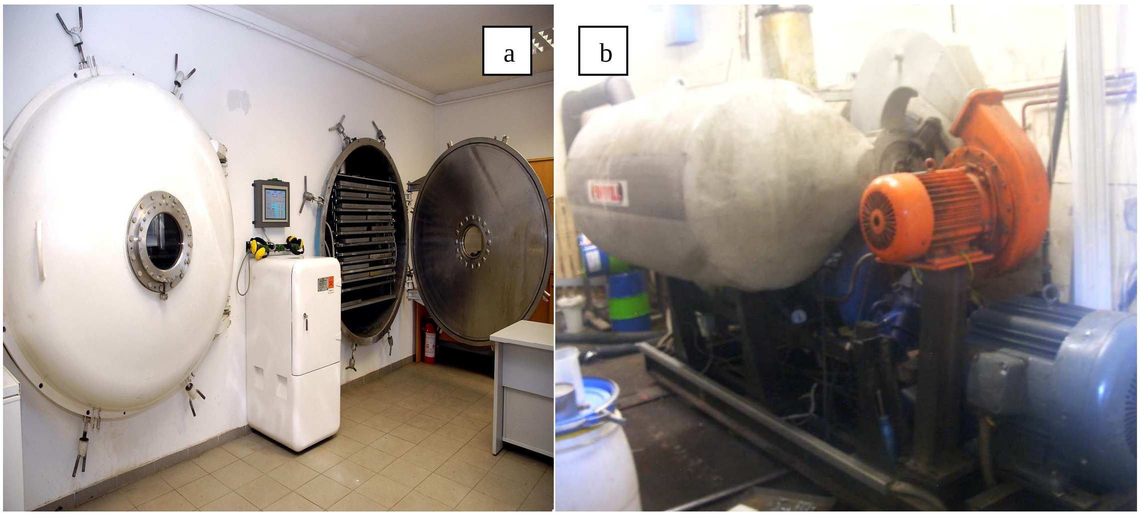

Figure 4. Factory-size trial lyophilisation equipment with its units

(Source: own photo)

2.3. Description of measuring instruments and measuring techniques

The characteristics influencing the quality of the dried products were measured and evaluated with the following instruments and methods:

- Moisture content measurement: PRECISA HA 60 type quick moisture meter.
- Measurement of the drying parameters of the convective method: TESTO 4510 type measuring instrument.
- Detection of the chemical composition of the material: with analytical procedures and instruments.
- Determination of the product strength: MGA-1091 type electronic penetrometer.
- Measurement of the rehydration activity of the dried material in moistening agent.
- Inspection of the texture: BRESSER BIOLUX type electro-microscope.

2.3.1. Analytical methods of the determination of the nutrient contents

The analytical measurements were done in the accredited laboratory of the Agricultural and Molecular Research Institute, College of Nyíregyháza. I also took part in the analysis of the samples. We analysed the following nutrient contents (for raw and dried samples) in accordance with the provisions of the effective Hungarian and European standards (Table 1).

Table 1. Determination of the chemical composition of the samples

Description	Test method
Moisture content	In drying cabinet till mass uniformity
Sugar content measurement	
Reducing sugars	Luff-Schoorl's method
Amount of carbohydrates	High-pressure liquid chromatography (HPLC)
Starch content	Method of polarimetry
Total acid content	Titration
Organic fruit acids	HPLC
Proteins	Dumas-Pregl's procedure
Fat content	Petroleum ether extraction in Soxhlet's device
Mineral content measurement	
Ash content	Drying cabinet
Macro- and microelements	Atomic absorption spectrophotometer and flame photometer
Flavouring agents	Gas chromatographic method
Dietary fibre content	Van Soest's method
Peroxide number	Titration
Detection of vitamins	
Vitamin E	HPLC
Vitamin C	Redox titration
Vitamin B group	HPLC
Flavonoids	HPLC on reversed phase
Carotenoids	HPLC on reversed phase

2.3.2. Measurement of product strength

The purpose of the test was to measure the resistance of the hard layer formed on the surface of the dried product as a result of the dehydration, and compare it with the surface strength of the raw material.

I performed the strength tests of the raw material and the dried product in the laboratory of the Department of Vehicle and Agricultural Engineering

The product strength was measured by means of the MGA-1091 type electronic penetrometer. The instrument is suitable for the direct measurement of the hardness of fruits and vegetables. It was developed with the cooperation of the Department of Physics-Automatics, Faculty of Food Science of Corvinus University of Budapest and the Institution of Agricultural Engineering of FVM (Ministry of Agriculture and Rural Development) *(Borsa et al., 2002).*

The electronic penetrometer consists of a spherical handle, a sensor placed in the handle and two sets of punches. The sensor includes a high sensitivity strain gauge cell. The accuracy of measurement is 0.50 N and the permitted maximum force is 65 N.

One of the sets of punches serves for the non-destructive measurement of the coefficient of elasticity, while the other for the Magness-Taylor's destructive hardness measurement *(Fekete and Felföldi, 1994).*

The electronic penetrometer can be connected to the computer with an RS232 serial bus through a measuring interface. The measuring interface includes a (12-bit) analogous/digital converter and an instrumental amplifier. The calibration and tarring of the penetrometer, the input of the configuration parameters as well as the display and storage of the measuring results are done by special software (Penetro) installed in the computer *(Fekete et al., 2001).*

With the non-destructive method I measured the surface hardness of the dried products and characterized it with the coefficient of elasticity defined by the following equation:

$$c_e = \frac{\sigma}{z} \quad , \tag{1}$$

where: c_e – coefficient of elasticity [kPa/mm], σ – compressive stress [kPa], z - deformation [mm] *(Fekete et al., 2001).*

I measured the skin and the flesh of the product at the specified points (usually six or eight points), from the edge of the sample to its interior. I performed the measurements several times a day, calculated the average of the data received in this way and recorded it in the minutes.

2.3.3. Measurement of the rehydration activity of the dried material

The process of the experiment was as follows: I measured the weight of the samples dehydrated by various methods, then placed them in pots filled with water of 35 °C and 75 °C. During the experiment, I ensured the permanent temperature of the liquid by means of liquid supply. I removed the samples from the liquid after 0.5, 5, 10, 15, 30, 60, 90 min periods and eliminated the surplus moisture from their surfaces with an absorbent. At the end of the experiment I measured the weights of the rehydrated samples and calculated the rehydration rate (RR).

The value of the rehydration rate (RR) shows how much the amount of the water absorbed again can increase the weight of the dried product. The rehydration rate can be calculated with the following formula *(Marques and Freire, 2006)*:

$$RR = \frac{m_{rh}}{m_d}\,, \qquad (2)$$

where: RR – the rehydration rate [-], m_{rh} – weight of the rehydrated sample [g], m_d – weight of the dried sample (status before rehydration) [g].

I performed the tests in accordance with the method applied by *Tein et al. (1998)* in the laboratory of the Department of Vehicle and Agricultural Engineering.

Kinetics of rehydration

In order to create the model of the rehydration process, out of the thin-layer product drying theories I selected *Lewis' (1921)* semi-empirical mathematic method because of its relatively simple mathematics background. Through the modification of the Lewis' theory it became possible to inspect the effect of rehydration as well for both the vacuum freeze-drying and convective drying. In this way the rehydration process can be demonstrated much more truly.

I calculated the model by integration and used Excel program for the data processing.

2.3.4. Inspection of the texture

I describe the deformations, damages of the plant tissues under the effect of the drying by microscopic tests. I inspected the vegetable and fruit cuttings with BRESSER BIOLUX AL type electro-microscope in the laboratory of the Department of Vehicle and Agricultural Engineering.

I made cuttings from the raw material and during the drying process at certain material moisture contents from the samples, then analysed them under the microscope.

I took photos of various (4× and 10×) magnification with the program named MicrOcular. Through the camera attached to the microscope I transmitted the photos to the computer.

3. MAIN STATEMENTS OF THE THESIS

3.1. Results of the tests of heat and mass transport

The data recording system developed and implemented with my participation allows exact, reliable measurements in order to know the drying action better and inspect the transport factors precisely.

With regard to the results of the heat and mass transport, I stated that the temperature and pressure applied for the freeze-drying is much less while the drying time is much longer than for the convection drying (Figure 5).

I revealed that the thickness and size of the drying material in the vacuum freeze-dryer are decisive factors from the viewpoint of the speed of the drying process. By applying optimal material thickness, the drying time of the process can be reduced (Figure 6).

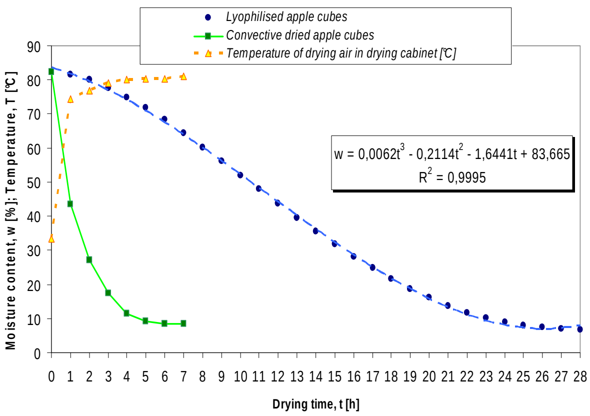

Figure 5. Drying curve of convectively and vacuum freeze dried apple cubes for the four varieties inspected

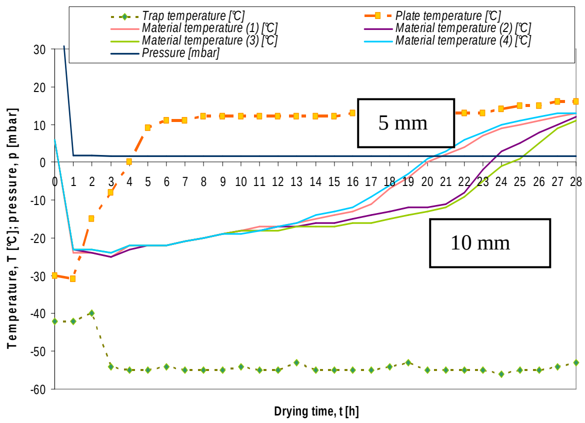

Figure 6. Change of temperature and pressure during the freeze drying of apple variety samples of various sizes (5, 10mm)

I demonstrated with the measuring results that the heat quantity necessary for the vacuum freeze drying is some 1.2-2.8 times as much as for the traditional drying. The power consumption of the lyophilisation is 3.7-9.4 times as much as the power consumption of the hot air drying procedure.

3.2. Analytical results of dried fruits and vegetables

Through the analytical inspection of dried fruits and vegetable I stated that the nutrient contents – carbohydrates, acids, proteins, fats, fibre materials, minerals, vitamins, flavonoids, carotenoids – reduced by 30% for the lyophilized samples, while 45-88%

reduction was measured for the materials dehydrated by convection as compared to the initial status.

In addition, the measuring results showed significant decrease in the amount of vitamin C which indicates its heat sensitivity. It may limit the possibility of increasing the temperature since the decomposition of vitamin C starts already above 45 °C. The extent of the reduction in vitamin B content was not so large under the effect of the heat treatment than in the ascorbic acid. Proteins precipitated at a relatively low drying temperature, from their original status they changed into denaturised status, therefore I experienced a decrease in this component. So proteins are heat-sensitive materials, similarly to vitamin B and C. When examining the chemical components for the samples of apple and sour cherry varieties, I found that vitamin E and flavonoids are less heat sensitive materials since usually I experienced an increase in the amount of components under the effect of the heat treatment. Out of the analysis of the nutrient content of the fruits it also turned out that the carbohydrate content, acid content and mineral content increased in the dried samples; it means that the carbohydrate, acid and mineral components of apple and sour cherry are relatively thermoduric so alterations did not occur.

3.3. Surface strength of dehydrated fruits and vegetables

Through the penetration tests, I stated that the surface of the vegetables and fruits dried with the convection method is at least 1.42-9.11 times as hard as that of freeze-dried products (Figure 7).

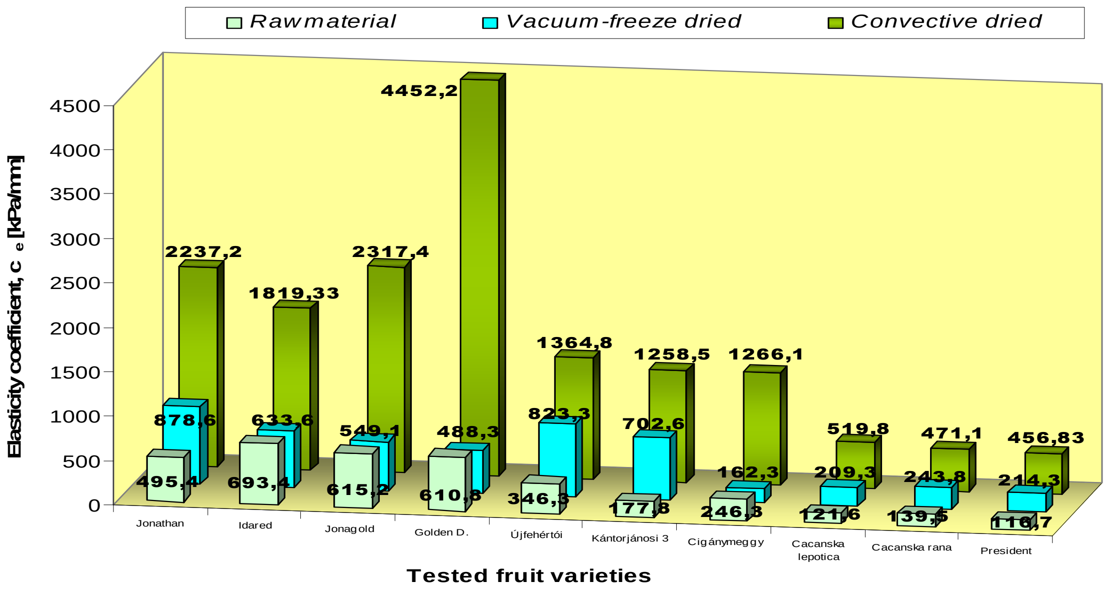

Figure 7. Comparison of the surface hardness of dried fruits to the surface hardness of the raw material

The reason for this is that during the drying the water leaves the surface of the product by evaporation and the evaporated water is supplied by diffusion from the internal layers. During its movement, the water diffusing from the internal parts takes dissolved materials along with it, which remain on the surface after the evaporation of the water, are concentrated and form a hard layer. During lyophilisation, no internal diffusion occurs since the sublimation starts from the surface, spreads to the deeper layers step by step and the ice is directly changed into steam without a liquid phase.

With the penetration diagrams prepared I proved that during the storage the coefficient of elasticity of the dehydrated materials will change under the effect of the relative humidity of the environment. So the product interacts in two directions with the surrounding medium. If the partial pressure on the surface of the material is higher than the partial pressure of the steam in the surrounding air, then the moisture transport will start in the air (desorption); in other words, the material will harden. If the moisture content of the dried product decreases below the threshold value characteristic of the variety, then the partial steam pressure difference will change to the opposite sign, which means that the material will take in moisture from the environment, so the material will moisten (absorption), that is the surface of the dried product will mollify (Figure 8). The occurring process shows well that the lyophilised material is extremely liable to absorb water from the air. However, it increases the risk of deterioration of quality therefore the physiological processes taking place during the storage of the dried product can be slowed by advanced storage and packaging technologies.

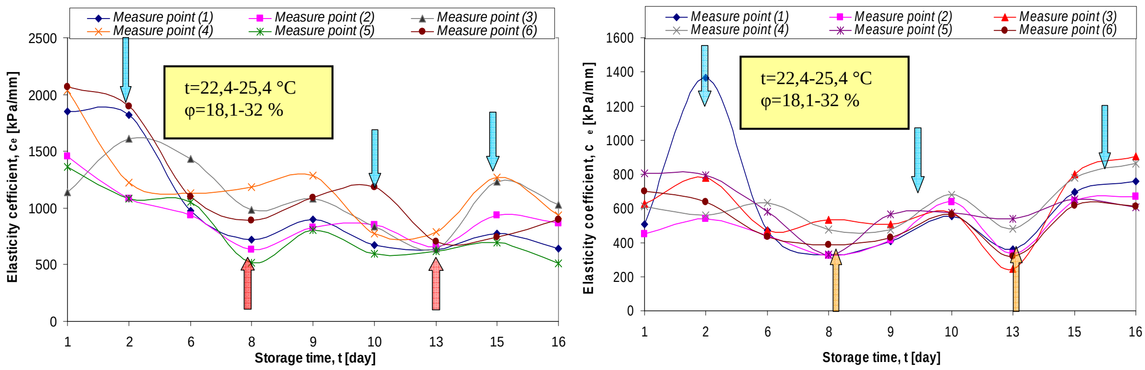

Figure 8. Change of the surface hardness of ‘Idared’ apple variety samples dried with convective method and freeze-drying against the storage time

After a while, equilibrium will be established between the relative humidity of the air surrounding and the dried material. This is a well-known process named equilibrium moisture content. In order to simulate this process exactly, certainly we should take sorption isotherms essential for the definition of the equilibrium moisture content of the products and it requires further research.

3.4. Results of the textural rehydration tests

I proved that during their rehydration the freeze-dried materials balance out almost at their original water content and keep their original shape and size as well. The reason for this is that the lyophilised products have porous, spongy structure (elasticity of the cell wall) which is able to absorb moisture and regenerate. Some lyophilised fruits (e.g. sour cherry) mean exception to it since during the measurements I experienced that the original moisture content could not be recovered because of the so-called glassy condition.

Through the rehydration tests I revealed that small of freeze-dried materials seemed to be softer after dehydration than the raw material. The samples dried with the convective method kept their hard, solid surface at the end of the rehydration process, so they could not recover their original shape and moisture content. In the 2. table I indicated the percentage moisture content of the rehydrated product as compared to the original moisture content.

Table 2. Moisture content of rehydrated dried fruits

Description of the tested varieties	Moisture content, w [%]			Compared to the raw material [%]	
	Raw material	Convective dried	Lyophilised	Convective dried	Lyophilised
Apple varieties					
Naményi Jonathan	83,34	61,8	78,11	74,15	93,72
Idared	86,23	68,32	82,62	79,2	95,8
Jonagold	84,2	63,55	79,57	75,4	94,5
Golden Delicious	85,2	60,04	79,21	70,5	93
Sour cherry varieties					
Újfehértói fürtös	82,14	43,21	73,3	52,6	89,2
Kántorjánosi 3	78,14	45,61	66,23	58,4	84,7
Small sour cherry	80,1	47,2	68,7	58,9	85,7
Plum varieties					
Cacanska lepotica	79,27	62,37	81,41	78,7	102,7
Cacanska rana	82,71	70,93	83,78	85,7	101,3
President	79,43	67,37	81,17	84,8	102,2

Out of the rehydration diagrams I stated that the lyophilised samples have higher rehydration rate and can be rehydrated more quickly than those dried with the convection method. In the moistening medium of higher temperature, the rehydration took place more quickly and the rehydration rate was higher. I experienced quicker moisture regain for the lyophilised samples when rehydrating at both lower and higher temperatures. The lower rehydration rate of the samples dried with the convection method results from the broken down structure, the volume shrinkage and the hard surface (Figure 9).

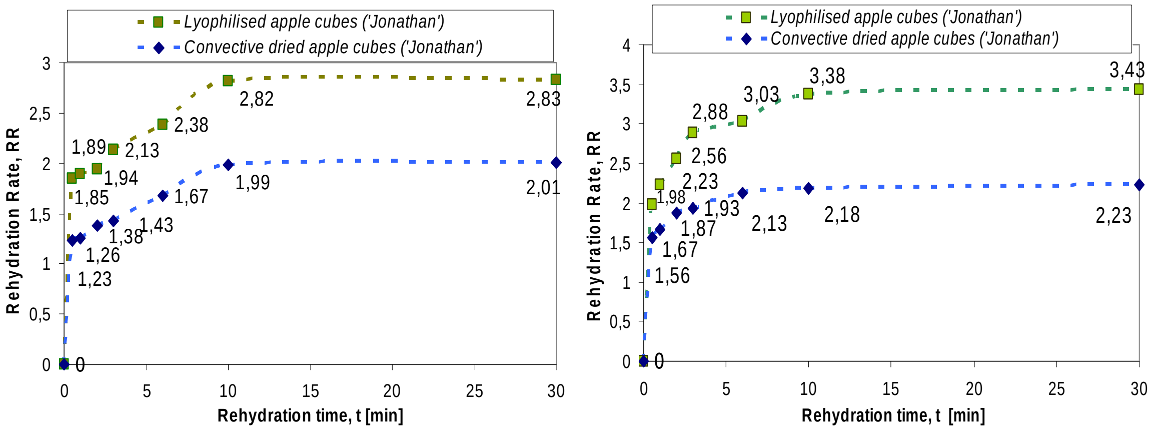

Figure 9. Rehydration of convection-dried and lyophilised 'Naményi Jonathan' apple samples at 35 °C and 75 °C

The experiments performed showed that the rehydration model successfully simulates the soaking process of the freeze-dried and convection-dried samples (moisture regain and saturation). I stated that the lyophilised materials have higher rehydration coefficient (k_r) than the materials dried in the traditional way (Figure 10). The model has not yet been used for the description of the rehydration of lyophilised samples and samples dehydrated with convective drying method.

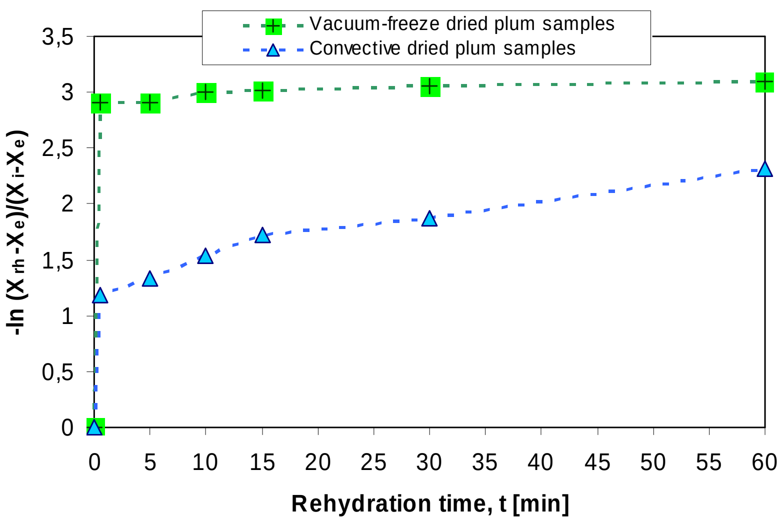

Figure 10. Rehydration coefficient of the freeze-dried and convective heat transfer dried samples of the'Cacanska rana' plum variety

3.5. Textural analysis of the dried products

From the photos taken by the electro-microscope I stated that the cell walls of the vacuum freeze-dried cuttings were damaged during the dehydration; little damage occurred, the cell walls became thinner, some of them separated from each other and took an irregular form as compared to the original (raw) condition. However, I did not experience any shrinkage since the ice crystals checked contraction.

For the samples dried with the traditional method, the cellules shrunk, the cell walls became thinner, separated from each other and went through deformation which did not recover even during rehydration (Figure 11).

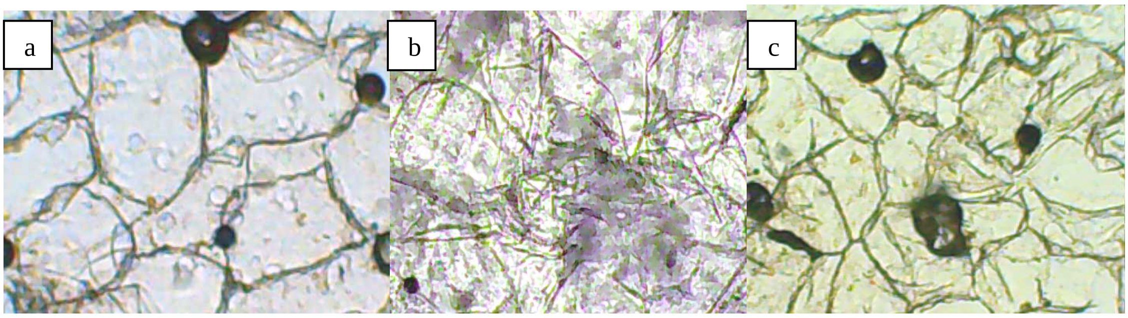

Figure 11. Tissue condition of **'**Jonagold' apple before treatment (a), after convective heat treatment (b) and after lyophilisation (c)

The slighter damage of the cell walls can be achieved with the reduction of the speed and temperature of the drying medium and the elongation of the drying time. The drying performed at too high temperature results in the denaturation of the product, the cell walls' becoming inelastic and the reduction of the swelling ability. When increasing the intensity of drying, the cell walls will shrink and distort.

3.6. Results of the factory tests

From the factory tests I stated that the factory sublimation dryer kept larger amount for almost all nutrient contents of the dried product as compared to the samples lyophilised in the laboratory. The reason for this is that the freezing of the product was quicker (by means of the turbo air refrigerator), which allowed that the micro ice crystals did not tear or only to a small extent tore through the cell walls, so the steam sublimating as a result of the drying took a small amount of nutrient content along with it towards the external surface of the dried product. Beyond this, the lower drying velocity also contributed to the relatively stable condition of the cell walls.

With the product strength tests I proved that the surface of the samples dehydrated in the factory is more elastic and softer than the surface of the samples treated in the laboratory; however, its liability to rehydrate showed the opposite since the materials lyophilised in the laboratory could be rehydrated to a much greater extent.

During rehydration, the great porosity ensured that the liophilised materials could regain their original properties. Certainly the large surface allowing quick re-swelling that is the porous structure increases the risk of oxidation. Therefore the packaging must be done in a neutral gas space (vapour-tight packaging) for the lyophilised dried products containing colour and flavour materials liable to decomposition.

Out of the inspection of the texture, I stated that greater deformation occurred in the tissue texture of the samples dried in the laboratory as a result of the lower speed of freezing. The vacuum freeze-dryer operating in the laboratory is equipped with a compressor refrigerator and, owing to the slower product freezing, relatively greater ice crystal were formed which injured the cell walls.

To sum it up, we can declare it was proven by the factory experiments that the sublimation dryer is suitable for the manufacture of the base materials of food supplements. It is favourable to observe the conditions supported by the experiments, especially the drying speed and time adjusted to the cell texture, since the material can be dehydrated in much shorter time; see the laboratory measurements. However, here we must consider the fact that the drying speed will decrease as a result of the micro-crystal structure formed during the quick-freezing. Beyond this, the otherwise high operational costs can be reduced if we install the turbo air refrigerator in a tempered place; thereby we can avoid the preheating of the cooling agent (oil) necessary for the operation of the vacuum pump.

4. NEW SCIENTIFIC RESULTS OF THE DISSERTATION

1. I defined a relationship for the characterisation of the drying processes of lyophilised fruits and vegetables. The processes can be approximated with third-degree polynomials. The functions representing the moisture content reduction of the drying materials can be described with the following equation.

$$\mathbf{w=at^3-bt^2-ct+k}$$

   where: *w* – moisture content of the product [%]; *t* – drying period [h], *a, b, c, k* – permanent multipliers of the third-degree polynomial the values of which depend on the characteristics of the material: the variety, the ripeness and the tendency to loose water.
   Their ranges: a=0.0229-0.005; b=0.8182-0.011; c=4.5966-0.059; k=95.736-69.532

2. I stated that the operational cost of freeze-drying is 3.7-9.4 times as much as the operational cost of the convective drying. The results show that we should take into account the drying time, the drying agent’s temperature, the ice’s sublimation heat, the hourly water amount discharge and the power requirement of the apparatuses.

3. Through the inspection of the nutrient contents I revealed that for the method of freeze-drying more components will remain in the dried product than for the vegetables and fruits dehydrated with the convective drying method. I proved by analytical measurements that vitamins B and C as well as proteins are characterised by heat sensitivity. Vitamin E and flavonoids are less sensitive to heat, and carbohydrate, acid and mineral contents are extremely thermoduric components since under the effect of the heat treatment I experienced increase in the quantity of these components.

4. I defined a new relationship using the kinetic equation of the Lewis’s drying procedure. I stated the equation of rehydration as a semi-empiric mathematics model suitable for the description of the rehydration processes of convectively dried and lyophilised materials as a function as follows:

$$X_{rh}=X_e+(X_i-X_e)\cdot e^{-kr.t},$$

where: X_{rh} – moisture content of the material during the rehydration [kg/kg], X_i – moisture content of the dried material [kg/kg], X_e – equilibrium moisture content of the rehydrated material [kg/kg], k_r - rehydration coefficient, t – rehydration time [s].

The k_r coefficient comes into the following ranges: 0.95-2.32 for convectively dried material, 1.39-3.09 for lyophilised material.

Criteria of the application of the mathematical model: the material should sink into the water in with full surface, the water temperature should be permanent during the rehydration, the samples should have the same moisture content (X_i; after drying) and the weight and size of the rehydrating materials should be equal.

5. By means of penetration tests, I proved that the material changes in the samples dehydrated with the convection drying method are more unfavourable than the material changes in the freeze-dried samples. The surface of the vegetables and fruits dried with the convective procedure is 1.42-9.11 times as hard as that of the freeze-dried ones.

6. I verified that the process of water absorption and loss of dried vegetables and fruits during storage can be characterised by hardness measurement.

5. PRACTICAL USEFULNESS OF THE RESULTS

Research-methodology results

1. Owing to the pressure applied in the dryer, it is difficult to solve the monitoring of the weight loss of the drying material in the vacuum freeze dryer, although it is essential for the simulation of the heat and mass transport. The drying function of the lyophilised materials can be taken up by means of the strain gauge platform cell placed on the bottom of the drying space and thereby we can receive more exact results about the processes taking place during the drying.

2. I stated that the economic efficiency of lyophilisation can be achieved mainly through the reduction of the drying time. Its determining factors include the thickness of the material to be dried, the application of small layer thickness, the extent of the material cooling (it is sufficient to cool it below the crystallization point, about -20 – 25 °C), and the intensive heat transfer (without melting of the material). We can reduce drying time, if we combine measured drying methods (convective and lyophilisation). The relative long operating time can be reduced by the observation of these proposals.

3. Hardness testers (penetrometers) applying various methods are used for the determination of the storage time and ripeness of vegetable and fruit species. My measurements proved that these instruments are suitable for the quality characterisation of the dried products as well.

4. The consistency test method applied by me (hardness test) makes it possible for the factories to quick test and control the moisture transport process of the dehydrated horticultural products.

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