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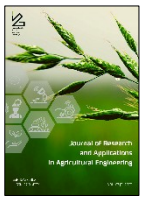

The influence of vacuum impregnation of apples by green tea with honey and elderflower juice on drying effects and selected quality factors of apple chips

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Vacuum impregnation (VI) was applied to *Jonagold* apple slices using green tea infusion with honey (*L1*) and green tea with honey and elderflower juice (*L2*). Samples were dried by convective (CD), microwave–vacuum (MVD) and freeze drying (FD), followed by determinations of dry matter, water activity, colour parameters (L^*, a^*, b^*), tensile properties and drying kinetics. VI slightly increased dry matter and reduced water activity in fresh slices; all dried variants reached low moisture content (9.65–13.31%) and low water activity (0.19-0.35), ensuring shelf stability. VI-modified apple chips showed higher redness and favorable colour characteristics than no pretreated. Tensile tests revealed that drying method strongly affected mechanical response at rupture: CD samples were stiff and strong but brittle, FD samples exhibited low strength and energy absorption, whereas MVD samples combined moderate stiffness with markedly higher deformation capacity and rupture work density, indicating enhanced mechanical resilience. In conclusion, VI with green tea, honey and elderflower is a promising pretreatment method to obtain stable, attractive apple chips.

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1. Introduction

Vacuum impregnation (VI) is an innovative pretreatment technique for fruits and vegetables that involves the incorporation of an impregnating solution with a designed sensory profile and health-promoting properties into plant tissue under reduced pressure conditions [1]. VI can be considered a modification of osmotic dehydration; however, several fundamental differences can be distinguished. First, the contact between the plant tissue and the solution is preceded by a stage in which, due to the action of a vacuum pump "in dry conditions," the air and free water are partially removed from the intercellular spaces until mechanical equilibrium is reached [2]. The evacuated intercellular spaces are subsequently filled with the impregnating liquid at an intensity dependent on the process conditions—applied vacuum level and treatment duration—as well as on the tissue porosity and the properties of the impregnation solution [3].

Secondly, the driving force of vacuum impregnation is the pressure difference generated by the vacuum pump, rather than the osmotic pressure gradient between the solution and the plant tissue, as in osmotic dehydration [4]. Consequently, the liquid uptake by the tissue proceeds very dynamically, and the impregnating solution does not necessarily have to contain osmotic agents such as salts or sugars. This feature is of key importance for the development of healthy, low-sugar, and low-salt food products [5].

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The impregnating medium can include not only osmotic solutions but also liquids with unique and beneficial physicochemical and nutritional properties containing probiotics, prebiotics, vitamins, nutraceuticals, antioxidants, and other bioactive compounds [6]. The intensive mass transfer between the solid matrix and the impregnating liquid enhances the physicochemical stability of the product and allows for the modification of its structure and sensory attributes [7].

The application of VI prior to drying allows for the modification of sensory characteristics of the dried product, such as color, taste, aroma, and texture [8, 9]. Consequently, the technique enables the development of dried products with attractive new flavor–aroma profiles, contributing to the diversification of commercial offerings and promoting healthy eating habits. Fruits and vegetables subjected to VI must possess appropriate tissue porosity and internal structural stability during impregnation, while the impregnating solutions can include fruit juices or any custom-designed formulations.

Therefore, the aim of this study was to determine the effect of apple slices pretreatment by vacuum impregnation with green tea sweetened by honey and elderflower juice on drying kinetics, physicochemical characteristics and mechanical properties of dried material.

2. Material and methods

2.1. Material preparation

Fresh *Jonagold* apples from the local market were cut into quarters and then sliced into 4±0.01 mm thick pieces.

2.2. Vacuum impregnation of apple slices

Apple slices were vacuum impregnated (VI) by using two infiltration liquids: *L1* - green tea infusion (Genmaicha, Naturalnie Zdrowe, Poland) with goldenrod honey (4,7 °Brx) and *L2* - green tea (Genmaicha, Naturalnie Zdrowe, Poland) with goldenrod honey and elderflower juice (10,9 °Brx). Goldenrod honey and elderflower juice were purchased from the local market. Impregnation was carried out by using patented laboratory installation (Institute of Agriculture Engineering, Wrocław University of Environmental and Life Sciences, Poland [10]) in three stages: 2 minutes at vacuum 0.7 bar on fresh apple slices, 4 minutes at vacuum 0.7 bar on apples with impregnation liquid *L1* or *L2*, 10 minutes at atmospheric pressure on apples with impregnation liquid. After VI slices were gently dried with a paper towel and forwarded to further processing.

2.3. Drying methods

The drying process was performed by three methods: convective drying (CD), microwave-vacuum drying (MVD) and freeze drying (FD).

CD tests were carried out in the prototype laboratory installation (Institute of Agriculture Engineering, Wrocław University of Environmental and Life Sciences, Poland) [11]. Apple slices (50 g) were dried in the single layer at the air flow rate 0.5 $m \cdot s^{-1}$ at temperature 70^0C until the constant weight was achieved. Experiments were repeated in triplicate.

MVD drying was conducted in the dryer Plazmatronika SM-200 (Institute of Agriculture Engineering, Wrocław University of Environmental and Life Sciences, Poland) [12]. Apple slices (50 g) were dried in the rotary glass chamber at the pressure 5-7 kPa and microwaves power 240 – 360 W until the constant weight was achieved. Experiments were repeated in triplicate.

FD was performed in Free-Zone 4.5 L. (Labconco, Fort Scott. USA) after freezing in the single layer at -26 ^{0}C, 24h at a cooling rate 1 $^0C \cdot min^{-1}$. Drying was carried out under the constant pressure of 50 Pa and shelf temperature of 22 ^{0}C for 24h.

Dried apple chips were vacuum packed (PA/PE clear film, thickness 80 μm) and stored until analysis.

2.4. Analysis

2.4.1. Dry matter and water activity

Dry matter (*d.m.*) of fresh and dried material was determined gravimetrically by drying the sample in the vacuum oven (V0101 Memmert, Schwabach, Germany) at 70 ^{0}C, 3 kPa until a constant weight was achieved [13].

Water activity (a_w) of fresh and dried material was determined by using the AquaLab 4TE (AquaLab, Warsaw, Poland) at room temperature in triplicate.

2.4.2. Kinetics of drying

Kinetics of CD and MVD was evaluated on the base of the moisture content ratio values, calculated as follows:

$$MR = \frac{M_\tau - M_r}{M_0 - M_r} \quad (1)$$

where MR is the moisture content ratio (-), Mτ is the water content after time τ (g water/g dry matter), M0 is the initial water content (g water/g dry matter) and Mr is the equilibrium water content (g water/g dry matter) [14].

For the mathematical description of the drying kinetics curves, Page's model was used [14]:

$$MR = a \cdot \exp(-k \cdot \tau^n) \quad (2)$$

where *a*, *k* and *n* are function coefficients, τ is time (min).

2.4.3. Colour changes

Colour of fresh and dried parenchyma tissue was described on the base of measurements L^*, a^* and b^* parameters by colorimeter Minolta-Conica RC-400 (Minolta Corp., Osaka, Japan) and the total colour difference *ΔE*, calculated as follows [15]:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (3)$$

$$\Delta L^* = L^*_{sample} - L^*_{reference} \quad (4)$$

$$\Delta a^* = a^*_{sample} - a^*_{reference} \quad (5)$$

$$\Delta b^* = b^*_{sample} - b^*_{reference} \quad (6)$$

where L^* is brightness (from 0 - black to 100 – white), a^* and b^* are chromaticity parameters (from a^* =(+)60 for red to a^*=(-)60 for green and from b^*=(+)60 for yellow to b^*=(-)60 for blue colour), *sample* is the dried material and *reference* is fresh material unprocessed.

2.4.4. Mechanical properties

The tensile strength of dried, vacuum-impregnated apple samples was determined using a universal testing machine (Instron UTM 5566, Instron®, USA). Apple slices were cut into rectangular specimens with a narrowed gauge section to promote failure within the central region of the sample. The geometric dimensions of each specimen, including width (a), thickness (b), length (L_0), were measured individually using a digital caliper with an accuracy of 0.01 mm. Tensile tests were performed under cyclic tensile loading at a constant crosshead speed of 0.1 mm·s^{-1} under ambient laboratory conditions. During testing, the tensile force (F) and crosshead displacement (ΔL) were continuously recorded until sample rupture.

Engineering stress–strain curves were constructed from the tensile test data based on the recorded tensile force and crosshead displacement. Engineering strain (ε) was calculated as the ratio of displacement (ΔL) to the initial gauge length (L_0) according to Eq. (7), while engineering stress (σ) was determined as the ratio of tensile force (F) to the initial cross-sectional area (A) of the specimen, as expressed in Eq. (8).

An apparent secant modulus (E) was calculated as the ratio of stress to strain at the rupture point according to the Eq. (9). This parameter represents the overall stiffness of the material up to failure and does not correspond to the true Young's modulus determined from the initial linear elastic region of the stress–strain curve [16].

$$\varepsilon = \frac{\Delta L}{L_0} \quad (7)$$

$$\sigma = \frac{F}{A} \quad (8)$$

$$E = \frac{\sigma}{\varepsilon} \quad (9)$$

The rupture work (W) was calculated as the mechanical work performed during tensile stretching up to the failure point (ΔL_f). It was determined as the area under the force–displacement curve using numerical integration (trapezoidal rule) according to Eq. (10).

$$W = \int_0^{\Delta L_f} F(\Delta L) \cdot d(\Delta L) \quad (10)$$

To enable comparison between samples with different cross-sectional areas, the work was normalized by the initial gauge volume ($A \cdot L_0$), where A is the initial cross-sectional area and L_0 is the initial gauge length. The work density (ϖ) was calculated using Eq. (11).

$$\omega = \frac{W}{A \cdot L_0} \quad (11)$$

2.5 Statistical analysis

The statistical analysis was carried out by using Statistica 10.0 (StatSoft, Poland). Data were recorded as means ± SD and analyzed by Excel 2007. Analysis of variance was performed by ANOVA procedures. Significant differences ($p \leq 0.05$) between the mean values of dry matter and water activity were determined by Duncan's multiple range test. Significant differences between the average values of mechanical and colour parameters were specified using Tukey's test by the significance level α=0.05. To confirm the Page's model fitting for the drying kinetics description, the following statistical coefficients were calculated: mean square error *RMSE*, reduced test values X^2 and the residual variation coefficient *Ve* [17].

3. Results and Discussion

3.1. Dry matter and water activity

Vacuum impregnation of apple slices resulted in a slight increase in dry matter content and a decrease in water activity, in samples impregnated with both liquids (Table 1). As a result of drying by all applied

methods, low-moisture content products were obtained, with water content ranging from 9.65% to 13.31%. The use of *L2,* an impregnating solution containing additional elderflower juice, resulted in a higher reduction in water content, which was most pronounced in the case of FD. Consequently, a_w of apple chips impregnated by *L2* was the lowest after FD (a_w=0.19), however a_w of CD and MVD apples was higher when the impregnation was used. All dried samples exhibited low a_w level, ensuring high storage stability (a_w=0.19÷0.35).

Table 1. Dry matter and water activity of apple slices before and after drying, initially impregnated with green tea, honey and elderflower juice or non-impregnated

Drying method	Impregnation	*d.m.* (%)	a_w (-)
fresh	*no imp*	14.20±0.70^a	0.98±0.01^a
	L1	16.62±0.02^b	0.96±0.88^b
	L2	16.74±0.07^b	0.96±1.16^b
CD	*no imp*	86.69±0.69^c	0.32±0.72^c
	L1	87.10±0.87^c	0.33±0.40^c
	L2	88.37±0.14^d	0.35±0.76^d
MVD	*no imp*	87.06±0.03^c	0.29±0.61^c
	L1	87.03±0.09^c	0.34±0.07^d
	L2	88.94±0.93^e	0.32±0.03^c
FD	*no imp*	87.95±0.61^d	0.26±0.11^e
	L1	88.29±0.98^d	0.24±0.38^f
	L2	90.35±0.42^e	0.19±0.62^g

Mean within one column with a different superscript are significantly different homogeneous groups ($p \leq 0.05$); *d.m.* - dry matter; a_w - water activity; *L1*- impregnation liquid 1: green tea with honey; *L2* - impregnation liquid 2: green tea with honey and elderflower juice; *no imp* – non-impregnated apple slices; CD – convective drying; MVD – microwave vacuum drying; FD- freeze drying

The observed effect of apple's impregnation in both sugar-containing solution *L1* and *L2* on the thermal drying (CD, MVD) effectiveness, analyzed by *d.m.* and a_w, corresponds with the results described by Authors in the previous study [18]. During drying of apple cubes, a sucrose solution incorporated into intercellular spaces leached out and at the surface of the tissue underwent a transition into a rubber state. As a consequence, a dense sucrose film inhibited effective water removal, resulting in samples about relatively low *d.m.* and high a_w.

3.2. Colour changes

The VI process caused only a slight change in the colour, compared to fresh material (Table 2) since the total colour difference (ΔE) was on the level perceptible only to a very attentive observer: ΔE=2.76÷3.10 (for *L1* and *L2* respectively).

The drying process resulted in important changes of apple slices colour in each of the drying techniques applied (ΔE=13.12÷34.64), however, the influence of VI on colour was inconclusive. The protective effect of VI on the colour stability of dried apples was observed only in case of FD when the total colour difference after drying without pretreatment was ΔE=25.51 and after VI ΔE=13.12÷19.46 for *L1* and *L2* respectively. No influence of VI on ΔE after MVD was found, whereas after CD the ΔE was higher in VI material (ΔE=29.58÷30.20 for *L2* and *L1* respectively) than in experiments when VI was not applied (ΔE=23.66).

The pre-impregnated CD samples were darker than the non-impregnated ones, which was reflected by a decrease of the L^* parameter for *L1* (↓3.6%) and *L2* (L^*↓3.22%) as well. In contrast, VI resulted in lightening of chips dried by MVD (L^*↑10.08-14.12%) and FD (L^*↑15.97-17.36%). Blanda et al. [19] described a strong darkening effect after FD of impregnated apples, higher than in non-impregnated apples, which is in opposition to results presented in this study.

VI caused also an increase of redness (a^*) of samples that underwent CD and MVD whereas during FD the pretreatment had no influence on redness of material. The redness increase may be interpreted as beneficial, as it suggests higher saturation with nutritive compounds.

Table 2. Colour characteristics of apple slices before and after drying initially impregnated with green tea, honey and elderflower juice or non-impregnated

Drying method	Impregnation	L^*	a^*	b^*	ΔE
fresh	*no imp*	83.18±5.67^{a}	-2.66±0.51^{a}	12.72±1.94^{a}	-
	L1	80.17±0.36^{b}	-2.70±0.83^{a}	11.99±1.40^{b}	3.10±7.51^{a}
	L2	80,50±0.40^{b}	-2.71±0.84^{a}	12.03±0.91^{b}	2.76±0.79^{a}
CD	*no imp*	77.20±8.56^{c}	0.29±0.46^{b}	35.42±2.85^{d}	23.66±0.98^{b}
	L1	73.36±3.94^{d}	5.55±2.00^{e}	40.57±4.54^{e}	30.20±3.54^{d}
	L2	73.64±2.89^{d}	4.78±0.89^{d}	39.71±1.48^{e}	29.58±2.00^{d}
MVD	*no imp*	66.36±4.52^{e}	4.71±2.34^{g}	44.87±3.73^{f}	33.41±3.74^{e}
	L1	75.73±2.66^{d}	6.64±1.93^{f}	45.25±3.29^{f}	34.64±0.87^{e}
	L2	73.05±3.11^{d}	6.33±1.98^{f}	44.38±1.72^{f}	34.44±1.34^{e}
FD	*no imp*	72.40±5.61^{d}	2.66±3.04^{c}	35.22±3.12^{d}	25.51±0.02^{b}
	L1	83.96±0.55^{a}	2.79±0.76^{c}	24.63±0.76^{c}	13.12±0.89^{f}
	L2	85.40±3.19^{a}	2.53±0.37^{c}	30.89±1.00^{g}	19.46±1.67^{c}

Mean within one column with a different superscript are significantly different homogeneous groups ($p \leq 0.05$). L^* - lightness (0÷100), a^*- redness ((-)60÷(+)60), b^*- yellowness ((-)60÷(+)60), *L1*- impregnation liquid 1: green tea with honey, *L2*- impregnation liquid 2: green tea with honey and elderflower juice, *no imp* – non-impregnated apple slices, CD – convective drying, MVD – microwave vacuum drying, FD- freeze drying.

It was noticed that VI influenced yellowness of chips when dried by CD (b^*↑12.11-14.54%) and FD (b^*↓12.29-32.00%). MVD dried apple's yellowness did not depend on VI.

The effect of VI on the colour changes can be evaluated as positive (more intensive redness and yellowness comparing to non-impregnated apples) especially in CD, drying method which is reported as the most popular but also destructive for pigmented biocomponents.

3.3. Dying kinetics

Figure 1 presents the drying kinetics of CD and MVD samples subjected to impregnation and non-impregnated samples. Preliminary impregnation resulted in a reduction of total drying time in both investigated drying methods: CD (10÷13% for impregnating solution *L1* and *L2* respectively) and MVD (19% for *L1* and *L2*). However, VI did contribute to a decrease in the drying rate during drying and an increase in the drying rate at the end of dehydration.

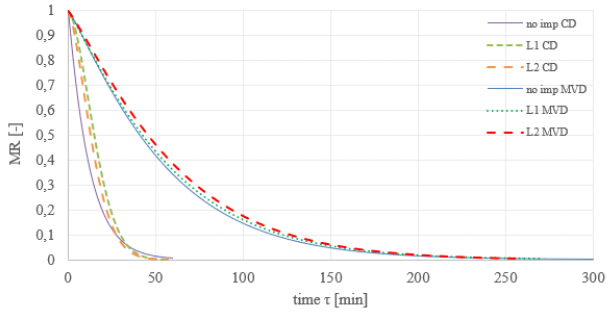

Fig. 1. Kinetics of CD and MVD of apple slices initially impregnated with green tea, honey and elderflower juice or non-impregnated

The shortening of drying time was also reported in the Authors' previous experiments concerning the impregnation of apple cubes in sucrose solution and in sucrose solution with the addition of citric acid [20].

3.4. Mechanical properties

3.4.1.Stress–strain behavior and tensile strength

The stress–strain curves obtained from tensile tests of dried apple samples are shown in Figure 2, while the corresponding mechanical parameters determined at the rupture point are summarized in Table 3. All samples exhibited a distinctly non-linear tensile response followed by abrupt failure, which is characteristic of dried plant tissues.

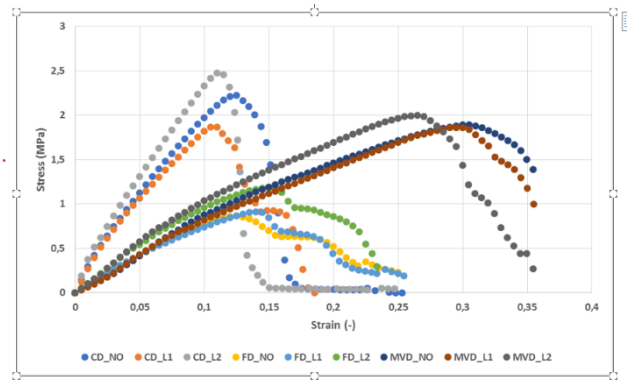

Fig. 2. Stress–strain curves of dried apple samples subjected to tensile loading, illustrating the effect of drying method and impregnation variant on mechanical response

Table 3. Mechanical parameters of dried apple samples determined at the rupture point

Sample	Stress σ (MPa)	Strain ε (–)	Work density (kJ·m^{-3})	Secant modulus (MPa)
CD_NO	2.22 ± 0.18	0.12 ± 0.01	162.1 ± 16.2	17.77 ± 1.42
CD_L1	1.87 ± 0.15	0.10 ± 0.02	111.1 ± 11.1	17.77 ± 1.42
CD_L2	2.48 ± 0.20	0.11 ± 0.01	151.9 ± 15.2	22.52 ± 1.80
FD_NO	0.86 ± 0.09	0.13 ± 0.01	61.6 ± 6.2	6.91 ± 0.55
FD_L1	1.10 ± 0.09	0.14 ± 0.01	89.3 ± 8.9	7.84 ± 0.67
FD_L2	1.18 ± 0.04	0.15 ± 0.02	106.7 ± 10.7	7.87 ± 0.63
MVD_NO	1.89 ± 0.15	0.30 ± 0.02	330.6 ± 33.1	6.30 ± 0.59
MVD_L1	1.86 ± 0.12	0.30 ± 0.01	311.4 ± 31.1	6.31 ± 0.54
MVD_L2	2.00 ± 0.16	0.26 ± 0.02	314.0 ± 31.4	7.54 ± 0.62

Convectively dried samples (CD) reached the highest tensile stresses at rupture, ranging from 1.87 to 2.48 MPa, with the maximum value observed for the CD_L2 variant (Table 3). These samples fractured at relatively low strain values (0.10–0.12), indicating a stiff and brittle mechanical behavior.

Freeze-dried samples (FD) exhibited substantially lower tensile stresses at rupture (0.86–1.18 MPa) and failed at moderately higher strains (0.13–0.15), reflecting a more compliant but mechanically weak structure.

Microwave–vacuum–dried samples (MVD) showed intermediate tensile stresses at rupture (1.86–2.00 MPa) but sustained markedly higher strains before failure (0.26–0.30), as illustrated by the extended stress–strain curves in Figure 2. This indicates enhanced deformation capacity compared to both CD and FD samples.

3.4.2. Secant modulus

The secant modulus at rupture (E), calculated as the ratio of stress to strain at the failure point, is presented in Figure 3 and listed in Table 3. Convectively dried samples exhibited the highest apparent stiffness, with E values ranging from 17.77 to 22.52 MPa. The highest stiffness was observed for the CD_L2 variant, consistent with its high tensile stress and low strain at rupture.

Freeze-dried samples showed significantly lower apparent secant modulus values (6.91–7.87 MPa), indicating limited resistance to deformation under tensile loading. Microwave–vacuum–dried samples exhibited comparable E values (6.30–7.54 MPa), despite their substantially higher strain at rupture. This mechanical response reflects a combination of moderate stiffness and enhanced deformability.

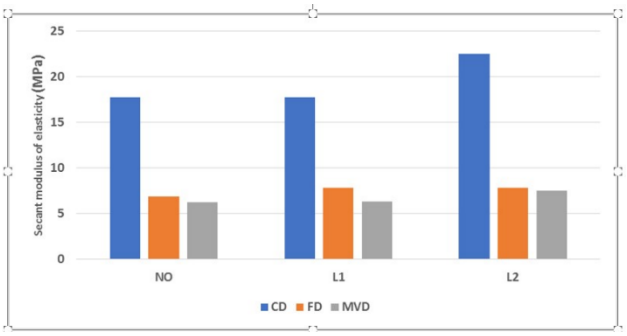

Fig. 3. Secant modulus at rupture of dried apple samples pre-impregnated under vacuum and dried using convective drying (CD), freeze drying (FD) and microwave–vacuum drying (MVD), determined from the stress–strain response at the failure point.

3.4.3. Rupture work density

The rupture work density (w), calculated as the rupture work normalized by the initial gauge volume, is shown in Figure 4 and summarized in Table 3. Normalization enabled a geometry-independent comparison of the energy absorption capacity of the samples.

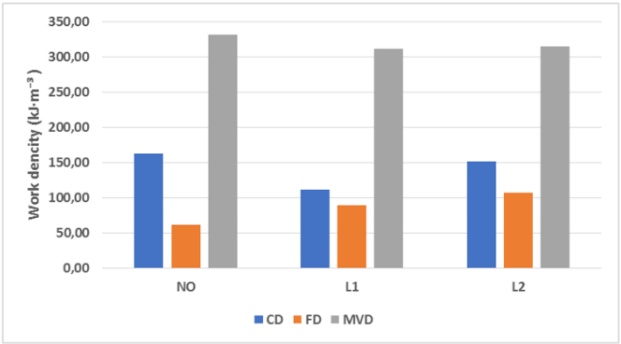

Fig. 4. Rupture work density of dried apple samples pre-impregnated under vacuum and dried using convective drying (CD), freeze drying (FD) and microwave–vacuum drying (MVD), calculated as the rupture work normalized by the initial gauge volume.

Rupture work density ranged from 61.6 to 330.6 kJ·m^{-3}. Microwave–vacuum–dried samples exhibited the highest energy absorption capacity per unit volume, with w values exceeding 300 kJ·m^{-3} for all impregnation variants. Convectively dried samples showed intermediate rupture work density values (111.1–162.1 kJ·m^{-3}), whereas freeze-dried samples exhibited the lowest values (61.6–106.7 kJ·m^{-3}).

3.4.4. Combined mechanical response at rupture

The combined analysis of stress–strain behavior, apparent secant modulus at rupture and rupture work density (Figure 2–4), together with the numerical values summarized in Table 3, demonstrates that the drying method governs not only the strength and stiffness but also the energy absorption mechanisms of dried apple samples.

Convectively dried samples exhibited the highest tensile stress and apparent secant modulus at rupture, combined with the lowest strain values, confirming a stiff and brittle mechanical response. Freeze-dried samples showed consistently lower stress, stiffness and rupture work density, indicating mechanically weak structures with limited resistance to tensile loading. In contrast, microwave–vacuum–dried samples combined moderate tensile stress and apparent stiffness with substantially higher strain at rupture and the highest rupture work density, reflecting an enhanced ability to absorb mechanical energy and mechanically resilient behavior under tensile loading.

4. Conclusions

In summary, the presented research results indicate a positive effect of vacuum impregnation of apple slices in a green tea infusion enriched with honey and elderflower juice on drying effects, as evaluated based on selected physicochemical parameters and drying kinetics. The samples obtained through CD, MVD, and FD processed by VI were characterized by low moisture content and water activity, ensuring high storage stability. The application of preliminary impregnation resulted in a beneficial shortening of the dehydration process in all experimental variants.

Vacuum-impregnated apple chips differed in colour from non-impregnated ones, exhibiting higher contributions of red and yellow hues, which is a positive effect as it enhances the sensory attractiveness of the product. The observed increase in crispness of pre-impregnated dried samples may also indicate the potential applicability of VI using the proposed solutions to improve both the sensory appeal and the nutritional quality of dried apple snacks.

The drying method significantly influenced the tensile behavior of dried apple samples. Convective drying resulted in stiff and strong but brittle structures, freeze drying produced mechanically weak materials with low stiffness and energy absorption, whereas microwave–vacuum drying yielded samples with moderate stiffness but markedly higher deformation capacity and the highest rupture work density. Normalization of rupture work by the initial gauge volume enabled a geometry-independent comparison and clearly distinguished the mechanical resilience of microwave–vacuum–dried samples from the other drying methods.

References

[1] Tiwari P., Joshi A., Thakur M.: Vacuum impregnation – a novel nondestructive technique for the development of functional foods. In: Emerging Technologies in Food Science, 2020, 3, 187–199. DOI: 10.1007/978-981-15-2556-8_16.

[2] Corrêa J.L.G., Pereira L.M., Vieira G.S., Hubinger M.D.: Mass transfer kinetics of pulsed vacuum osmotic dehydration of guavas. Journal of Food Engineering, 2010, 96, 498–504. DOI: 10.1016/j.jfoodeng.2009.08.032.

[3] Panarese V., Dejmek P., Rocculi P., Gomez-Galindo F.: Microscopic studies providing insight into the mechanisms of mass transfer in vacuum impregnation. Innovative Food Science & Emerging Technologies, 2013, 18, 169–176. https://doi.org/10.1016/j.ifset.2013.01.008

[4] Fito P.: Modelling of vacuum osmotic dehydration of food. Journal of Food Engineering, 1994, 22, 313–328. DOI: 10.1016/0260-8774(94)90040-X.

[5] Zhao Y., Xie J.: Practical applications of vacuum impregnation in fruit and vegetable processing. Trends in Food Science & Technology, 2004, 15, 434–451. DOI: 10.1016/j.tifs.2004.01.008.

[6] de Lima M.M., Tribuzi G., de Souza J.A.R., de Souza I.G., Laurindo J.B., Carciofi,B.A.M.: Vacuum impregnation and drying of calcium-fortified pineapple snacks. LWT – Food Science and Technology, 2016, 72, 501–509. https://doi.org/10.1016/j.lwt.2016.05.016

[7] Contreras C., Martin M.E., Martinez-Navarrete N., Chiralt A.: Effect of vacuum impregnation and microwave application on structural changes occurring during air-drying of apple. LWT – Food Science and Technology, 2005, 38, 471–477. DOI: 10.1016/j.lwt.2004.06.017.

[8] Koc B., Eren I., Ertekin F.K.: Modelling bulk density, porosity and shrinkage of quince during drying: the effect of drying method. Journal of Food Engineering, 2008, 85, 340–349. DOI: 10.1016/j.jfoodeng.2007.07.029.
[9] Kręcisz M, Klemens M, Kolniak-Ostek J, Stępień B, Combrzyński M, Latański A. Antioxidant Capacity, Volatile Profile, and Physical Properties Changes of Kohlrabi Treated with Onion and Beetroot Juices Using Vacuum Impregnation Process. Molecules. 2025; 30(17):3563. https://doi.org/10.3390/molecules30173563
[10] Pasławska M., Nawirska-Olszańska A., Stępień B., Klim A.: The influence of vacuum impregnation on nutritional properties of fluidized-bed dried kale (*Brassica oleracea* L. var. *Acephala*) leaves. Molecules, 2018, 23(11), 2764. DOI: 10.3390/molecules23112764.
[11] Jałoszyński K., Szarycz M., Jarosz B.: Wpływ suszenia konwekcyjnego i mikrofalowo-podciśnieniowego na zachowanie związków aromatycznych w pietruszce naciowej (in Polish). Agricultural Eng, 2006, *10*(12 (87), Wrocław, s. 209-215.
[12] Jałoszyński K., Szarycz M., Surma M., Stępień B., Pasławska M.: Analiza suszenia mikrofalowo-próżniowego owoców róży dzikiej (in Polish). Agricultural Eng, 2010, 14, Wrocław, s. 223-228.
[13] ASAE Standard: Moisture content content measurement – Grain and seeds. *ASAE S361.1*, 1986.
[14]Kręcisz M., Stępień B., Pasławska M., Popłoński J., Dulak K.: Physicochemical and quality properties of dried courgette slices: impact of vacuum impregnation and drying methods. Molecules, 2021, 26(15), 4597. DOI: 10.3390/molecules26154597.
[15]Sutar P.P., Prasad S.: Modeling microwave vacuum drying kinetics and moisture content content diffusivity of carrot slices. Drying Technology, 2007, 25, 1695–1702. DOI: 10.1080/07373930701590956.
[16]Adiyaman P., Kanchana S., Mahendran P.P.: Development and stability of bio-food colour from beetroot by spray drying. Carpathian Journal of Food Science and Technology, 2012, 4(2), 63–73.
[17]Stropek Z., Gołacki K.: Method applied to compare stress relaxation curves for various plant materials (in Polish). Agricultural Engineering, 2006, 12, 473–479.
[18] Wiktor A., Łuczywek K., Witrowa-Rajchert D., Hankus M., Królikowski K.: Mathematical modeling of microwave-assisted convective drying of oregano leaves. Advances of Agricultural Sciences: Problems and Issues, 2013, 573, 61–73.
[19] Pasławska M., Stępień B., Nawirska-Olszańska A., Maślankowski R., Rydzak L.: Effect of vacuum impregnation on drying kinetics and selected quality factors of apple cubes. International Journal of Food Engineering, 2017, 13(1), 1–16. DOI: 10.1515/ijfe-2016-0309.
[20] Blanda G., Cerretani L., Bendini A., Cardinali A., Scarpellini A., Lercker G.: Effect of vacuum impregnation on the phenolic content of *Granny Smith* and *Stark Delicious* frozen apples. European Food Research and Technology, 2008, 226, 1229–1237. DOI: 10.1007/s00217-007-0643-9.