Dielectric properties of deformed early potatoes

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Abstract: The permittivity of potato tissue was studied during uniaxial compression of cylindrical specimens prepared from two early varieties. Both the real and the imaginary permitivity components were determined repeatedly during the loading and unloading tests. The analysis of the results obtained shows that small differences exist between the permittivity of the late and early potato varieties. The differences are concentrated mainly at frequencies higher than 1 kHz with a maximum between 10 and 100 kHz. The effect of deformation is concentrated into frequencies between 1 and 100 kHz. The effect of deformation on the permittivity values can be divided into reversible and irreversible parts. The results obtained in the loading/unloading tests give some more information on the proportion of both parts.

Keywords: soft plant tissue; conductivity; permittivity; frequency; deformation; reversibility

The deformation of agricultural products changes their internal structure (Dejmek & Miywaki 2002). The main change in this process is the loss of water due to the squeezing out of the cellular sap. The water content can be detected also by means of electric conductivity measured at different frequencies (Nelson & Trabelsi 2005). In biological materials, the water content is usually responsible for the permittivity-frequency spectral character in these materials (Kaatze 2005; Pissis 2005). The electromagnetic waves are used frequently in many disciplines of food science and food technology. At present, the most frequent is the use of the microwave heating for cooking and baking of food products (Wilson *et al.* 2002; Vollmer 2004). The main advantage of the microwave cooking consists in quickness of the whole operation because the cooking proceeds continuously in the whole volume of the approximately homogeneous body cooked. The alternate electric power can be understood as low-frequency electromagnetic waves penetrating the specimen tested.

Complex relative permittivity is the parameter that rationalises the interaction of electromagnetic waves with bodies. It contains information either on electrical conductivity of the body (by imaginary part of the complex relative permittivity) or on the real permittivity (by real part of the complex relative permittivity) (Nelson & Trabelsi 2005). For this reason, the relative permittivity is studied so frequently in the complex form (Venkatesch & Raghavan 2004) and many special instruments for the dielectric measurements were developed (Venkatesch & Raghavan 2005).

The impedance measurements of the real capacitor are the basis for the determination of the material dielectric properties at low frequencies (e.g. Blahovec & Million 1985; Sobotka *et al.* 2006; Blahovec & Sobotka 2007; Krejčí 2007). This paper deals with the measurements of complex relative permittivity in potato cylindrical specimens deformed uniaxially in loading/unloading test.

METHOD OF TESTING

The varieties Adora and Impala cultivated in the same standard conditions were tested in June 2007. The harvested tubers were transported from the field directly to the laboratory and were subsequently stored in a refrigerator for one to three days at (7 ± 1)°C. On the day preceding the test, the tubers were washed in cold water and then 20 defect-free tubers of mediate size (5 to 8 cm in diameter) were selected for one day testing. All tubers of one variety were tested on the same day.

One specimen of cylindrical shape (approximately 15 mm in diameter and 20 mm in height) was cut from the central part of each tuber so that its axis

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was parallel to the stem-bud axis and the pith of the tuber was excluded preferably. A cork borer and special double knives were used for this purpose. After a more precise determination of the specimen size, the specimen was deformed axially by compression in the loading/unloading test with the deformation rate of 0.0167 mm/s up to the strain of 10%. The mechanical tests were performed in a testing machine Instron® 4464. The compression metallic isolated plates served at the same time as electrodes for a continual two point impedance measurement of the specimen tested. The measurement was based on three AC voltages determined by three 34401A Agillent digital multimeters in the net with serial connection of the Agillent Generator 33220A with signal 10 V, stable Ohmic resistor (220 Ω) and the tested sample. The generator frequency sequence of 0.1, 0.5, 1, 5, 10, 50, 100, 500 kHz was used periodically, and for each frequency the above mentioned voltage data were stored. The whole process was controlled by a computer using the Agillent software VEE, version 7. The data from the mechanical part of the test (time, displacement, and force) were recorded every 0.1 s, the data in the electrical part (time, frequency, and the corresponding three voltages) were recorded every 1 s. The collected data were recalculated by a special Fortran programme. The data were based on the direct electrical measurements, the corresponding mechanical values were interpolated from the rich data samplings available. The corresponding strain (ε_i) and stress (σ_i) values were the basic data in mechanical tests and further calculations. The true (Hencky's) strain and stress were used systematically (Blahovec & Sobotka 2007).

In every test, the hysteresis losses (*HL*) and the degree of elasticity (*DE*) were also calculated using the following formulas:

$$HL = \frac{W_L - W_U}{W_L} \tag{1a}$$

$$DE = 1 - \frac{d_r}{d_m} \tag{1b}$$

where:
W_L and W_U – respective loading and unloading deformation works
d_m and d_r – maximum and residual deformation, respectively

The complex impedance Z of the specimen (Sobotka *et al.* 2007) served as a basis for the calculation of dielectric properties. The relative permittivity ε_r of the potato tissue is then calculated as:

$$\varepsilon_r' = -\operatorname{Im}\left(\frac{1}{Z}\right) A \tag{2a}$$

$$\varepsilon_r'' = \operatorname{Re}\left(\frac{1}{Z}\right) A \tag{2b}$$

$$A = \frac{1}{2\pi f \varepsilon_0} \times \frac{l_0}{S_0}\,(1 - \varepsilon_j)^2 \tag{2c}$$

(2b)

where:
ε_r' and ε_r'' – respectively, the real and the imaginary part of the complex tissue relative permittivity
f – signal frequency
ε_0 – vacuum permittivity
l_0 – initial specimen length
S_0 – initial specimen cross section

The term in brackets in Eq. (2c) represents the corrections of the changes of the dimensions of the deformed specimen, i.e. the changes of its length and cross section.

RESULTS AND DISCUSSION

Mechanical test

The basic parameters of the mechanical test (Blahovec & Sobotka 2007) are given in Table 1. The data published previously for Nicola and Saturna are also included in this table for comparison. The table shows that the basic mechanical data with the early varieties are very similar to those obtained previously for the late varieties.

Table 1. The basic mechanical characteristics of the loading/unloading test (MV – mean value, *CV* – coefficient of variation, *n* = 20); data for Nicola and Saturna (Blahovec & Sobotka 2007) are given for comparison

	Modulus of elasticity		Hysteresis losses		Degree of elasticity	
	MV	*CV*	MV	*CV*	MV	*CV*
Impala	2.50	23.7	0.378	8.2	0.622	5.0
Adora	2.40	25.9	0.411	8.4	0.589	5.9
Nicola	3.33	25.9	0.392	6.6	0.608	4.3
Saturna	2.67	17.6	0.418	10.6	0.582	7.6

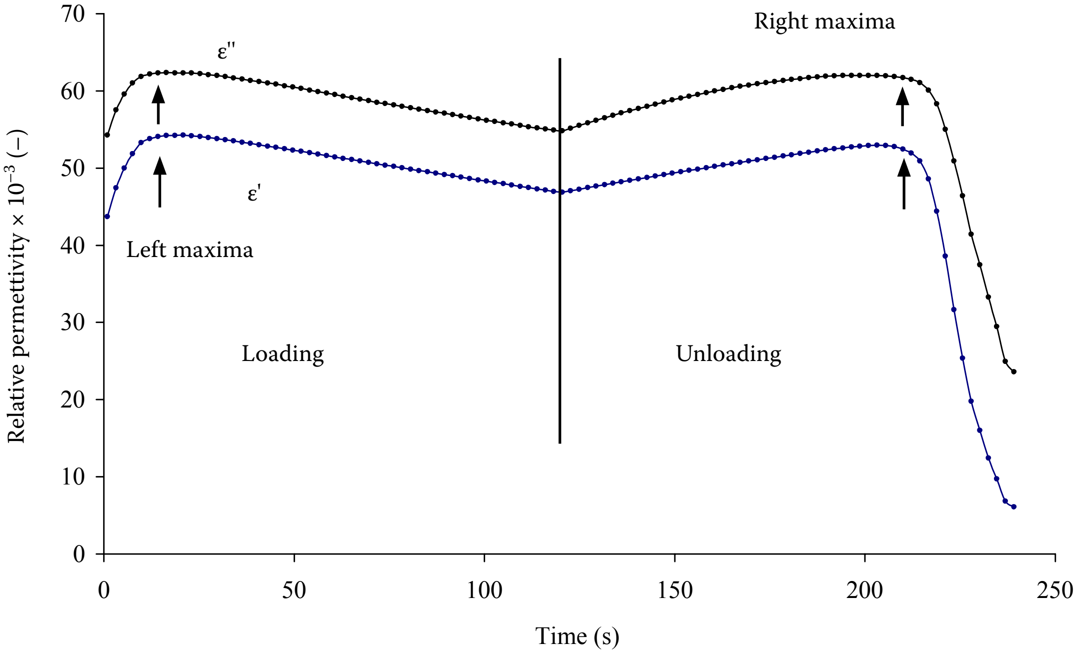


Figure 1. Typical results obtained in one test for the real (ε') and imaginary (ε") parts of the relative permittivity in the unloading (left part)/unloading (right part) tests (Nicola, 10 kHz); the graph represents plot in time in which strain increases in the loading part and decreases in the unloading part; the maxima of the plots are connected with the time development of contact between specimen and the electric circuit

Electrical data

Both permittivity parts (real and imaginary) decrease with increasing frequency, similarly as it was observed previously with late potatoes deformed in February (Blahovec & Sobotka 2007). This is why we will give our results via some relative change in relation to some basic value. The effect of a variety is given as a relative difference in relation to the results obtained for the variety Nicola. The data are given here as the values measured in maxima (see Figure 1) appeared just when the specimen is going into the full contact (left maximum) and at the time when the full contact of the specimen with the electric circuit is lost (right maximum). The effect of deformation is given as a relative change of the measured values during the specimen deformation.

Differences between different varieties

The relative difference between the values measured with a variety and the corresponding results obtained with Nicola are expressed usually by the following formula:

$$x_i = \frac{X_i - X_n}{X_n} \quad (3)$$

where:

x_i – relative difference between parameter X_i measured with variety i and the same parameter measured with variety Nicola (X_n)

Figure 2 shows that the greatest difference between Nicola and the other varieties lies at the lowest frequencies. It means that, at the frequency of 0.1 kHz, the real part of the permittivity is about 40% higher than in the other varieties, and in the case of the imaginary part this difference is different for different varieties and varies between 20 and 40%. With increasing frequency, the difference decreases similarly in both maxima. This decrease is greater at low frequencies for the real part of the permittivity whereas for the imaginary part the decrease is slow at low frequencies while a steeper decrease is observed at frequencies from 10 to 100 kHz. In the real part of permittivity, the highest relative difference was observed with Saturna whereas the early variety Impala is closer to the Nicola values in the whole range analysed. Adora real part of permittivity is less than the corresponding values of Nicola at frequencies higher than 1 kHz.

The imaginary part of the permittivity of Saturna is higher than the corresponding value of Nicola, even if this difference slowly decreases with increasing frequency. With both early varieties, the relative difference in the imaginary part of the permittivity is higher than in Saturna at frequencies lower than 10 kHz. At higher frequencies, the relative difference decreases sharply, and in the case of Adora, the sharper decrease leads to negative values of the relative difference in the range of hundreds of kHz.

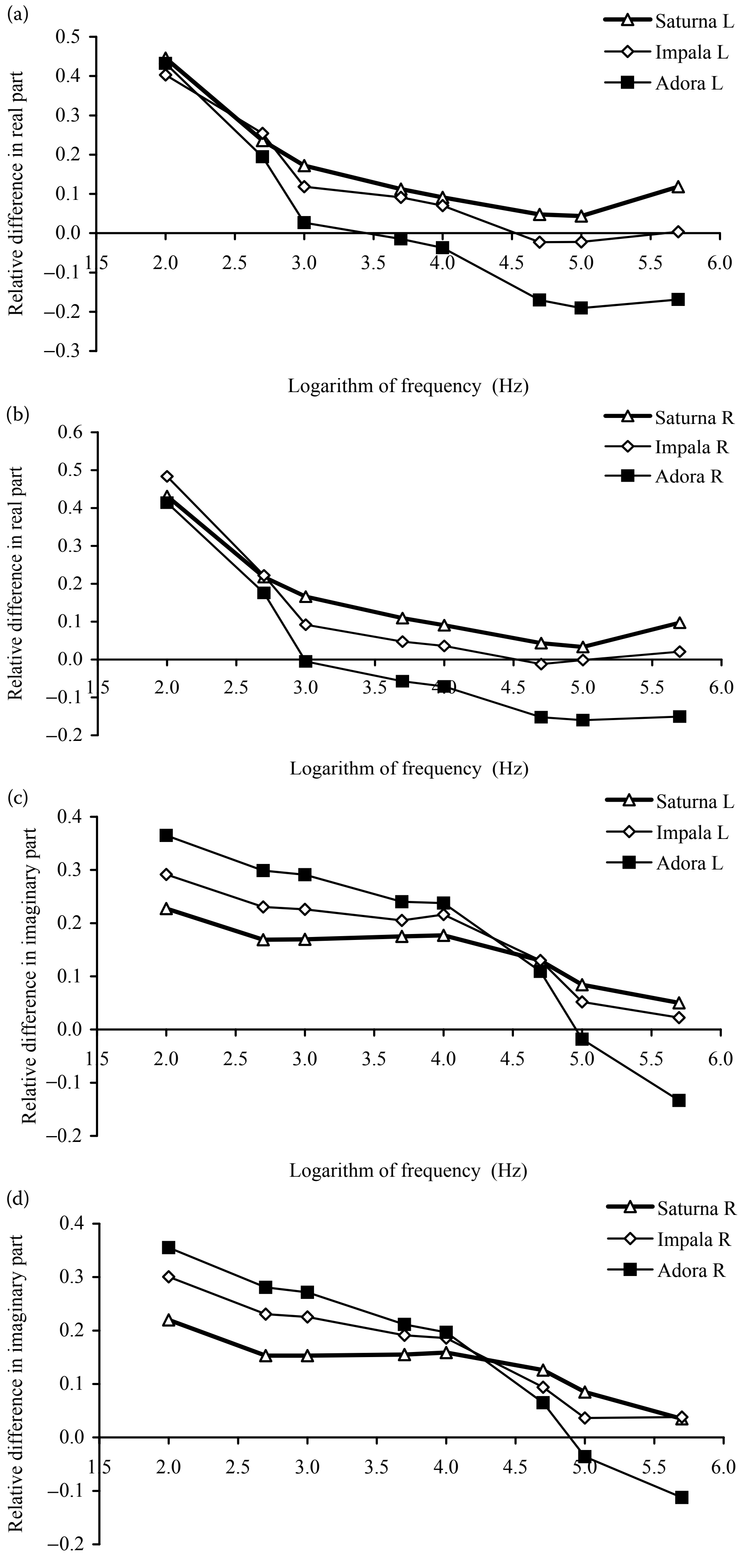
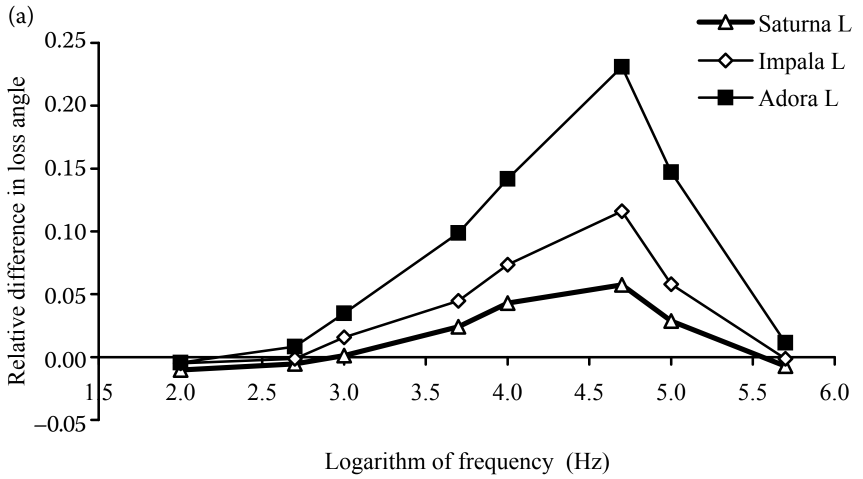


Figure 2. Relative difference between permittivity of the measured varieties and corresponding permittivity of Nicola (see Eq. (3)) measured in local maxima described in Figure 1; (a) real part of permittivity in the left maxima, (b) real part of permittivity in the right maxima, (c) imaginary part of permittivity in the left maxima, (d) imaginary part of permittivity in the right maxima; all data are plotted versus frequency



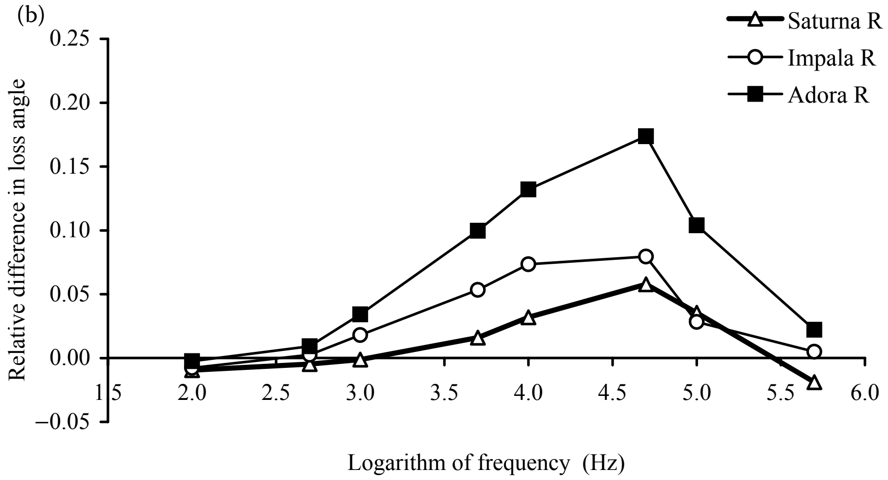


Figure 3. Relative difference between the loss angle of the measured varieties and the corresponding loss angle of Nicola (see Eq. (3)) measured in local maxima described in Figure 1; (a) real part of the permittivity in the left maxima, (b) real part of the permittivity in the right maxima; all data are plotted versus frequency

Table 2. Position and values of loss angle minima from Figure 4 determined by the approximation of the data by cubic polynomial

Variety	Minimum of loss angle	
	position (kHz)	value (radian)
Impala	79.9	0.667
Adora	89.8	0.722
Nicola	59.6	0.608
Saturna	66.2	0.636

More information can be obtained from relative differences in the loss angle φ calculated as follows (e.g. Dekker 1957):

$$\phi = \tan^{-1}\frac{\varepsilon''}{\varepsilon'} \tag{4}$$

The differences in the loss angle calculated using Eq. (3) are given in Figure 3. The data in Figure 3 are related to the maxima calculated for the real part of permittivity. The loss angle calculated for maxima

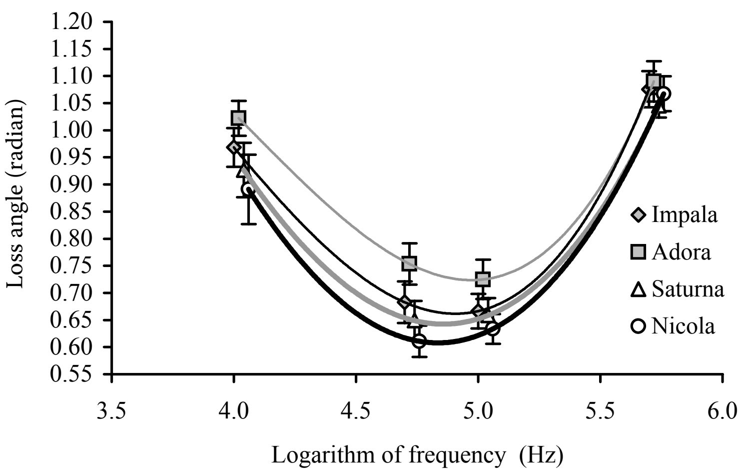


Figure 4. The loss angle plotted versus logarithm of frequency for early(Impala and Adora) and late (Nicola and Saturna – Blahovec & Sobotka 2007) varieties given at maximum deformation. The data are limited to frequencies 10–500 kHz. The data are approximated by cubic polynomial.

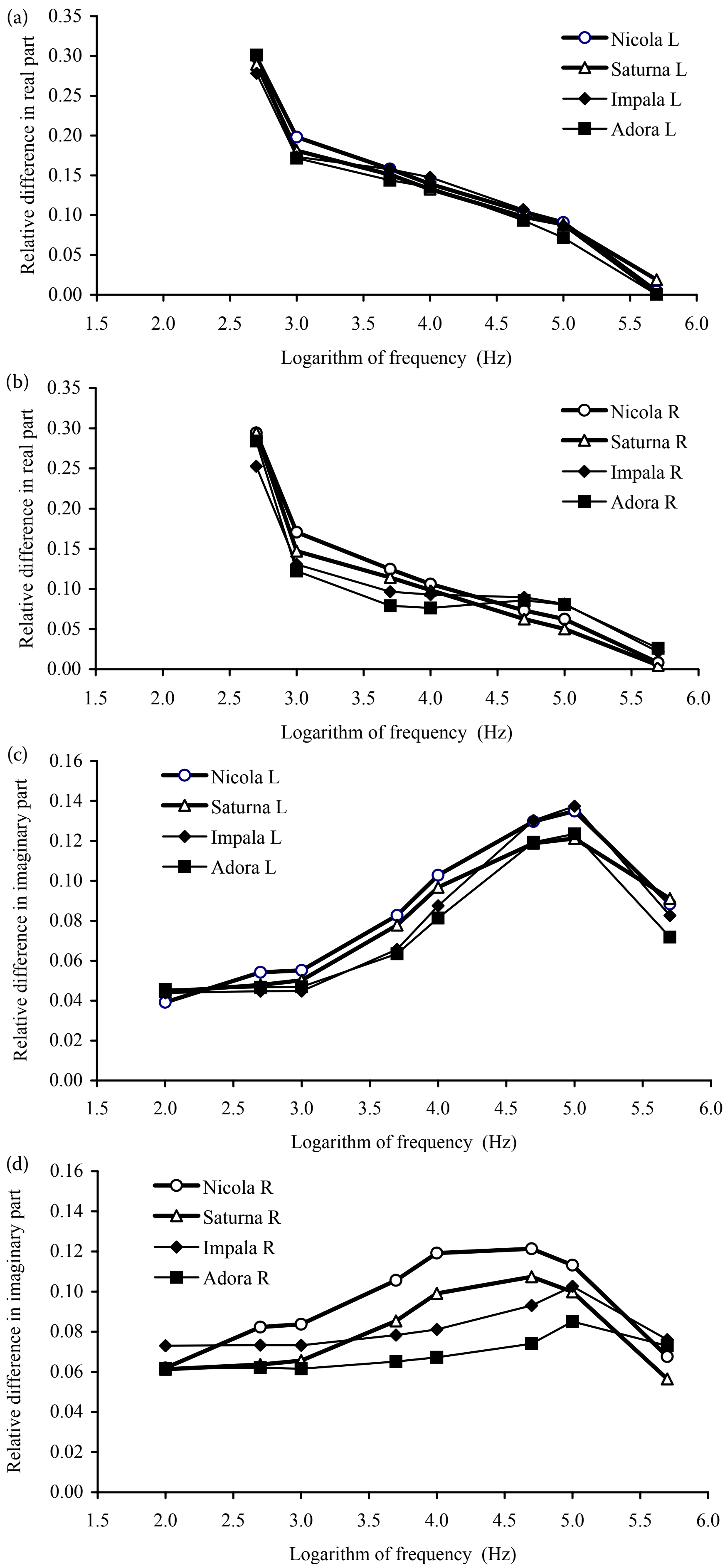


Figure 5. Relative difference between permittivity maxima and its corresponding value at the highest deformation plotted against the current frequency: (a) real part and the left maximum, (b) real part and the right maximum, (c) imaginary part and the left maximum, (d) imaginary part and the right maximum

of the imaginary part of permittivity gave results very similar to those in Figure 3. Figure 3 shows that the greatest differences between the varieties lie at frequencies between 1 and 500 kHz. This range of frequencies corresponds to a minimum of the loss angle plotted against frequency as described in Figure 4 for the state of maximum specimen deformation. The data in the figure were approximated by cubic parabolas as a basis for the determination of the plots minima. The results of the analysis are given in Table 2. This figure shows that a lower minimum value is followed also by its location at lower frequencies. The lowest values of both quantities were observed with Nicola and the increasing values were then obtained in the sequence: Saturna, Impala, Adora. Both the early varieties (Impala and Adora) had higher values of the minimum parameters than were the corresponding values of the later varieties (Nicola and Saturna).

Change of permittivity due to deformation

Both parts of the relative permittivity decreased with increasing loading and the observed decreases were at least partly reversible during the unloading parts of the test (Figure 1). A great part of the relative permittivity changes during deformation is of linear character (Figure 1) but some parts, especially those ones close to the maxima, should be classified as nonlinear ones. The information about the relative decrease of permittivity during the loading period is given here via the relative difference between the maximum value (left or right) and the minimal value reached at the maximum deformation. The quantity is then expressed as:

$$x = \frac{X_m - X_d}{X_m} \qquad (5)$$

where:

x – relative difference of the quantity X

X_m and X_d – quantity values in the quantity maximum and in the state of maximum deformation, respectively

The results of the analysis for both parts of permittivity are presented in Figure 5. The relative difference of the permittivity real part decreases with increasing current frequency from about 30% at 0.1 kHz to nearly zero at 500 kHz. The decrease is very similar with all the varieties tested. For the right maxima (i.e. for the unloading state), data similar to those measured prior to loading were obtained. For the imaginary part of permittivity, different results were obtained. The relative difference increases in a large part of the frequency range with increasing frequency, and only at

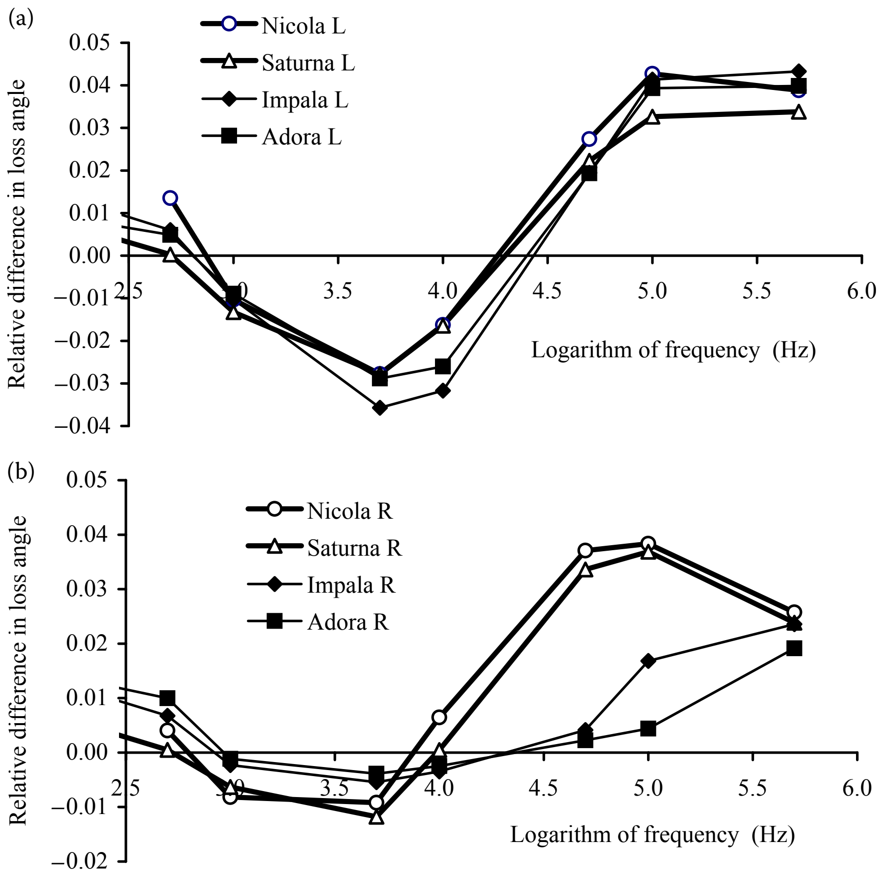


Figure 6. Relative difference between the loss angle in the permittivity maxima and the corresponding loss angle at the highest deformation plotted against the current frequency: (a) left maximum, (b) right maximum

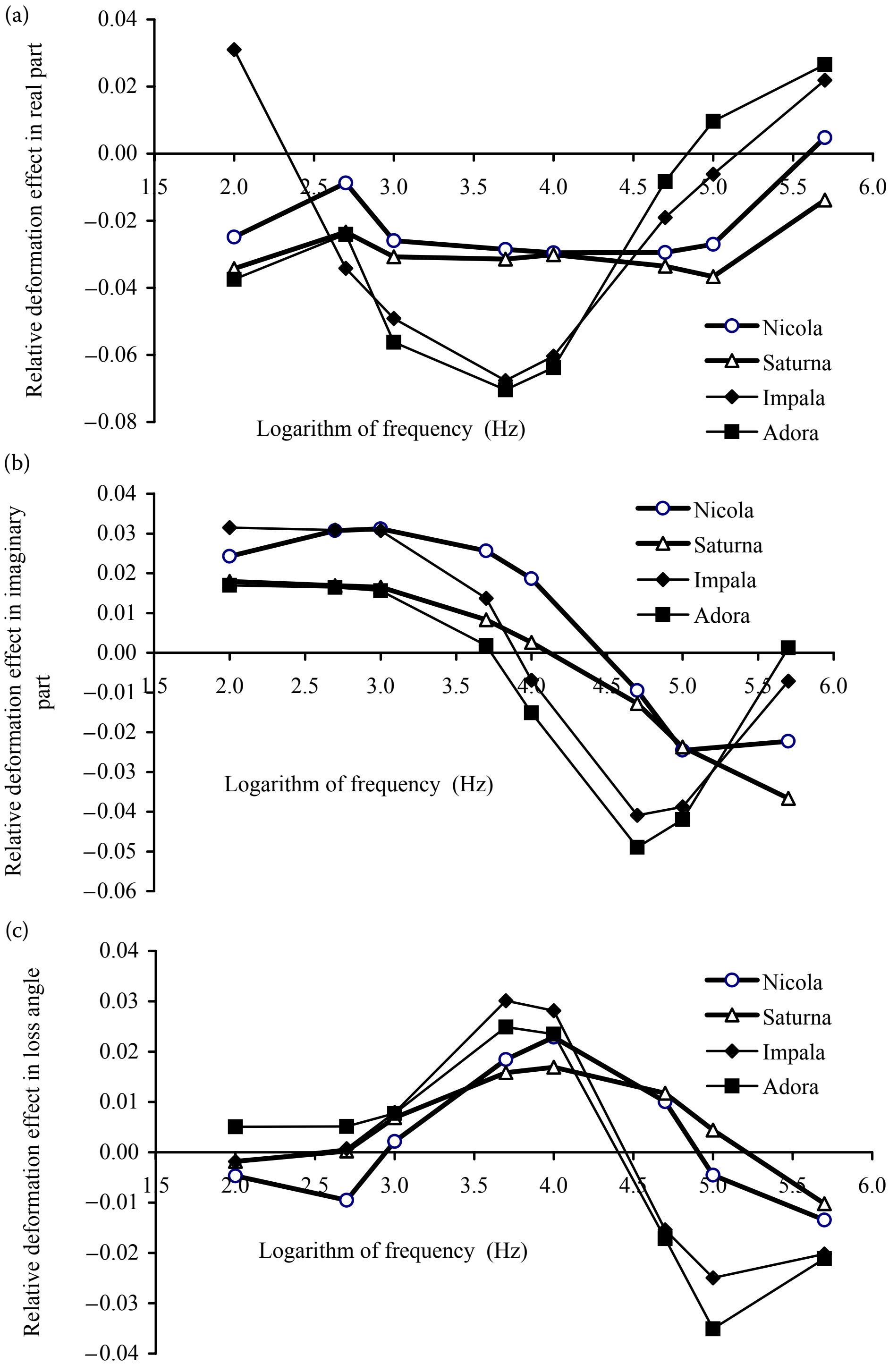


Figure 7. Relative irreversible effect of the deformation process on the permittivity quantities plotted against the current frequency; the effect value was calculated as a ratio of the difference of the right and left quantity maxima (see Figure 1) divided by the left maximum; (a) real part of permittivity, (b) imaginary part of permittivity, (c) loss angle

frequencies higher than 50 kHz some decrease was indicated. Moreover, the relative differences relating to the right maximum behave a little differently than the ones determined relating to the left minimum in some cases (compare Figure 5c and d). The differences between the different varieties are also higher in this case than those ones obtained in the real permittivity part.

Information about the relative change of the loss angle is given in Figure 6. The figure shows that the relative differences represent only, a few percents in this case; being negative in the kHz range and positive at frequencies above 10 kHz. Some additional effects were observed in the right maximum, i.e. in the unloading part of the test. Different results were observed in this part for different varieties. The positive values at frequencies higher than 10 kHz are strongly reduced in early potato varieties Impala and Adora. It seems that the relative changes of the loss angle could be the parameter that can be used as an indication of some differences between the properties of the tubers tested.

The resultant irreversible effect of the deformation cycle was determined by the relative difference of the calculated quantities in both maxima (left and right). The effects are plotted in Figure 7: the real part of the relative permittivity in Figure 7a, the imaginary part of the relative permittivity in Figure 7 b, and the loss angle in Figure 7c. The results are very variable even if they differ by less than only few percent. The results do not have the same sign, thus positive and negative values were observed in different parts of the spectrum. Most data for "the effect" in the real part of the real permittivity are negative, but also in this case some positive values were observed at higher frequencies, especially in the case of the early potatoes. Figure 7a indicates that the real part of permittivity decreased a little in most cases (especially in the late varieties), but this decrease is not the same over the whole frequency range and in some cases, especially at high frequencies, the real part of permittivity increased. Figure 7b indicates that the imaginary part of permittivity increased during the loading/unloading test at lower frequencies (lower than approximately 10 kHz) whereas at higher frequencies it rather decrease. The loss angle rather increased during the loading/unloading test, especially at the medium frequencies of 1–100 kHz. Outside this frequency range, the effect was either very low and/or opposite. The effect of variety is visible in this case but it is not yet clear.

CONCLUSIONS

The potato varieties can be classified on the basis of the loss angle; especially in the range between 10 and 1000 kHz where typical minimum is observed. Direct position of the minimum as well as the loss angle is variety-variable, giving higher values of both data with early varieties than with late varieties. The deformation of the tuber is followed by a decrease in both parts of permittivity; the real part is most sensitive to the deformation at lower frequencies, the imaginary part is most sensitive to the deformation at frequencies close to 100 kHz. Special properties of different varieties influence mainly the unloading branch of the loading process. The same can be concluded in relation to the loss angle. The irreversible effect of the loading/unloading process on the permittivity variables is not monotonic and fully clear either up to now.

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Abstrakt

Blahovec J. (2008): **Dielektrické vlastnosti deformovaných brambor.** Res. Agr. Eng., **54**: 113–122.

Permitivita bramboru byla studována během prosté tlakové zkoušky cylindrických vzorků připravených z hlíz dvou raných odrůd. Obě – reálná a imaginární – složky byly opakovaně určovány během zatěžovacího a odtěžovacího testu. Analýza získaných výsledků ukazuje, že existují malé rozdíly mezi permitivitou pozdních a raných brambor. Tyto rozdíly se pozorují při frekvencích vyšších než 1 kHz a jsou koncentrovány do oblasti mezi 10 a 100 kHz. Probíhající deformace ovlivňuje měřené veličiny zejména v oblasti 1–100 kHz. Vliv deformace na hodnoty permitivity může být rozdělen na vratnou a nevratnou část. Výsledky získané v zatěžovacích a odtěžovacích testech dávají prvotní informace o zastoupení obou těchto částí.

Klíčová slova: měkké rostlinné pletivo; permitivita; frekvence; deformace; vratnost

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