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The Effect of Pectin Branching on the Textural and Swelling Properties of Gel Beads Obtained during Continuous External Gelation Process

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Abstract: The aim of the study was to produce gel beads under continuous conditions. Pectins obtained from black and red currants and commercial apple pectin were used as the material. For the production of gel beads, a self-designed device was used. The designed device allows for the production of gel beads in a continuous process, the properties of which are similar to those obtained in the classic, batch process. Thanks to the device, it is possible to obtain a repeatable product while reducing the workload. The produced gel beads were tested for water absorption and textural properties. The water absorption of the obtained gel capsules is strongly influenced by the pectin chain structure. Pectin beads obtained from currant pectins have a less hard structure and are more sensitive to deformation than those from apple pectin. Shorter and more branched chains of currant pectin than apple pectin form gels with a delicate structure, which strongly absorbs water, and unlike apple pectin gel, it disintegrates. The results show that the use of raw material obtained from different sources allows for obtaining products with various properties, using the same method; moreover, the used device is fully scalable and can be used in large scale.

Keywords: continuous process device; external gelation; redcurrant; blackcurrant; gel beads; swelling

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1. Introduction

Pectins are a group of ionic polysaccharides with high average molecular weight. Their unique properties are determined by a specific chain structure consisting of linear *smooth regions* (homogalacturonan) and highly branched *hairy regions* (rhamnogalacturonan I and II). Homogalacturonan is a linear polymer of uronic acid, whose acid residues can be esterified to varying degrees, while rhamnogalacturonan I and II are highly branched regions that consist of a uronic acid backbone with a variety of glycan side chains (Figure 1) [1].

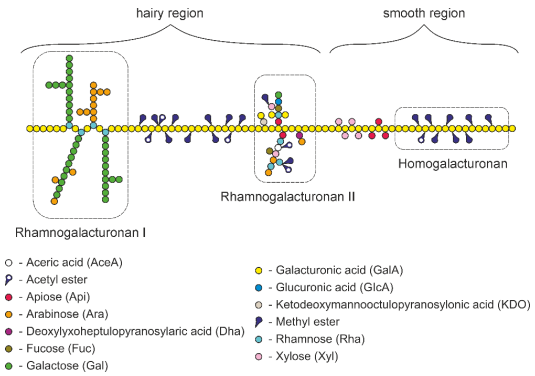

Figure 1. Scheme of the general structure of pectins (based on [1]).

Average molecular mas of pectin range from 150 kDa to 1020 kDa, and depends both on the botanical origin and the isolation method. Due to the specific structure of the chain, these polysaccharides are able to form gels, which strength is determined by the average molecular weight, galacturonic acid content, chain structure as well as the degree of substitution of acid groups [2]. According to studies [3] the gelation is due to the association of sequences of galacturonate residues for pectin, which are linked di-axially along the chain. The presence of non-esterified acid residues promotes gelling in the presence of divalent ions, e.g., Ca^{2+}, which results in the formation of the structure described by the egg-box model [2–5]. In the case of pectins with an average molecular mass above 300 kDa, the formed gels are characterized by a dense, compact structure, which determines their high mechanical strength, including breaking strength [6,7]. The presence of simple sugars in the branched structure of pectins may negatively affect gelation, they constitute a hindrance to the formation of bonds between acid residues and Ca^{2+} ions [8]. The degree of esterification of acid residues (DM) has a strong influence on the gelling capacity of pectins. Pectins with low DM (DM < 50%) most often form gels of high hardness, due to their ability to interact with divalent ions [2,5].

Ionotropic gelation involves the cross-lining of chains with divalent ions. The process may be carried out in two ways: internal or external gelation [2]. Internal gelation consists of mixing a polymer solution with a slightly soluble salt; this mixture is then acidified in order to gradually release calcium ions, and gelling occurs in the entire volume of the mixture [5,9,10]. On the other hand, in the external gelation process, a polymer solution is added (usually dropwise) to a solution containing easily soluble calcium salts (e.g., calcium chloride); due to the high availability of calcium ions, gelation occurs almost immediately [4,7,11–14]. The external gelation method allows to obtain a stronger gel with a more compact structure than internal gelation; moreover, it occurs much faster, and therefore it is used in the production of small particles, gel beads, while internal gelation is used to produce gels with larger dimensions [2,10]. Ionotropic gelation offers wide possibilities of use in various branches of industry; therefore, it is interesting both to search for new sources of raw material that can be used and to develop the possibility of the efficient use of the method on a large scale. So far, most of the researchers have focused on the gelation of low-methylated pectins derived from citrus fruits and apples. The rheological and swelling properties of gels obtained through the internal gelation of pectins with citrus fruits with the following characteristics were investigated: DM = 38%, weight average molecular weight 317–387 kDa [10]. The work of Lootens et al. [9] presents the effect of temperature and concentration of Ca^{2+} ions on the gelling ability of pectins (Mw = 200 kDa) with a low degree of esterification (DM = 27%) and amidated (DM = 28.7% and DA = 18%) as well as the rheological properties of these gels. In the work of Secchi et al. [15], the internal and external gelling of pectins with DM = 38% (Mw = 317 kDa) was investigated with the use of photon correlation imaging (PCI), dynamic light scattering (DLS) and measurements of rheological properties. Jantrawut et al. [16] investigated the effect of the texture of gels obtained from low methylated pectins (DM = 30% DA = 0% and DM = 25% and DA = 21%) using external and internal gelation on the release rate of rutin from calcium pectinate beads. On the other hand, the influence of process parameters, such as the concentration of pectin solution and the rate of dripping into the solution on selected properties of calcium pectinate bead, is presented in the work of Lee et al. [11]. The authors of the study performed dimensionless number analysis using Reynolds (Re) and Ohnersorg (Oh) numbers and determined the basic relationship between them. Low methylated pectins with DM = 27–33% and DA = 20–25% were tested. Zhao et al. [14] studied the influence of the molecular structure of apple (Mw = 427 kDa, DM = 28%) and citrus (Mw = 435 kDa, DM = 24%) pectins on their gelling and morphological properties using external gelation process. In the work of Gunter et al. [7], water absorption (swelling) of beads obtained from low-methylated pectins obtained from *Lemna minor* L. and *Tanacetum vulgare* L. and commercial apple pectin (Mw = 401 kDa, DM = 36–44%) were investigated. The isolated pectins were characterized by DM = 4–25%, and the values of their weight

average molecular mass varied in the range from 138 kDa to 500 kDa, linearity R1 = 3.4–14.3 and branching R3 = 6.9–13.3, while analogous parameters determined for commercial pectin apple juice were R1 = 13.0 and R3 = 2.0.

The gelling of high-methylated pectins is less described in the literature [12,13,17]. One of the few articles is the publication [17] in which the molecular characterization of pectin isolated from *Silene tatarica* L. It was found that this pectin is characterized by DM = 73.7%, with an average weight molecular weight of 425 kDa, R1 = 5.8 R3 = 12.9. The gelation of solutions of this pectin was investigated with the use of external gelation as well as swelling properties in gastric, intestinal and colonic conditions. Vityazev et al. [13] investigated the external gelation of apple pectin with DM = 43% (Mw = 401 kDa) and 82% (Mw = 506 kDa) in the presence of glycerol as well as the swelling properties and texture of beads. The study by Popov et al. [12] presents the results of research on the swelling of pectin beads obtained during the external gelling of apple pectin with DM = 43% and Mw = 401 kDa. The analysis of the literature shows that there are no reports describing the textural and swelling properties of gels obtained on the basis of pectins obtained from red and black currants using a continuous external gelation process.

2. Materials and Methods

2.1. Materials

The pectin was isolated from black and red currant fruits, using water extraction. Thawed fruits were homogenized and mixed with distilled water; after an appropriate time, the mixture was filtered to obtain a clear filtrate. The pectins were precipitated from the solution using acetone, then filtered off and dried, according to the method described in [18]. Their physicochemical properties were previously described in refs. [18,19]. Commercial apple pectin, with DE = 59% (Pektowin Jasło) was used as comparative material. Other chemicals were of analytical grade.

2.2. Preparation of Gel Capsules

Gel capsules were prepared using the external gelling method with the help of the experimental stand presented in Figure 2a–c. The device consists of a body and a screw conveyor, with crosslinking solution flow realized in the counter current in order to maintain a constant concentration of Ca^{2+} ions. The pectin solutions of concentrations 1.5, 3 and 4.5% for apple pectin, 3% for red currant and 1.5% for black currant pectin were added dropwise (using 1.8 mm inner diameter nozzle) to the 1% calcium carbonate crosslinking solution and held for 60 s; the process was carried out at room temperature. Then the gel beads were washed with deionized water. The flow rate trough the nozzle was 4 mL·min^{-1}, and the distance from the nozzle to the calcium chloride surface was 4 cm. Process parameters were selected based on previous experience. The beads were measured and weighed directly before further analysis.

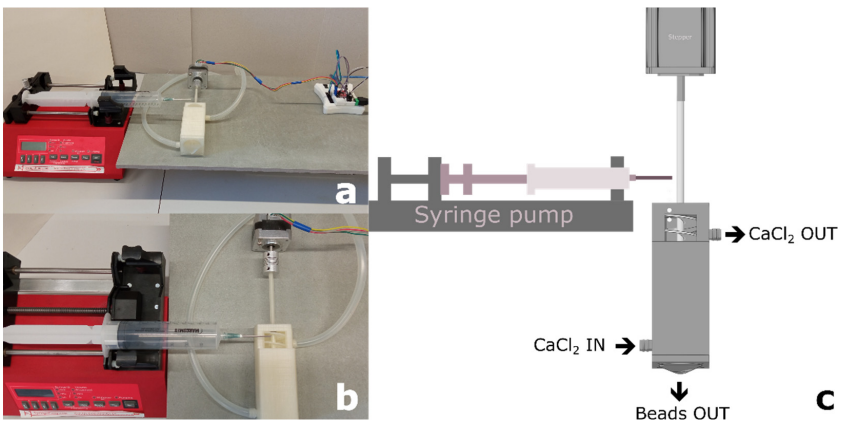

Figure 2. Photo of the prototype (**a**,**b**) and schematic diagram (**c**) of experimental stand.

2.3. Water Absorption (Swelling)

The gel capsules were immersed in a constant volume of deionized water for 210 min. At 5 min intervals, the capsules were pulled out and subjected to a weight test. The amount of water absorbed was determined as the difference between the weight of the sample and the starting sample after the lapse of time. The swelling ratio W_i was calculated as the ratio of the weight of absorbed water per gram of primary sample:

$$W_i = \frac{m_i - m_0}{m_0} \left[\frac{g_{H_2O}}{g_{gel}} \right] \quad (1)$$

m_i is the weight [g] of the swollen gel bead at time t_i, and m_0 is the initial bead weight [g]. All determinations were performed in at least three replications.

Changes in swelling properties were described by two kinetic models of $W(t)$ dependence on time. The first one is a simple model presented in [20]:

$$W(t) = \frac{k_1 \cdot t}{(1 + K \cdot t)^a} \quad (2)$$

The estimated parameters (k_1, K) can be interpreted as a water-swelling rate constant (k_1 [$g_{H2O} \cdot (g_{gel} \cdot min)^{-1}$]) describing the increase in water amount in gel per minute and K as a water diffusion resistance constant [min^{-1}]. This model was successful fitted to the $W(t_i)$ data obtained for 4.5% and 3% apple pectin gel. With the 1.5% apple pectin as well as red (3.0%) and black (1.5%) currant gels, the swelling ratio dependence on time showed a maximum of W_i. It required a modification of fitted model to the form

$$K = K_0 \cdot e^{K \cdot t_i} \quad (3)$$

In this case K constant was affected by the time of swelling.

The estimation process was carried out with the help of the Marquardt–Levenberg method. The target function was described by the following equation:

$$\chi^2 = \sum_{i=1}^{n} \left\{ W_i - \frac{k_1 \cdot t_i}{[1 + K_0 \cdot e^{K \cdot t_i}]} \right\} \underset{k_1, K_0, K \geq 0}{\rightarrow} min \quad (4)$$

2.4. Instrumental Texture Profile Analysis (ITPA)

The texture characteristics of the produced pectin beads were measured using a texture analyzer SHIMAZU EZ Test EZ-LX (Shimadzu Scientific Instruments, Kyoto, Japan) with high-precision load cell with a maximum capacity of 5 N. A two-cycle compression test (a classical texture profile analysis, TPA), with an aluminum cylindrical press jig (ϕ = 36 mm, height = 40 mm) was performed in 10 repetitions for each system at 20 °C. The measurements were conducted on a single sphere with a diameter of 3.5 mm. A 50% compression with a jig movement speed of 0.5 $mm \cdot s^{-1}$ in both cycles of experiment was applied. A relaxation time between first and second compression was 5 s. Results of tests were recorded as raw data in a form time (s), force (N) and displacement (mm). These parameters were used to calculate the texture characteristics: hardness, adhesiveness, springiness, cohesiveness, gumminess.

2.5. Statistical Analysis

A one-way analysis of variance and the HSD-Tukey test was carried out as further analysis (post-hoc analysis) in the case of texture parameters. The significance level was p = 0.05. Statistical analysis was carried out using package R [21].

3. Results and Discussion

Most often, researchers using external gelation use manual periodic devices to make gel beads [6,12–14]. Manually producing beads is associated with the possibility of a

manufacturing error related to the lack of repeatability during the dropwise addition of the agent to the cross-linking solution. Moreover, their possible subsequent production on an industrial scale is cumbersome and time consuming. To avoid the influence of the human factor during processing and provide the possibility of the effective, automated production of gel beads, a prototype device was designed. The device consists of a body and a screw conveyor, the regulated rotations of which allow to adjust the residence time of the medium drop in the cross-linking solution. The $CaCl_2$ flow is realized by the body of device in the counter current by means of a peristaltic pump, from an external reservoir, in order to maintain a constant concentration of Ca^{2+} ions. The polysaccharide solution is added using a needle attached to a syringe pump that allows flow rate control. The device is scalable and can be used both on a laboratory and industrial scale.

The low flow rate used in the needle means that the influence of the viscosity of the pectin solutions has only a slight impact on the formation of the beads. The surface tension, which for all solutions is close to the surface tension of water, is responsible for the formation of the spherical shape of the beads. For this reason, the device made it possible to obtain repeatable pectin spheres in terms of shape and size. Commercial apple pectin was selected as the reference material, and spheres were made from aqueous apple pectin solutions of three concentrations in order to enable the comparison of properties with the tested material. For the currant pectin, concentrations were selected that would allow for obtaining similar dimensions of spheres so that their properties could be compared with the reference material. For all pectin solutions obtained, the gel spheres were approximately 3.50 ± 0.32 mm in size and they were gelatinized throughout the entire volume. The properties of the obtained gel beads were consistent with those produced using the batch method.

Red currant pectin is characterized by an average molecular weight of 1020 kg·mol^{-1} [19], which is almost 9 times higher than blackcurrant pectin (115 kg·mol^{-1}) [18] and significantly lower than an average molar weight of a commercial apple pectin 1576 kg·mol^{-1} (Table 1) [22]. Additionally, the aqueous fractions of pectin extracted from both currants contain a lot of simple sugars, the composition of which indicates strong branching, especially in the case of blackcurrant pectin (Table 1) [18]. The chain structure strongly influences the hydrodynamic properties of the biopolymer, especially the water-binding capacity and strength of the gel formed [6–8], which is reflected in the results obtained from the water absorption and texture test.

Table 1. Molar masses and chain properties of pectin from different sources [18,19,22].

Pectin	M_w kg·mol^{-1}	M_n kg·mol^{-1}	Dp	R1	R3	c* g·dL^{-1}
Red currant	1020	53	273	2.27	1.03	0.78
Black currant	115.78	24	124	1.50	8.77	0.43
Apple	1576	81	5730	1.44	1.58	1.5

Dp—degree of polymerization, R1—chain linearity, R3—chain branching.

3.1. Water Absorption

The phenomenon of swelling of the gel beads was tested for 210 min. Obtained results are presented in a graph (Figure 3). In all cases, swelling to the maximum value was observed, while in the case of the lowest concentration of apple pectin gel (1.5%) and pectin gels obtained from black and red currants, after reaching the maximum value of Wi, they decreased rapidly over time. The highest increase in absorbed water was found for the 4.5% apple pectin gel.

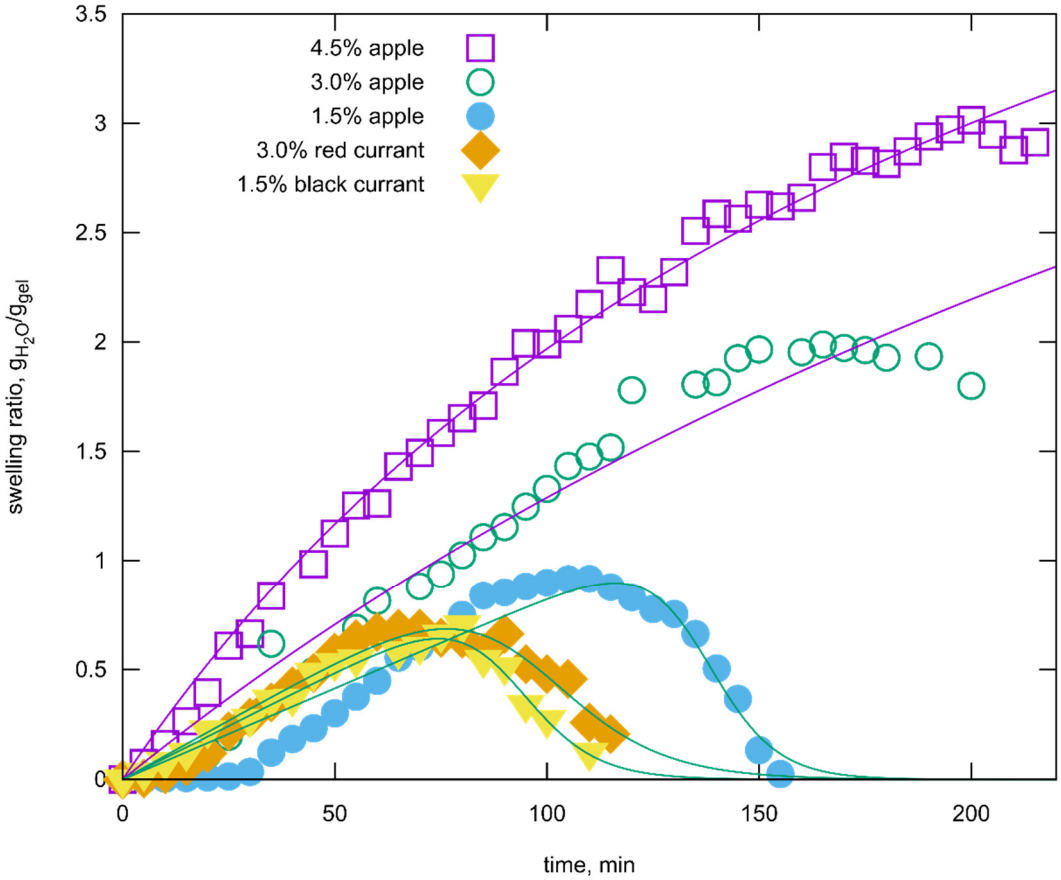

Figure 3. Swelling of gel beads in distilled water.

The rate constant k_1 reached the value of 0.028 $g_{H2O} \cdot (g_{gel} \cdot min)^{-1}$ and it can be understood as the increase in the mass of absorbed water in each minute of the experiment (Table 2). The lower value of this coefficient describes the swelling rate of 3.0% gel of the same pectin, which obviously corresponds to the lower water absorption intensity (Figure 3). The values of the inhibition constant are low, which indicates a constant diffusion resistance in the gel over this time interval. The *K* value for the 3% gel is lower in comparison to 4.5%, which reflects the difference in the gel structure, probably resulting from the concentration of the pectin solution. In both cases, the concentration of the external gelling solution is above the first critical concentration (c*), which means that the external gelation solutions are classified as semi-dilute. Moreover, the changes in $W(t)$ are characteristic for water-absorbing gels until the equilibrium value is obtained [13,16,17]. In the case of a gel obtained from a 1.5% solution, which corresponds to the first critical concentration, the dynamics of the water absorption phenomenon changes: in the tested time period, a maximum appears on the $W(t)$ curve. For this reason, the kinetic model describing the swelling phenomenon is also changing: the resistance constant *K* changes as a function of time. Due to the low initial rate of water absorption, the rate constant k_1 = 0.0080 $g_{H2O} \cdot (g_{gel} \cdot min)^{-1}$, while *K* has a high value of 0.1260 min^{-1}.

Table 2. Swelling properties of beads prepared from pectins obtained from different sources.

Pectin	C %	m_0 g	$k_1 g_{H2O}$ $(g_{gel} \cdot min)^{-1}$	K min^{-1}	K_0	χ^2	d mm
Red currant	3.0	0.3051 ± 0.0145	0.0110 ± 0.0005	0.0792 ± 0.0103	4.6×10^{-4}	3.06×10^{-1}	3.50 ± 0.32
Black currant	1.5	0.2305 ± 0.0124	0.9750 ± 0.0375	0.1170 ± 0.0153	2.2×10^{-5}	3.44×10^{-1}	
Apple	1.5	0.1305 ± 0.0012	0.0080 ± 0.0038	0.1260 ± 0.0844	3.1×10^{-8}	1.79×10^{-1}	
	3.0	0.1410 ± 0.0041	0.0156 ± 0.0012	0.0021 ± 0.0007		6.80×10^{-1}	
	4.5	0.1454 ± 0.0032	0.0280 ± 0.0008	0.0045 ± 0.0003		2.87×10^{-1}	

A similar pattern of the absorption process was observed for gels obtained from pectins extracted from black and red currants. In both cases, gels were obtained from solutions with a concentration higher than the first critical concentration, which is 0.78 $g \cdot dL^{-1}$ for red currant pectin and 0.43 $g \cdot dL^{-1}$ for black currant pectin (Table 1). First of all, it can be observed that, in the studied time period, the $W(t)$ values are generally lower as compared to the apple pectin gel. The exception is the first hour of the experiment, during which the initial values of the rates are similar to those obtained for the 3% apple pectin gel and greater than those determined for 1.5%. After one hour, the maximum for W_t is observed, which means that the gel beads are fully saturated with water; after it is reached, these values decrease, and the beads disintegrate. This phenomenon was also observed by Moreira et al. [10] who investigated the swelling of 2% citrus pectin gels (DM = 38%) and Popov et al. [12] for 1.5% gels and 2% of apple pectin swelling in distilled water. In the case of the 3% red currant gel, the behavior of which in the first hour of the experiment is consistent with the 3% apple pectin gel, the k_1 rate constant is 0.0110 $g_{H2O} \cdot (g_{gel} \cdot min)^{-1}$, whereas the 1.5% black currant pectin gel in the first 20 min of the experiment absorbs water at a rate similar to 4.5% of the apple pectin gel.

The reasons for the differences in the ability to absorb water can be found in the molecular structure of tested pectins. The amount of absorbed water is primarily determined by the degree of esterification (DM): the smaller it is, the greater the ability to absorb water [16]. The degree of polymerization (Dp) as well as linearity (R1) and branching (R3) of pectic chain are of no less importance. All tested pectins were characterized by a high DM > 50%, and therefore special attention should be paid to Dp, R1 and R3 (Table 1). The highest Dp value was found in commercial apple pectin (5730), followed by red currant pectin (273) and finally black currant pectin (124). With a similar degree of esterification (DM = 59%, 57%, 67%), it means that the apparent concentration of unesterified galacturonic acid residues was the highest in the case of apple pectin, which mainly determined the high water absorption capacity of 3% and 4.5% gels for this pectin. Another important parameter is the degree of chain branching (R3), the highest value of this parameter was obtained for blackcurrant pectin. This value determines the nature of polymer–water and polymer–polymer interactions [18] in solutions below the overlap concentration (c*) and gives a view of the behavior in the range of semi-dilute concentrations. The ability to absorb water, characteristic of non-esterified groups of galacturonic acid, is screened by the presence of neutral sugars that create steric hindrances. Based on the results of measurements from NMR and membrane osmometry [18,19], for both red and black currant pectin, water–pectin interactions are not preferred, even in diluted solutions, and this phenomenon is exacerbated in the semi-dilute regime [23].

3.2. Texture

Hardness is a textural parameter defined as a maximum value of force measured during the first compression cycle (simulating first bite) [24]. Textural studies carried out with the use of the texture profile analysis (TPA) showed that spheres obtained with the use of an apple pectin solution with a concentration of 4.5% were characterized by the highest hardness, 1.8516 ± 0.0151 N. The lowest values of this attribute were noticed in the case of beads produced using solutions of black and red currants with a concentration of 1.5

and 3.0%, respectively (Table 3). The increase in apple pectin concentration results in an increase in the hardness of beads. Gel beads obtained on the basis of the blackcurrant pectin solution were soft. The mean hardness was 0.0648 ± 0.0012 N, and it was 10 times lower compared with apple pectin spheres obtained from solution of the same concentration, 0.6469 ± 0.0499 N. The use of a 3.0% redcurrant pectin solution resulted in a gel with 17 times lower hardness than gel from an apple pectin solution of the same concentration. The values of this parameter are influenced by the molar mass of the polysaccharides used in the form of pectin. It was shown that the higher molecular weight of pectin results in faster gelling velocity and increases the gel strength [6,25]. These observations are consistent with ours. Black and red currant pectin have a lower molecular weight than apple pectin (Table 1). The obtained values of hardness of currant pectin beads are an order of magnitude lower than in the case of the production of coffee caviar with sodium alginate. On the other hand, the values obtained for apple pectins oscillate around similar values [26]. Vityazev et al. presented similar results of hardness using apple pectin for the gel beads production in the external gelation process with Ca^{2+} ions [13]. Comparable values of this parameter were also obtained in the case of amidated low-methoxyl pectin beads with Lb. casei [27].

Table 3. Texture parameters.

Texture Attributes *	Apple 1.5%	Apple 3.0%	Apple 4.5%	Black Currant 1.5%	Red Currant 3.0%
Hardness, N	0.6469 ^{c} ± 0.0532	1.2581 ^{b} ± 0.0286	1.8516 ^{a} ± 0.0151	0.0648 ^{d} ± 0.0012	0.0746 ^{d} ± 0.0020
Cohesiveness, -	0.6840 ^{a} ± 0.0499	0.4694 ^{b} ± 0.0469	0.6622 ^{a} ± 0.0229	0.2560 ^{c} ± 0.0189	0.3808 ^{d} ± 0.0339
Springiness, -	0.6577 ^{c} ± 0.0739	0.4327 ^{d} ± 0.0450	0.7215 ^{c} ± 0.064	1.2150 ^{a} ± 0.0908	1.1295 ^{b} ± 0.1291
Gumminess, N	0.4869 ^{c} ± 0.0508	0.6201 ^{b} ± 0.0048	1.2196 ^{a} ± 0.0304	0.0172 ^{d} ± 0.0017	0.0300 ^{d} ± 0.0013
Adhesiveness·10^3, N·m	−0.0329 ^{b} ± 0.0034	−0.0404 ^{a} ± 0.0021	−0.0222 ^{c} ± 0.0020	−0.0014 ^{d} ± 0.0002	−0.0204 ^{c} ± 0.0032

* Mean value ± SD. Means followed by a common letter are not significantly different by the HSD-Tukey test at the 5% level of significance.

Cohesiveness is calculated as the ratio of the work performed in the second compression to the work done in the first compression. It is related to the forces of inner bond links, which maintain the predetermined shape of the product [23,24]. The obtained values of cohesiveness oscillate in the range from 0.2560 ± 0.0189 to 0.6840 ± 0.0499. Lower values were recorded for currant pectin and higher for apple pectin. This means that the gel formed by currant pectin has a lower resistance to deformation. This is a consequence of the characteristic structure of their chains, which have numerous branches [18,19]. It was shown that the presence of simple sugars may have a negative effect on the gelling process in the presence of Ca^{2+} ions [4,8]. The value of this parameter is also influenced by the molecular weight. Shorter and more branched chains of currant pectin than apple pectin form gels with a delicate structure. The obtained results are lower compared to the data presented by other authors [27]. This shows the wide possibilities of creating individual textural properties by using pectin extracted from various sources.

Springiness in the case of currant pectins had a value greater than one. This means that the first compression is followed by irreversible deformation of the sample. This behavior indicates that the structure of the formed gel is unstable such that the viscous properties dominate over the elastic properties. The structure of the formed gel is not able to store a large amount of energy and dissipates it, which results in its disintegration. Such observations indicate that the gelling process of the currant pectin leads to the formation of a gel structure softer than the apple pectin gel. The Ca-dependent gelation of pectin is based on the binding between pectin and Ca^{2+}. Therefore, branched chains can negatively affect the gelation process [8]. Obtained values of springiness indicate that apple pectin gel from a 4.5% pectin solution has the greatest flexibility.

Gumminess is defined as the energy required to break a semisolid food into fragments until it is ready to swallow [24]. The beads produced with the use of currant pectin were characterized by very low values of this parameter, with 0.0172 and 0.0300 for black and red currant pectin beads, respectively (the differences in the values are not statistically significant). The highest value was noticed for apple pectin gel produced from 4.5% solution of pectin. The differences in the value of this parameter in the case of the used pectin type indicate that these pectins will generate varied sensory feelings.

Adhesiveness is calculated as the negative force area of the first compression measure during TPA test. It represents the work necessary to pull the compressing plunger away from the sample [24]. In fact, adhesiveness can be defined as the force required to separate the food bite that sticks to the teeth during grinding food in the mouth [28]. The obtained values oscillated in the field from 0.0014×10^{-3} to 0.0404×10^{-3} J, respectively, for the blackcurrant pectin and apple pectin beads. Low adhesion values indicate that the obtained pectin beads are a product with a fine texture. For this reason, the sensory sensations generated while eating them will be similar to those experienced when consuming semi-solid food with low viscosity, e.g., yogurt [29].

The analysis of textural properties, especially hardness and cohesiveness, completes the discussion of gels properties. These two parameters characterizing the strength properties of the gel and its internal consistency confirm the observations made so far. Apple pectin gel beads are characterized by the highest hardness; moreover, they are the most internally coherent. In combination with a high affinity to the aqueous solvent (the values of the second virial coefficient B2 [22]) and the highest Dp value, it is indicated that the produced gels are characterized by a compact and durable gel structure, easily absorbing water up to the equilibrium water content without disintegration of the gel bead. The different behavior of black and red currant pectin gels can be explained by the low values of cohesiveness, and very low hardness values (over 10 times lower than in the case of apple pectin gel), which may be the cause of the tendency to disintegrate the beads.

4. Conclusions

The use of the continuous method of pectin beads production allows to obtain a product with repeatable properties, compatible with those obtained in batch processes, but with less human work. The gel beads made of blackcurrant pectin had the highest value of the water swelling ratio, which means that they absorb water the fastest among the tested gels. Currant pectin gels degrade faster due to water absorption compared to apple pectin gels. This is the effect of the high chain branching of currant pectins which hinders the diffusion of Ca^{2+} ions. Not only the molar mass and concentration, but also the branching of the chain affects the water absorption of the pectin gel. The gel beads obtained from currant pectins are characterized by a significantly lower hardness, which indicates their lower mechanical strength, and therefore a more delicate structure compared to apple pectin gel beads with the same pectin concentration. The water absorption and texture characteristic indicate that the structure of the gel formed from currant pectins differs from that of commercial apple pectin gel. Springiness values indicate degradation of the gel after first compression, which means that in currant pectin beads, viscous behavior predominates over elastic behavior, which is caused by a large branching of the chain.

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