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Mechanical properties of *Polygonatum multiflorum* Mill. leaves after treatment with growth stimulants

Anna Ciupak, Bożena Gładyszewska, Władysław Michałek, Katarzyna Rubinowska

Anna Ciupak, Department of Physics, University of Life Sciences, Lublin, Poland

Bożena Gładyszewska, Department of Physics, University of Life Sciences, Lublin, Poland

Władysław Michałek, Department of Plant Physiology, University of Life Sciences, Lublin, Poland

Katarzyna Rubinowska, Department of Plant Physiology, University of Life Sciences, Lublin, Poland

Correspondence: Anna Ciupak, e-mail: anna.ciupak@up.lublin.pl

Abstract: Mechanical properties of leaves are important in many aspects of plant science. Because of their delicate structure, leaves are sensitive to different, potentially harmful environmental factors. The mechanical properties of leaves are important factors affecting leaf quality, longevity, susceptibility to damage and decomposition. Two growth stimulants were applied to investigate selected mechanical properties of Solomon's seal '*Variegatum*' (*Polygonatum multiflorum* Mill.) leaves, grown under field cultivation and an unheated polytunnel. The mechanical properties of leaves were assessed by measuring Young's modulus. The agents used in the treatment were Actisil Hydro Plus at the concentration of 0.4% in the first series, and Pentakeep V at the concentration of 0.04% in the second one. Foliar treatment with the stimulants was conducted six times, at weekly intervals. The control plots were sprayed with distilled water. The research was carried out between 2012 and 2014. In comparison to the test series, the respective effects of Actisil Hydro Plus and Pentakeep V on the change in Young's modulus value was more notable in plant leaves obtained from the tunnel than those

from field cultivation. Specifically, growth stimulants had more impact on the stiffness of leaves obtained from plants grown in the tunnel. Generally, plant leaves from field cultivation were stiffer than those from the tunnel.

Key words: Actisil Hydro Plus, Pentakeep V, Young's modulus, leaves.

INTRODUCTION

Ornamental plants, including cut greenery, are plants that are grown for decorative purposes. They are grown in urban green spaces, parks and backyard gardens to improve the aesthetic value of our surroundings and provide economic benefits in the horticultural trade all over the world (Riaz et al. 2002; Zaidi et al. 2016; Sajjad et al. 2017). Since ornamental plants play such an important role in our lives, there is a need to produce high quality plant material. In this context, quality requirements applicable to ornamental plants, be it intended for personal, ceremonial or commercial use, are becoming increasingly strict (Zaidi et al. 2016; Sajjad et al. 2017). For that reason, leaves should be reasonably stiff and strong to maintain mechanical stability under various stressors (Onoda et al. 2015). Due to their variety in shape, size, internal structure and even location on the plant, leaves perform different functions. During their development, they are also subjected to different environmental factors, including those causing damage. The leaves of most green plants are flat, thin and usually develop in such a way to absorb as much sunlight for photosynthesis as possible (Chabot and Hicks 1982; Read and Stokes 2006; Onoda et al. 2011). At the same time, Read and Stokes (2006) emphasize that such a horizontal arrangement of leaves on the stem increases the risk of their damage due to bending forces. Apart from static interactions, leaves are also subjected to dynamic loads such as bending, twisting or friction which are caused by abiotic factors - usually wind and atmospheric precipitation, as well as damage caused by biotic factors (insect feeding, being eaten by herbivorous animals) (Aranwela et al. 1999; Read and Sanson 2003; Read and Stokes

2006). Bearing in mind the possibility of limiting the losses in the production of plant material (leaves) and preserving their integrity, as well as the required quality and durability - referred to as "leaf life cycle"; - it is important to learn about the impact of environmental factors on the mechanical properties of leaves. Moreover, mechanical strength is not without considerable significance as in the commercial context, cut greenery is often subjected to difficult transport and storage conditions which may cause mechanical damage to the leaves.

The complex internal structure of the plant material makes it difficult to describe its strength in terms of basic physical quantities (Sitkei 1986). Despite the existing limitations, many techniques drawing on construction engineering as well as principles and equations of classical mechanics have been applied in the study of plant products (Morrow and Mohsenin 1966; Sitkei 1986; Niklas 1999; Niklas et al. 2006). As far as plant leaves are concerned, strength is determined based on three main groups of mechanical tests - the shear test, puncture test and tensile test (Aranwela et al. 1999; Read and Sanson 2003; Onoda et al. 2011). Based on these methods, Onoda et al. (2011) attempted to compare and synthesize the results of the available data concerning the mechanical properties of the leaves of almost 3000 plant species obtained from 90 locations in the world. By means of the above-mentioned tests, Read and Sanson (2003) determined the mechanical properties of the leaves of 32 plant species adapted to conditions of water scarcity (sclerophytes). Aranwela et al. (1999) conducted a series of mechanical tests on *Solanum laciniatum* leaves, thus determining the influence of the specific test parameters on leaf cracking properties. Using the puncture test, Onoda et al. (2008) attempted to explain the phenotypic changes in the mechanical properties of *Plantago major* leaves in relation to their anatomy and mass balance. Determining the cutting work and the force needed to tear the leaf allowed Enrico et al. (2016) to create a quantitative description of mechanical strength of the leaves of 72 plant species growing in south-eastern Australia. The researchers also focused on determining the influence of the leaf's main vein on its mechanical strength.

As for mechanical properties that characterize plant material in terms of damage resistance, Mohsenin (1986) mentions, among other elements, compressive strength, tensile and shear strength, stress relaxation as well as the determination of Young's modulus, Poisson's ratio and mechanical hysteresis.

Young's modulus (modulus of longitudinal elasticity) is the ratio of stress σ and strain ε during compressing or extending an elastic solid material. It expresses the stiffness (the resistance to deformation) of the material and gives a useful information of how easily the solid material can be contracted and stretched, and may be described mathematically by the equation:

$$E = \frac{\sigma}{\varepsilon} = \frac{F l}{S \Delta l} \quad (1)$$

Where: σ - stress (MPa), ε - strain (dimensionless), F - force acting normal to the surface (N), S - cross-sectional area (mm²), l - original length (mm), Δl - change in length (mm) (Mohsenin 1986; Fekete 1994; Bourne 2002; Brulé et al. 2016).

Due to the lack of dependence between the values and the geometrical dimensions of the samples, Young's modulus is the basic physical quantity characterizing the material in terms of mechanical properties and it is determined for small deformations obtained e.g. in the compression or tensile test. Most often, the Young's modulus is determined from the tangent of the stress-strain curve angle in its linear (elastic) part, where the stress is proportional to the deformation, and the material returns to the initial dimensions after the load ceases (Mohsenin 1986; Sitkei 1986; Sağsöz and Alayunt 2001; Burgert 2006).

The single-axial tensile test was used to determine various strength parameters of leaves; e.g. cabbage (*Brassica oleracea* L.) varieties (*Satsuki-oh*, *Satsuki-jyoooh*, *Hatsukoi*, *Irodori*, *Nakawase No. 2*, *Sweet Cabbage 007*) (Kohyama et al. 2008), lettuce (*Lactuca sativa* L. 'Saladin') (Newman et al. 2005), spinach (*Spinacia oleracea* L.) (Tang et al. 2011; Watanabe et al. 2017), chives (*Allium schoenoprasum* L.) (Pinzón et al. 2013), *Solanum laciniatum*

(Aranwela et al. 1999), as well as many grass species (*Anthoxanthum odoratum* L., *Agrostis tenuis* Sibth., *Festuca ovina* L., *Holcus lantus* L., *Deschampsia flexuosa* L.) (Wright and Illius 1995), rosemary stems (*Rosmarinus officinalis* L.) (Arévalo et al. 2013) and various thin-film plant materials (Gładyszewska 2007; Gładyszewska and Ciupak 2009; Gładyszewska and Stropek 2010; Gładyszewska et al. 2011).

In addition, the use of plant biostimulation reduces their vulnerability to biotic and abiotic stress factors, increases their resistance to pathogens and pests, strengthens tissues and cellular membranes. Actisil Hydro Plus is a liquid fertilizer, easily water-soluble, intended for fertigation and foliar fertilization of plants. The active silicon (Si) (orthosilicic acid and free silica) contained in Actisil Hydro Plus after foliar spray diffuses through cuticle and epidermis and is then stored in cell walls in leaves, what results in their thickening and increasing mechanical defense reaction (Adamiak and Hetman 2006). Silicon acts as a physical barrier and is deposited beneath the cuticle to form a cuticle-Si double layer, which can mechanically impede penetration by fungi and thereby, disrupt the infection process (Fauteux et al. 2005). The active substances of Pentakeep V is 5-aminolevulinic acid (ALA), one of the naturally occurring compound in plants which act as a chlorophyll precursor (Smoleń and Sady 2010). ALA also can stimulate the growth of photosynthesis efficiency, which can directly affect the rate of plant growth, development and productivity. In addition, ALA reduces the susceptibility of plants to water stress, thermal stress and deficiency of excess light (Watanabe et al. 2000, Youssef and Awad 2008). Si and ALA affect the vase-life of the cut plant material. Silicon influences water relations in leaves cut off from the mother plant: it induces the formation of a silica cuticle double layer under the leaf epidermis which reduces water losses through cuticular transpiration (Gong et al. 2003), Si also reduces stomatal conductance in relation to turgor loss in guard cells resulting from Si deposition and modified cell wall properties (Zhu and Gong 2014) and up-regulation of aquaporin genes (Liu et al. 2015). ALA can delay leaf senescence,

especially at suboptimal conditions, such as nitrogen shortage or environmental stresses (Wei et al. 2012). Song et al. (2008) found that ALA application to spinach seedlings during growth could promote postharvest storability, implying that ALA delayed plant senescence.

Solomon's seal (*Polygonatum multiflorum* L.) leaves were selected for mechanical tests due to the growing popularity of this perennial plant in Polish gardens. Its leafy stalks are commonly used as filler elements in floral arrangements. The structure and color of its leaves allow florists to create unique compositions and provide a viable alternative to imported cut greenery. The main advantage of Solomon's seal stems from the ease of its cultivation in a variety of weather conditions - it is suitable both for open field and tunnel cultivation. Given the above, there has been a considerable growth in the demand for this type of floral elements, which has in turn encouraged producers to seek ways of improving the quality and potentially also durability of their product.

It is important to determine the influence of the cultivation method, the additives used and the storage time on the usefulness of Solomon's shoots for floristic purposes. These environmental factors strongly affect the leaves mechanical properties, that determine the functional value of the plant. Therefore, herein we present the analysis of strength parameters.

MATERIALS AND METHODS

Plant material

Field experiments were located on the Experimental Farm 'Felin', belonging to the University of Life Sciences in Lublin (Poland N51°13'28.22", E22°37'56.3"). The experimental plant was Solomon's seal 'Variegatum' (*Polygonatum multiflorum* Mill.), mainly used for decorative greenery, which was grown in field conditions as well as in unheated foil tunnel in 2012-2014. Treatments were arranged in a completely randomized two factor design with three replications.

Six plots constituted one replication, each plot was built on six plants. Five shoots were sampled from each plant.

The first factor was unheated foil tunnel or outdoor soil (field conditions). The tunnel frame was constructed of galvanized tubular elements with dimensions: 3.5 m height, 6.4 m width, 32 m length, covered with double UV10 foil, equipped with a sun screen.

The second factor was the growth stimulator used: Actisil Hydro Plus or Pentakeep. Control plots were sprayed with distilled water. In the experiment, weeding and loosening treatments were systematically carried out. Each plant was watered using an irrigation system. On hot days, this treatment was carried out twice a day. Due to the fact that the studied plants are shade-loving, at the beginning of the vegetative period, a sun cover was extended over them to provide protection against excessive solar radiation. In the spring, plants were fertilized two times with Azofoska at the concentration of 0.3% (0.5L of solution per plant). Plant protection treatments were carried out every 10 - 14 days, using preparations against aphids and spider mites - Karate Zeon 050 CS 0.05%, Mospilan 0.01%, Magus 200 SC 0.06%. In order to protect the plants against fungal diseases, the following preparations were used interchangeably: Amistar 0.1%, Bravo 0.2%, Dithane 0.1%, Guarantor 0.2%, Rovral Flo 0.2%, Topsin 0.1%, and Previcur 607 SL at a concentration of 0.15% for watering (4-6 L solution/1 m²).

In order to increase leaf resistance to mechanical damage during cultivation, they were sprayed with a water solution of Actisil Hydro Plus and Pentakeep V. Two growth stimulants were used during the growing season of plants: Actisil Hydro Plus (Ca 20 g L⁻¹, Si 60 g L⁻¹, choline) at the concentration of 0.4% in the first series, and Pentakeep V (ALA, N - 9,5% MgO - 5,7%, B - 0,14%, Cu - 0,02%, Fe-DTPA - 0,6%, Mn - 0,23%, Mo - 0,02% and Zn - 0,16%) at the concentration of 0.04% in the second one. The concentrations of preparations used in the experiment were selected based on previously conducted test experiments, taking into account the manufacturer's recommendations. The preparations were applied using a hand sprayer (0.5

L per plant). Foliar treatment with the stimulants was conducted six times at weekly intervals. The control plots were sprayed with distilled water.

Mechanical test and sample preparation

The tests of the mechanical properties of the leaves were carried out on the tensile testing machine, utility model protected patents rights PL 66377 Y1. The Young's modulus was determined based on the authorial method, that uses image analysis of mutual positions of markers randomly placed upon the material (the random markers method) (Gładyszewska 2007). This method also makes it possible to omit boundary conditions, thus making the obtained results independent from material deformations occurring in the area of critical sections (Gładyszewska 2006).

The examination of mechanical properties of Solomon's seal leaves was conducted in the first half of July for a period of 3 years. In the first measurement (at harvest) leaves were collected from each combination and examined immediately after cutting the shoots of the plant (the single-axial stems with leaf blades embedded on them), while in the second measurement the examination took place after a week's storage of the leaves in a laboratory room, at room temperature in the normal day and night cycle (7d storage). During storage the ends of the stems were submerged in tap water changed daily.

In mechanical tests the same leaves were always selected from the shoot to be examined - two from the bottom, one from the middle, and two from the top, including the apical leaf. The leaves were cut off very carefully so as not to damage their surface. In each measurement series (control, group with the respective growth stimulator) 30 plant shoots would be analyzed, with 5 leaves collected from each as per the description above. The samples for laboratory tests were shaped like dumbbells of 50 mm in length and 20 mm in width, and they were cut out by means of a specially designed blanking die in such a way that the main leaf vein was located on the symmetry axis of the dumbbells. This method requires the provision of a third dimension

(thickness) of the sample to be cut out for examination. The measurement of this size was made in 10 places by means of a micrometer screw accurate to within 0.01 mm.

The sample was then fastened to the terminals of the testing machine and then stretched at the rate of force F accretion of 0.13 N s^{-1} . The starting point of the measurements was preceded by the application of powdered graphite markers by means of a special brush. The image of the surface of the stretched sample was transferred from the camera to the computer analyzing the appropriate changes in the distance between the points during the stretching process (Gładyszewska 2007).

The value of Young's modulus E for each sample was determined from the tangent of the rake angle of a straight line describing a single dependence $\varepsilon_x = f(\sigma)$, where:

$$\sigma = \frac{F}{S} \quad (2)$$

ε_x - deformation of the sample towards the acting force F ,

σ - tension value (MPa),

F - tensile force acting on the sample (N),

S - cross-sectional area of the sample (mm^2).

The total value of the modulus of elasticity E for a single stem was the averaged value obtained from five individual measurements. Therefore, the final value of Young's modulus in each of the studied groups (control and group with the respective growth stimulator) was the averaged result of 30 individual measurements. Data collection during the measurement and the necessary calculations to obtain the desired strength parameters were controlled by the computer program 'Videoo' (Gładyszewska and Chocyk 2004).

Statistical analysis

Statistical analysis of the results was conducted using StatSoft Inc. STATISTICA ver. 12 program (StatSoft Inc. 2016). Because in single cases the measurable variables failed to fulfill

the assumptions required for the application of parametric statistical tests, the analysis of the results was based on non-parametric tests. In order to analyze the differences in Young's modulus E between the control group and the one with an appropriate additive, as well as to determine the differences in E values depending on the year of research, cultivation area, the additive used and storage time (at harvest and 7d storage) the ANOVA signed rank Kruskal-Wallis test was used along with a median test followed by multiple comparisons of average ranks for all the assays at the significance level of $\alpha = 0.05$ (Stanisz 2006). To ascertain the correlation between Young's modulus and the research year, the cultivation area (tunnel, field), the additive used (Actisil Hydro Plus 0.4%, Pentakeep V 0.04%, control series), the storage time (at harvest and 7d storage), Spearman's coefficients R were determined.

RESULTS AND DISCUSSION

When analyzing Spearman's coefficients R , significant single-correlations were observed between Young's modulus E and each of the factors: the research year, the cultivation area (tunnel, field), the additive used (Actisil Hydro Plus 0.4%, Pentakeep V 0.04%, control series) or the storage time (at harvest and 7d storage) (data not shown).

Statistical analysis ($\alpha = 0.05$) showed differences in the values of Young's modulus (leaf stiffness) determined in the direct measurement (at harvest) for all the leaf groups under examination defined by the cultivation years in the tunnel. The leaves of the plants grown in the field and examined immediately after being collected from the plant were characterized by the absence of differences in E value between 2012 and 2014. After a week's storage leaves from tunnel cultivation, had differences in the E value in the period of 2012-2013 and 2013-2014; - while for those from field cultivation differed between the groups from the years 2012 and 2014 and those from 2013-2014 (Table 1).

The lowest value of Young's modulus (at harvest) amounting to 27.6 MPa (median) for the leaves from the tunnel and 29.4 MPa (median) for those from the field was determined in 2013 for annual shoots the leaves from the field were stiffer than those grown in the tunnel (Table 2). The seven-day storage of the stems with the leaves at room temperature caused a reduction in the E value in all the groups under examination, except for the leaves of the tunnel plants tested in 2012. In the remaining cases the leaves were less stiff in comparison with the direct measurement (at harvest) (Table 2).

Tables 3 and 4 present the average values of Young's modulus E along with the standard deviation (Table 3) and the median of Young's modulus (Table 4) of Solomon's seal leaves determined in long-term studies. Because of multiple comparisons of mean ranks for all the assays at the significance level of $\alpha = 0.05$, differences in leaves stiffness from the tunnel tested in 2012 (at harvest) were obtained between the control group and the groups with the specific additive. However, no differences in E values were observed in the groups of plants treated with Actisil Hydro Plus 0.4% and Pentakeep V 0.04% growing in the tunnel or in the field. In both cases the E value was at a similar level (Tables 3 and 4).

On the other hand, in the case of leaves obtained from field cultivation tested in 2012 through direct measurement, the value of Young's modulus was approximately twice as high as that of the leaves from the tunnel cultivation. But after a week of plant storage in laboratory conditions, the leaves from the tunnel were approximately two times stiffer than those from field cultivation (Table 4). Moreover, differences in the E value were observed in plants treated with the same additive but growing in different environments (the tunnel and the field). Over two times higher value of E was obtained for the leaves of plants from the field treated with Actisil Hydro Plus 0.4% (median value of 78.3 MPa) than for those coming from the tunnel and treated with the same preparation (median of 37.03 MPa). A nearly three times higher E value was observed in the case of the leaves treated with Pentakeep V 0.04% growing in the field (median of 78.7

MPa) in comparison to those growing in the tunnel (Table 4). In addition, after storage in laboratory conditions there were observable differences in Young's modulus relative to the control group and plants treated with the same additive but grown in different locations (field, tunnel). An over two times higher E value (median of 34.48 MPa) was obtained for the control group from the tunnel than for the group from the field. The plants treated with Actisil Hydro Plus 0.4% growing in the tunnel obtained the E value which was over twice as high as in the analogous group growing in the field. Similarly, the addition of Pentakeep V 0.04% in plants from the tunnel caused the leaves to be stiffer than those from field cultivation (Table 4).

After storage of plant leaves from the field, a clear reduction in the E value for the leaves from the control group was observed - from 80.91 MPa (direct measurement) to 15.56 MPa - after a week's storage, while for those treated with Pentakeep V 0.04% and Actisil Hydro Plus 0.4% the reduction in E value was approximately 82% and 78% respectively, as compared to the direct measurement (Table 4). There were no differences in the values of Young's modulus after the weekly storage between the control group and the plant groups treated with Actisil Hydro Plus 0.4% and Pentakeep V 0.04% growing in the field. However, varied E values were observed in the case of plant leaves from the tunnel, between the groups treated with appropriate additives (Table 4).

In the case of annual plant leaves (studies in 2013) differences in leaves stiffness in the direct test were obtained only for the plants coming from the tunnel and only between the control series and the series in which Actisil Hydro Plus 0.4% was used (Table 4). On the other hand, storage time influenced the E value for the leaves from the tunnel as well as those from the field. A reduction in E value for the control samples growing in the tunnel from 28.57 MPa (median) to 7.14 MPa (after the weekly storage). In leaves treated with Actisil Hydro Plus 0.4% the reduction was from 24.39 MPa (direct measurement) to 8.72 MPa after a week's storage. The leaves of plants from the field stored for a week in laboratory conditions obtained about

two times lower value of Young's modulus as compared to the leaves examined immediately after being collected from the mother plant (Table 4).

In the case of biennial plant leaves (studies in 2014), differences in leaves stiffness in the direct measurement occurred only between the groups of plants treated with Actisil Hydro Plus 0.4% and Pentakeep V 0.04% coming from field cultivation. The E value for those leaves after the application of Actisil Hydro Plus 0.4% amounted to 90.9 MPa and was about 30% higher than that of the leaves subjected to Pentakeep V 0.04% (Table 4). After a week's storage, the leaves from the tunnel were less stiffer than those from the field. Storage time had an influence on the E value of the leaves of the plants from the tunnel subjected to both additives, which was different from the control series. No effect of growth stimulants on the values of Young's modulus between these groups was observed (Table 4). As for leaves from the field, after a weekly storage differences in E values were noted only in the case of the controls and the leaves of the plants treated with Pentakeep V 0.04%. In all the cases, the seven-day storage time reduced the value of Young's modulus of the leaves as compared to the initial measurement (Table 4).

In addition, in the case of biennial plant leaves (direct studies in 2014) from field cultivation treated with Actisil Hydro Plus 0.4%, there were large variations in E values among the individual leaves under examination. The high value of the standard deviation in this assay resulted from the differences in stiffness of leaves No. 2, 3 and 4 (Fig. 1). As for the leaves from the field stored for seven days at room temperature, a large range of Young's modulus was obtained for those treated with Actisil Hydro Plus 0.4% (Table 3). In this case, the high value of the standard deviation was mostly influenced by leaf No. 4 with Young's modulus at 119 MPa (Fig. 2).

In comparison, Méndez-Alonzo et al. (2013) determined Young's modulus E for individual leaf structures of 27 species of shrubs growing in California (USA). In the case of whole leaves, the

E value determined in the studies mentioned above was within the range of 0.64-18.7 MPa (average of 4.2 MPa). The leaf blade obtained the E value at the level of 0.39-16.4 MPa (average of 3.9 MPa), while for the main vein Young's modulus assumed the values between 0.52 MPa and 41.1 MPa (average of 6.8 MPa). Kawai and Okada (2016) received the E value of approximately 29 MPa for *Quercus crispula* leaves, and approximately 44 MPa for *Quercus serrata* leaves. When stretching grass leaves, Balsamo et al. (2006) obtained the value of Young's modulus E at the level of GPa. Such a high value is stems from differences in leaf architecture and cell wall chemistry in monocotyledonous species and suggests that the leaf's tensile properties are strongly influenced by the level of tissue hydration (Balsamo et al. 2006). Our research shows that the stiffness of Solomon's seal leaves, intended mainly for decorative greenery, differs depending on the plant age and the cultivation location. The leaves of annual shoots were characterized by the lowest E value as compared to the other years of study. The E value of plant leaves from field cultivation was higher in comparison with those from the tunnel. The seven-day storage period of stems with their leaf blades resulted in leaf stiffness decreasing over 7 days at room temperature. The impact of Actisil Hydro Plus 0.4% or Pentakeep V 0.04% on the value of Young's modulus, in comparison with the plants from the control series, was more clearly marked in the case of the leaves from the tunnel than those from field cultivation. The basic benefit of determining the mechanical properties of leaves, including Young's modulus, is the desire to understand how, e.g. leaf strength and stiffness differ between plant varieties and ecosystems. Understanding the basics of mechanical properties of leaves is also associated with issues related to longevity of leaves, susceptibility to damage caused by herbivores and decomposition of leaves (Méndez-Alonzo et al. 2013). Therefore, plant leaves with a high Young's modulus value are better used for floristic purposes because of their stiffness and resistant to deformation. This is important to the cut greenery presented for a long time in bouquet or during transport and storage without, e.g. damage of the leaf surface.

In addition, an important feature of the Young modulus is that its value is independent of the size of the sample and leads to objective results that can be compared with the results of other plants from different ecosystems. Based on this research, the value of Young's modulus of leaves differed with the age of plants, cultivation type, storage times, growth stimulators used. Therefore, it creates the possibility to assess and compare the effectiveness of different treatments, agrotechnical treatments, choosing optimal doses of stimulators and fertilization and water and lighting conditions. Further investigation can provide some solutions and recommendation for growers.

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Table 1. Median value of Young's modulus E (MPa) of Solomon's seal leaves coming from field and tunnel cultivation, determined in subsequent years of study (at harvest) and after a seven-day storage period (7d storage).

Environment	Year		
	2012	2013	2014
Polytunnel			
at harvest	36.48 b	27.60 a	58.82 c
Field			
at harvest	80.91 b	29.41 a	70.91 b
Polytunnel			
7d storage	33.33 b	15.63 a	30.30 b
Field			
7d storage	15.56 a	16.24 a	40.00 b

Means of 3-replications - values marked with different letters (in rows) are different at $p \leq 0.05$ using the Kruskal–Wallis test by ranks.

Table 2. Median value of Young's modulus E (MPa) of Solomon's seal leaves, determined in direct measurement (at harvest) and after a seven-day storage period (7d storage).

		Year		
Environment		2012	2013	2014
Polytunnel (Tunnel)	at harvest	36.48 a	27.60 b	58.82 b
	7d storage	33.33 a	15.63 a	30.30 a
Field	at harvest	80.91 b	29.41 b	70.91 b
	7d storage	15.56 a	16.24 a	40.00 a

Means of 3-replications - values marked with different letters (in columns) are different at $p \leq 0.05$ using the Kruskal–Wallis test by ranks.

Table 3. Average values of Young's modulus E (MPa) with a standard deviation, determined for Solomon's seal leaves in long-term studies.

Environment	Year					
	2012		2013		2014	
Tunnel	At harvest	7d storage	At harvest	7d storage	At harvest	7d storage
Control	56.16±27.91 b	33.63±4.11 b	37.01±15.23 b	14.92±18.44 a	58.99±11.38 a	52.56±11.98 b
Actisil 0.4	33.10±10.60 a	41.81±8.44 c	20.63±12.29 a	18.23±18.20 a	59.53±13.78 a	20.33±10.26 a
Pentakkeep						
0.04	30.56±15.32 a	23.40±7.40 a	29.70±8.73 ab	20.98±3.86 b	56.28±7.88 a	27.72±7.23 a
Field						
Control	83.53±15.46 a	15.92±4.27 a	28.30±9.18 a	13.39±4.75 a	75.06±25.82 ab	45.98±9.97 b
Actisil 0.4	78.03±11.80 a	17.75±8.59 a	27.96±7.07 a	15.04±9.31 ab	93.12±33.13 b	55.73±37.55 ab
Pentakkeep						
0.04	83.03±16.10 a	15.27±4.27 a	31.56±9.51 a	17.68±6.72 b	67.66±17.96 a	35.44±15.18 a

Means of 3-replications - values marked with different letters (in columns) are different at $p \leq 0.05$ using the Kruskal–Wallis test by ranks.

Table 4. Median values of Young's modulus E (MPa) of Solomon's seal leaves determined in long-term studies.

Environment	Year					
	2012		2013		2014	
Tunnel	At harvest	7d storage	At harvest	7d storage	At harvest	7d storage
Control	45.56 b	34.48 b	28.57 b	7.14 a	61.43 a	51.43 b
Actisil 0.4	37.03 a	40.00 c	24.39 a	8.72 a	58.82 a	20.41 a
Pentakkeep 0.04	27.78 a	25.03 a	28.57 ab	20.68 b	58.82 a	28.57 a
Field						
Control	80.91 a	15.56 a	27.78 a	13.36 a	66.67 ab	45.45 b
Actisil 0.4	78.30 a	16.87 a	28.33 a	16.13 ab	90.90 b	35.71 ab
Pentakkeep 0.04	78.70 a	14.29 a	34.54 a	17.80 b	66.67 a	33.33 a

Means of 3-replications - values marked with different letters (in columns) are different at $p \leq 0.05$ using the Kruskal–Wallis test by ranks.

Fig. 1. Average values of Young's modulus E (MPa) of individual Solomon's seal leaves along with standard deviation, cultivated in the field, determined in 2014 at harvest

Fig. 2. Average values of Young's modulus E (MPa) of individual Solomon's seal leaves along with standard deviation, cultivated in the field, determined in 2014 after a week of storage in laboratory conditions