

VARIABILITY OF SOME PARAMETERS IN THE LEAF GEOMETRY DESCRIPTION IN *Solanum nigrum* L.

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Abstract. The study analyzed the variability of some foliar parameters in the description of leaf geometry in *Solanum nigrum* L. 50 leaves were taken from mature plants of *Solanum nigrum* L. from the Didactic and Experimental Resort area, BUASVM Timisoara, Timis County, Romania. Randomly, 25 leaves were taken for analysis. The length (L) and width (w) parameters of the leaves were determined. The leaves were scanned and the perimeter (Per) and scanned leaf area (SLA) were determined. The fractal geometry of the leaves was evaluated by fractal analysis, and the fractal dimension (D) was determined by the box-counting method. The mean values for the foliar parameters considered were: $L=7.820\pm0.206$, $w=4.647\pm0.151$, $Per=23.273\pm0.686$, $SLA=19.266\pm0.968$, $D=1.628\pm0.007$. Very strong correlations between SLA and D ($r=0.960^{***}$) have been identified. Strong correlations were recorded between L and w ($r=0.836^{***}$), between SLA and Per ($r=0.839^{***}$), between D and Per ($r=0.820^{***}$). Moderate correlations were recorded between Per and w ($r=0.747^{***}$), between SLA and w ($r=0.733^{***}$), between D and w ($r=0.722^{***}$). Weak correlations were recorded between Per and L ($r=0.616^{**}$), between SLA and L ($r=0.570^{**}$), between D and L ($r=0.615^{**}$). In all cases, the correlations presented statistical certainty ($** p < .01$, $*** p < .001$). Regression analysis facilitated the obtaining of equations that expressed the parameters variation in the description of the studied leaves geometry ($p < 0.001$). 3D and isoquant models were obtained to describe the SLA variation in relation to L and w, and the D variation in relation to L and w, respectively in relation to L and Per. The variability of the analyzed parameters, in descending order was $CV_{SLA}=25.1231$, $CV_w=16.2707$, $CV_{Per}=14.6691$, $CV_L=13.1813$, $CV_D=2.2802$. The fractal dimension (D) was the most stable parameter, among those analyzed, for characterizing the leaf geometry in the *Solanum nigrum* L., with the lowest variability and the lowest degree of values dispersion.

Keywords: correlation, fractal dimension, leaf geometry, leaf parameters, models, variability

INTRODUCTION

Plant leaves fall into different types, shapes and sizes in relation to the plant species (subspecies, variety, etc.) (Ronellenfisch et al., 2015; Bucksch et al., 2017; Osnas et al., 2018).

Within the same species, the leaves differ in relation to the position on the plant, age, the conditions of growth and development of the plants, stress factors, spatiotemporal elements (Al Afas et al., 2007; Atherton et al., 2017; Guo et al., 2020; Li et al., 2020).

To describe and characterize the leaves of plants are used various parameters and indices that capture and express elements and anatomical, morphological, physiological, chemical, biochemical, molecular, genetic aspects of plants (Liu et al., 2019; Ren et al., 2020; Teobaldelli et al., 2020).

Morphological and physiological parameters of the leaves were studied in relation to different genotypes, but also in response of plants to eco-physiological or technological factors specific to natural or anthropogenic ecosystems (Rawashdeh and Sala, 2014; Datcu et al., 2017; Williams et al., 2017; Isaac et al., 2018; Dampney et al., 2022).

Elementary dimensional parameters (length, width) are frequently used in studies to determine leaf area, foliar indices, or other plant-specific assessments in relation to leaf treatments. Different methods are used to evaluate these parameters, from simple measurement methods to sensor-based methods and imaging analysis (Wu et al., 2018; Teobaldelli et al., 2019; Zhang, 2020; Wang et al., 2021). Some studies have comparatively evaluated other foliar parameters (eg leaf thickness, number of chloroplasts, AML, etc.) in relation to different plant species and geographical regions (Oláh et al., 1997).

Foliar biochemical parameters of vegetation, such as photosynthetic pigments (chlorophyll a, b, carotenoids), leaf area per mass, etc., were studied for the evaluation and quantification of photosynthetic processes (Du et al., 2020).

For the automation and efficiency of studies at the foliar level (eg leaf geometry, foliar surface, the degree of damage to the leaf area of diseases, pests, stress factors, etc.) models, applications and systems have been developed on different platforms (Drienovsky et al., 2017a,b; Liu et al., 2019).

Leaf parameters have been used with high accuracy for the recognition and discrimination of some plant species (Viscosi and Cardini, 2011; Mirouze et al., 2012; Zhang et al., 2017; Liu et al., 2018). Also, leaf parameters were used for digital studies and research of plants, construction of virtual plants based on the most

realistic models (Wang et al., 2013).

The present study analyzed leaf samples in *Solanum nigrum* L. based on classical leaf parameters, leaf size (L, w), perimeter (Per), scanned leaf area (SLA) and based on leaf shape, through fractal dimension (D), and highlighted the degree of variability of the parameters taken into account for the characterization of leaf geometry.

MATERIAL AND METHODS

The study took into account the analysis of the variability of some foliar parameters in the description of the leaf geometry in the species *Solanum nigrum* L.

For the study, 50 leaves were taken from mature plants of *Solanum nigrum* L., from the Didactic and Experimental Resort area, BUASVM Timisoara, Timis County, Romania.

From the samples collected, 25 leaves were taken randomly and analyzed. Foliar parameters length (L) and width (w) of leaves were determined. The leaves were scanned, Figure 1 (a), and the leaf perimeter (Per) and the scanned leaf area (SLA) were determined.

To characterize the fractal geometry of the leaves, the binarized digital images, figure 1 (b), were analyzed and the fractal dimension (D) was determined by the box-counting method (Voss, 1985; Rasband, 1997), equations (1), (2) and (3). The box-counting method is frequently used to analyze the fractal geometry of different shapes and geometric surfaces (Li et al., 2009; Long and Peng, 2013). Parameters R^2 and Standard Error (SE) for regression line, figure 2, were used for the safety of the fractal analysis.

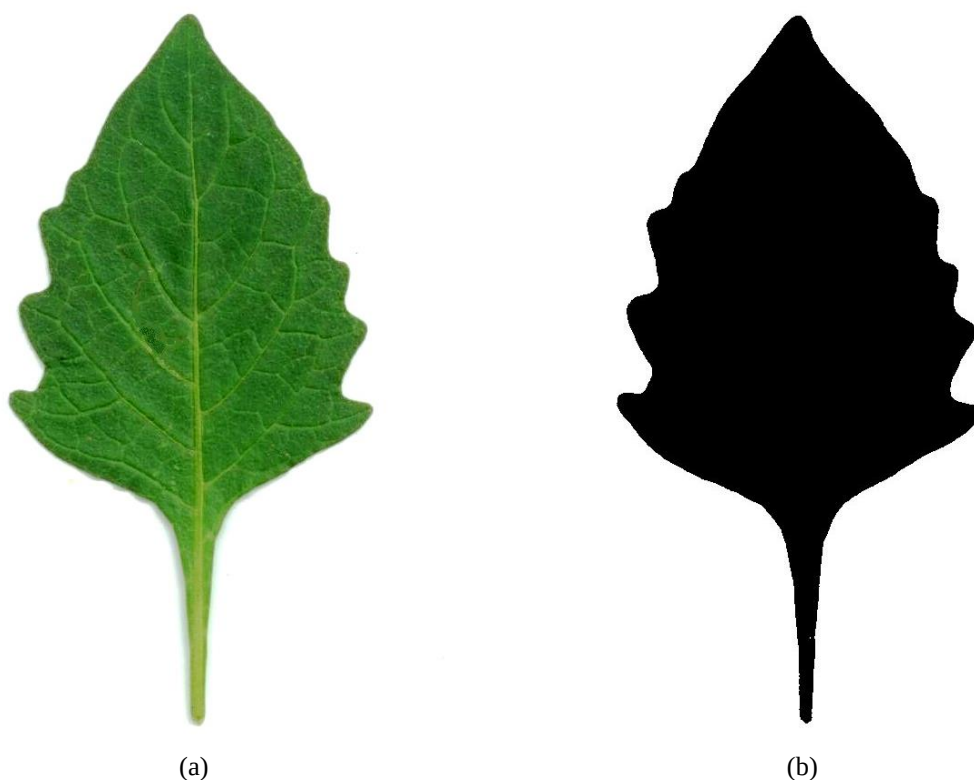


Figure 1. Leaves of *Solanum nigrum* L.; (a) original color image; (b) binarized image

$$\text{Mean } D = \sum (D) / \text{GRIDS} \quad (1)$$

$$D = m \left[\frac{\ln(F)}{\ln(\varepsilon)} \right] \quad (2)$$

where: D – fractal dimension; m – slope to regression line, in equation (3); F – number of new part; ε – scale applied

$$m = \frac{(n \sum SC - \sum S \sum C)}{(n \sum S^2 - (\sum S)^2)} \quad (3)$$

where: m – slope of regression line; S – log of scale or size; C – log of count; n – number of size

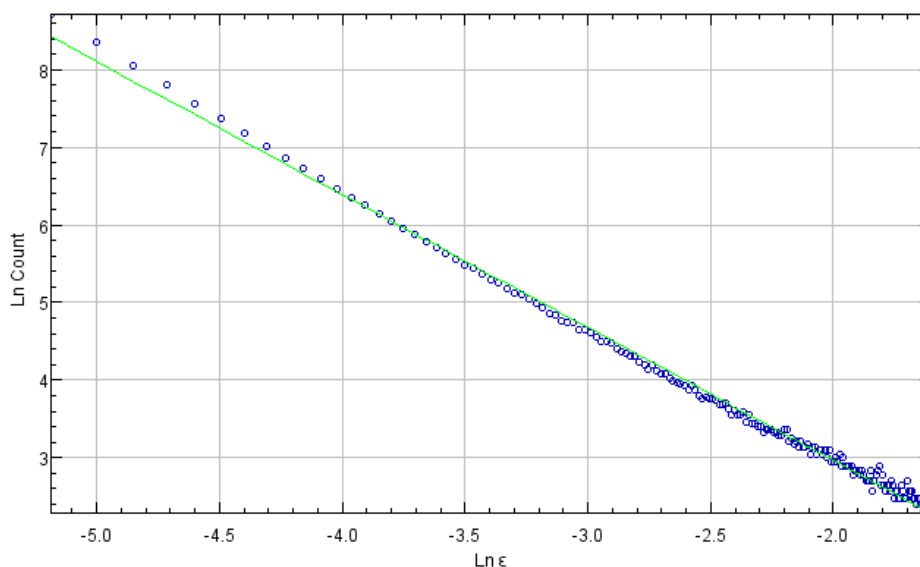


Figure 2. Log-log regression line for *Solanum nigrum* L. sample leaf

The experimental data obtained, regarding the parameters taken into account, were evaluated by the ANOVA test, Descriptive statistics analysis, Correlation analysis, Regression analysis. Mathematical and statistical analyzes evaluated the behavior of the data series within each parameter in describing the geometry of the sample leaves studied. Appropriate statistical safety parameters were used, consistent with each type of analysis.

For the purpose of mathematical and statistical analysis of data series, for the parameters considered, and for generation the graphical models (3D, and isoquants), PAST software (Hammer et al, 2001), Wolfram Alpha (2020), and JASP software (2022), were used.

RESULTS AND DISCUSSIONS

The values of the parameters taken into account for the study of the 25 leaf samples randomly selected from the 50 samples collected, were analyzed by Descriptive statistics, and the results obtained are presented in table 1.

The number of samples, the average value, the minimum and maximum values in the data series for each parameter are presented, as well as the corresponding Standard Error and Standard Deviation. The graphical distribution of the values of the studied parameters, in the form of boxplot, which includes all the determined values, is presented in figure 3.

Table 1. Descriptive statistics for studied parameters

Categories	L	w	Per	SLA	D
Valid randomized sample	25	25	25	25	25
Missing	0	0	0	0	0
Mean	7.820	4.647	23.373	19.266	1.628
Std. Error of Mean	0.206	0.151	0.686	0.968	0.007
Std. Deviation	1.031	0.756	3.429	4.840	0.037
Minimum	5.400	3.250	16.560	11.481	1.554
Maximum	9.900	6.450	29.598	32.878	1.709

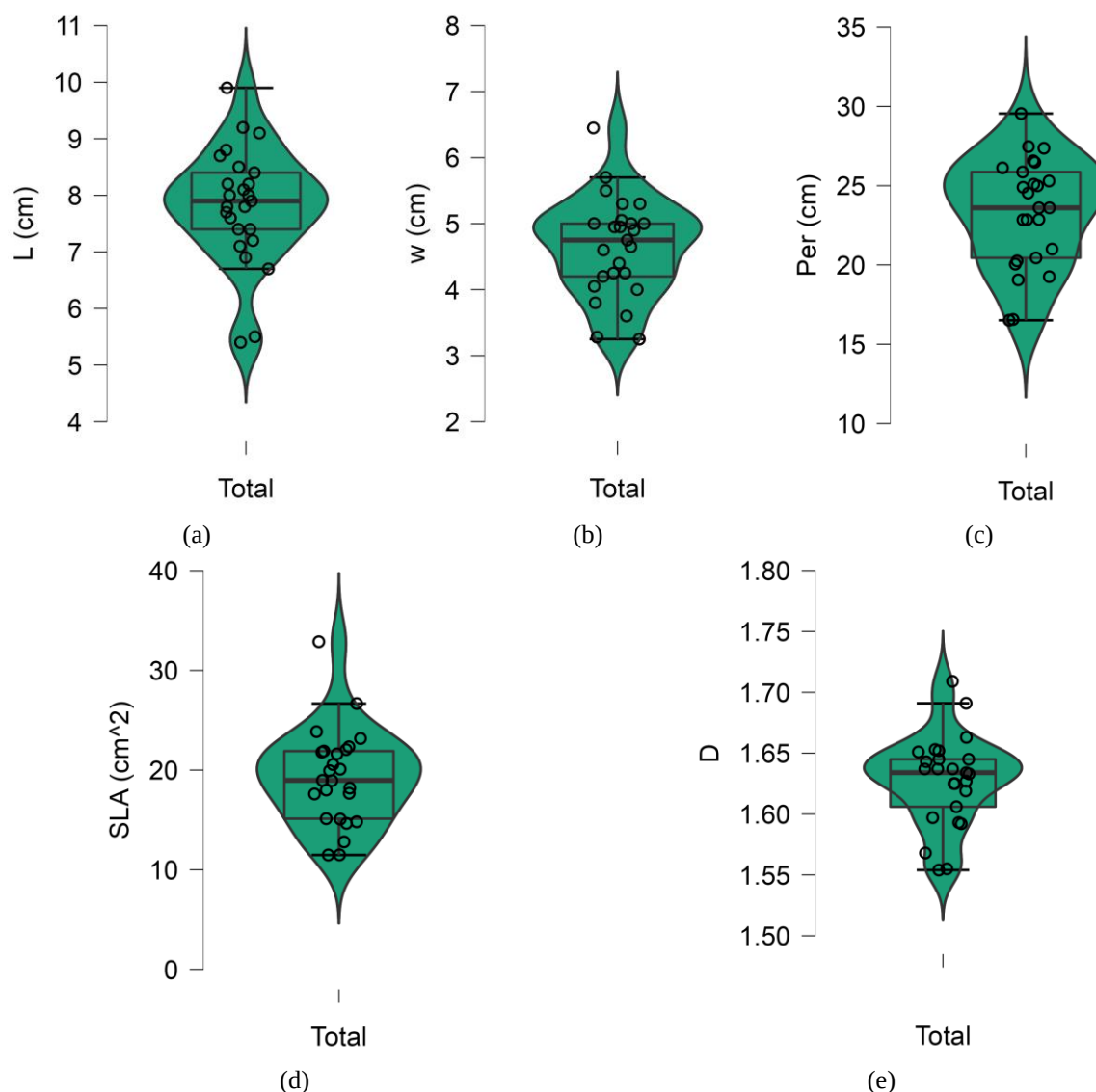


Figure 3. Distribution of the studied parameters values in the leaves of *Datura stramonium* L.

The dispersion of the values in the case of each parameter studied for the characterization of the *Solanum* leaf geometry, was highlighted by Circular correlation, table 2, figure 4. High dispersion was recorded at foliar parameters L, w, Per and SLA, and low dispersion was recorded for values at fractal dimension (D). This shows that the fractal dimension (D) is the most stable parameter in characterizing the geometry of the leaf samples studied.

Table 2. Circular correlation data obtained

Statistical categories	Leaf parameter				
	L	w	Per	SLA	D
Valid	25	25	25	25	25
Missing	0	0	0	0	0
Mean Direction	1.635	4.644	0.532	2.109	1.628
Standard Deviation	0.970	0.741	1.925	2.336	0.036

Note. all values are calculated on a normalized period of 2π

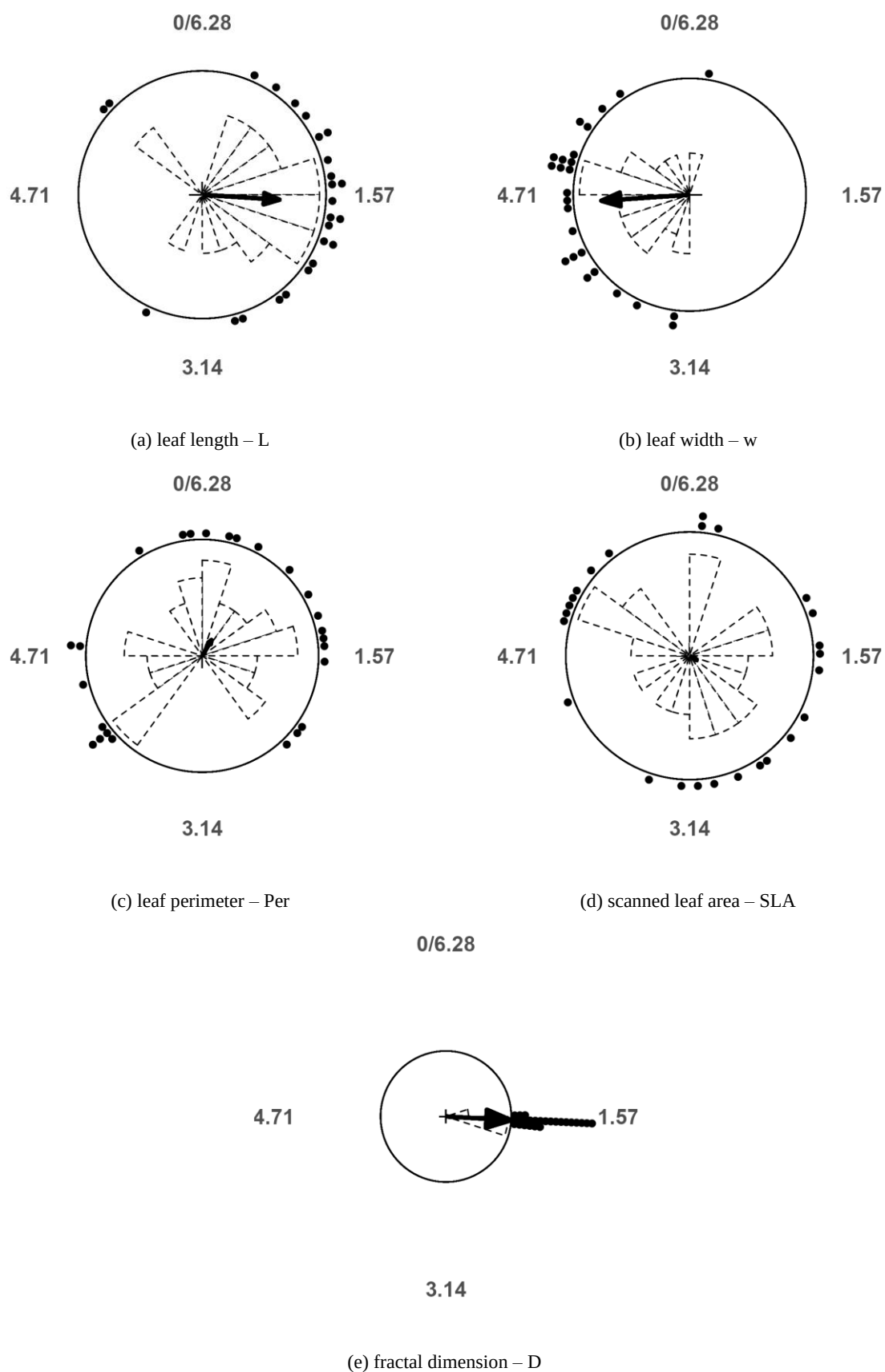


Figure 4. Values dispersion in the case of the parameters studied in the leaf samples, *Solanum nigrum* L.

Correlations of different intensity levels were recorded between the studied parameters, in statistical safety conditions (**p < 0.01, ***p < 0.001), table 3. Very strong correlations between SLA and D (r=0.960***), have been identified. Strong correlations were recorded between L and w (r=0.836***), between SLA and Per (r=0.839***), between D and Per (r=0.820***). Moderate correlations were recorded between Per and w (r=0.747***), between SLA and w (r=0.733***), between D and w (r=0.722***). Weak correlations were recorded between Per and L (r=0.616**), between SLA and L (r=0.570**), between D and L (r=0.615**). Lower intensity correlations were also recorded between some parameters.

Table 3. Correlation table between foliar parameters, *Solanum nigrum* L.

Variable		L	w	Per	SLA	D
L	Pearson's r	—				
	p-value	—				
w	Pearson's r	0.836***	—			
	p-value	< .001	—			
Per	Pearson's r	0.616**	0.747***	—		
	p-value	0.001	< .001	—		
SLA	Pearson's r	0.570**	0.733***	0.839***	—	
	p-value	0.003	< .001	< .001	—	
D	Pearson's r	0.615**	0.722***	0.820***	0.960***	—
	p-value	0.001	< .001	< .001	< .001	—

p < .01, *p < .001

The regression analysis facilitated the obtaining of some models, in the form of linear and polynomial equations, which described the variation of the studied parameters. The variation of w in relation to L was described by a linear equation, equation (4), under conditions of $R^2=0.699$, $p<0.001$, $F=53.373$. The SLA variation in relation to Per was described by a polynomial equation of degree 2, equation (5), under conditions of $R^2=0.713$, $p<0.001$, $F=27.305$. The variation of parameter D in relation to Per was described by equation (6), under conditions of $R^2=0.672$, $p<0.001$, $F=47.205$, and the variation of D in relation to SLA was described by equation (7), in conditions of $R^2=0.953$, $p<0.001$, $F=224.79$.

$$w = 0.6132 L - 0.1483 \quad (4)$$

$$SLA = 0.03603Per^2 - 0.453Per + 9.766 \quad (5)$$

$$D = 0.008876 Per + 1.42 \quad (6)$$

$$D = -0.00018SLA^2 + 0.01482SLA + 1.413 \quad (7)$$

The SLA variation in relation to the dimensional parameters of the leaves (L, w), as independent participation and in interaction, was described by equation (8), in statistical safety conditions ($R^2=0.976$, $p<0.001$, $F=167.577$). The graphical distribution of SLA in relation to L and w is presented in the form of a 3D model in figure 5 (a), and in the form of isoquants model in figure 5 (b).

$$SLA = ax^2 + by^2 + cx + dy + exy + f \quad (8)$$

where: SLA – scanned leaf area; x – L, leaf length; y – w, leaf width;

a, b, c, d, e, f – coefficients of the equation (8); a = -2.26607434; b = -1.55267402; c = 13.85296444; d = -19.94881228; e = 4.83996908; f = 0.

Fractal dimension (D), as an important parameter in the description of leaf fractal geometry, was analyzed in relation to classical foliar parameters (L, w, Per, SLA).

The variation of the fractal dimension (D) in relation to L and w was described by equation (9), in statistical safety conditions ($R^2=0.999$, $p<0.001$, $F=8634.49$). The graphical distribution of the fractal dimension D in relation to L and w, is presented in the form of a 3D model in figure 6 (a), and in the form of isoquants model in figure 6 (b).

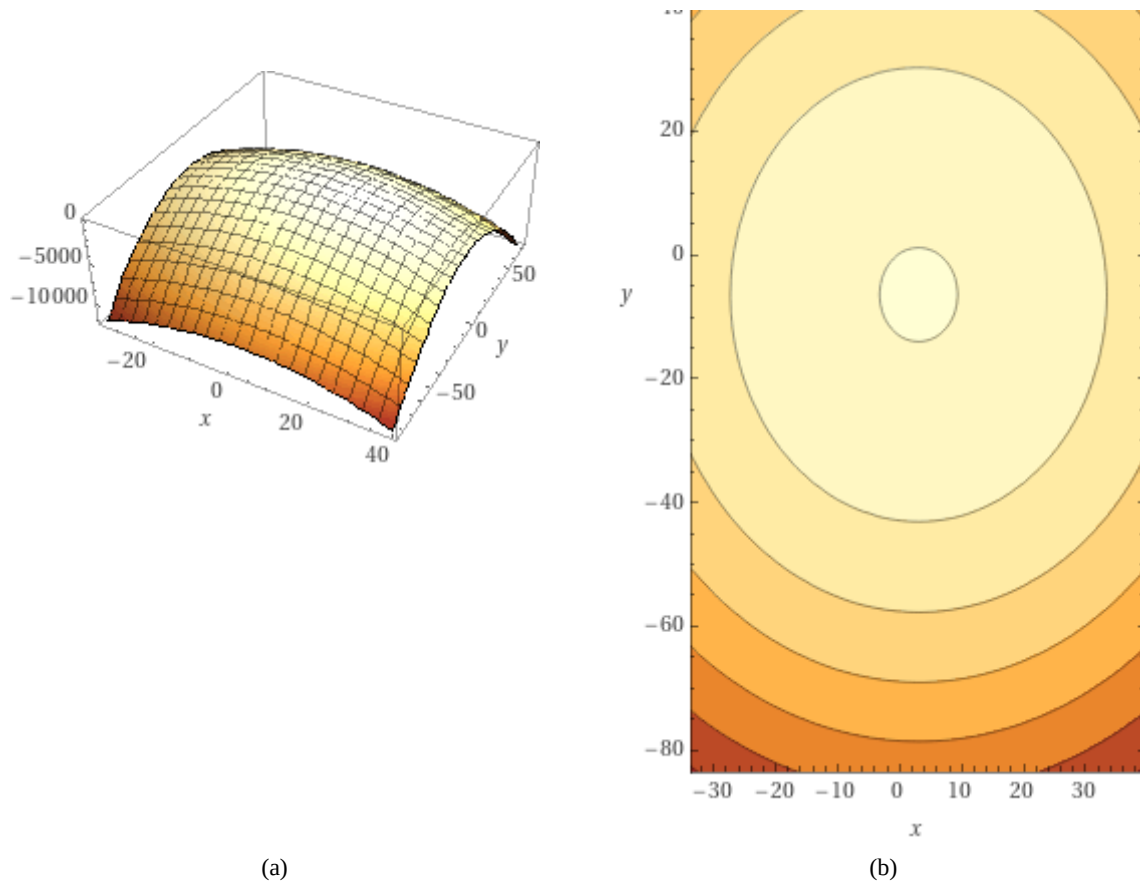


Figure 5. Graphical distribution of SLA in relation to L (x-axis) and w (y-axis) at *Datura stramonium* L.; (a) 3D model; (b) model in the form of isoquants

$$D = ax^2 + by^2 + cx + dy + exy + f \quad (9)$$

where: D – fractal dimension of the leaf geometry; x – L, leaf length; y – w, leaf width;
a, b, c, d, e, f – coefficients of the equation (9); a = 0.00984613; b = 0.05308221; c = 0.25400161;
d = 0.27343143; e = -0.09245200; f = 0.

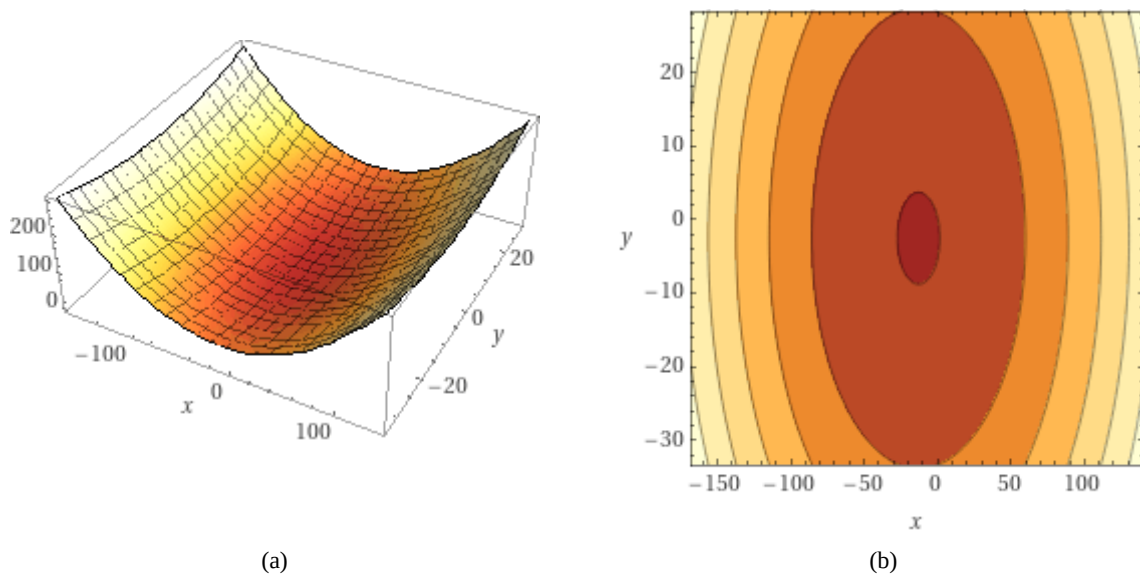


Figure 6. Graphic distribution of the fractal dimension D in relation to L (x-axis) and w (y-axis), *Datura stramonium* L.; (a) 3D model; (b) model in the form of isoquants

The variation of the fractal dimension (D) in relation to L and Per was described by equation (10), in statistical safety conditions ($R^2=0.999$, $p<0.001$, $F=9080.118$). The graphical distribution of the fractal dimension D in relation to the considered parameters, L and Per, is presented as a 3D model in figure 7 (a) and as isoquants in figure 7 (b).

$$D = ax^2 + by^2 + cx + dy + exy + f \quad (10)$$

where: D – fractal dimension of the leaf geometry; x – L, leaf length; y – Per, leaf perimeter;
a, b, c, d, e, f – coefficients of the equation (10); a= -0.01294373; b= -0.00177726; c= 0.16947519;
d= 0.07950966; e= 0.00129306; f= 0.

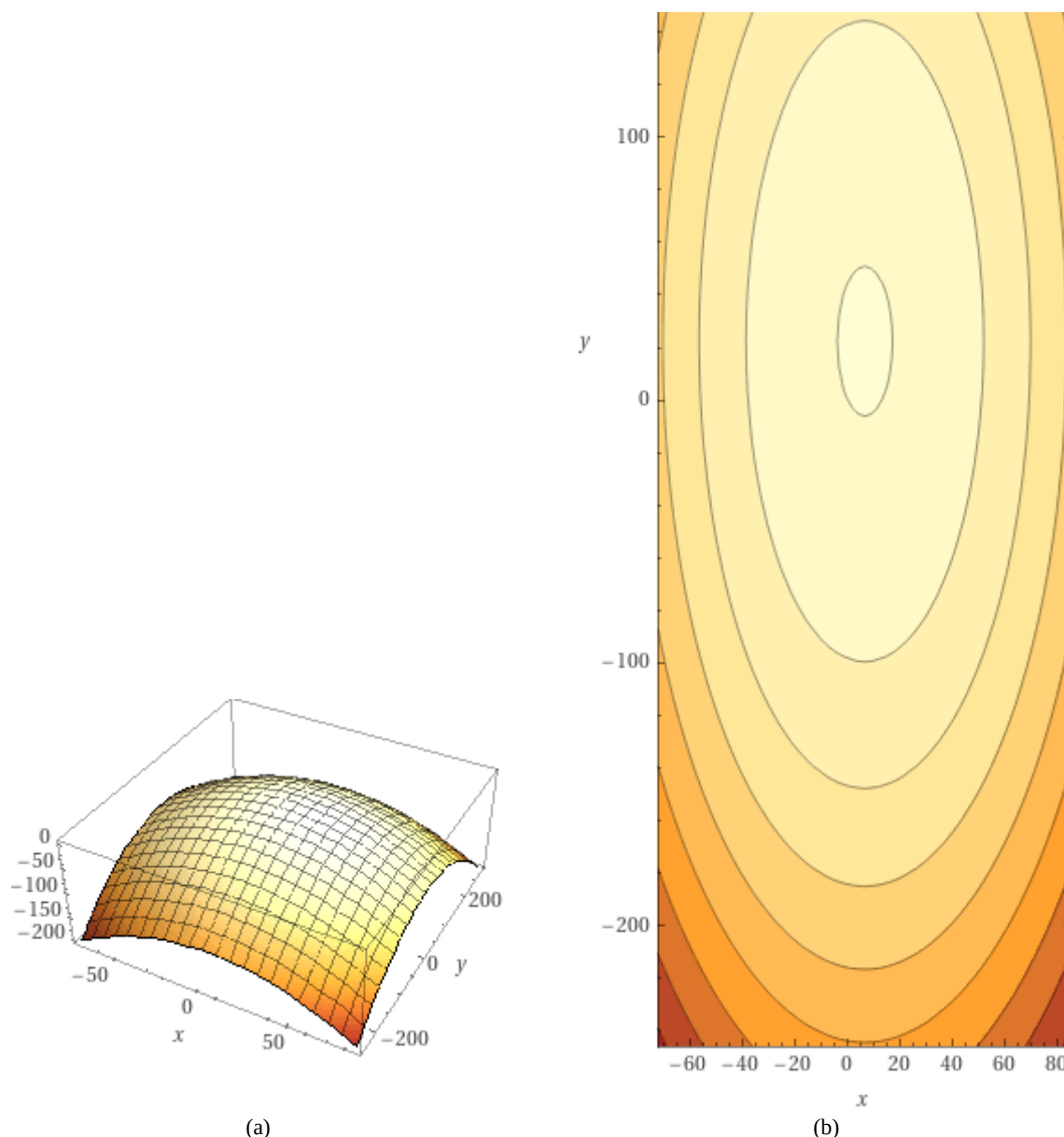


Figure 7. Graphic distribution of the fractal dimension D in relation to L (x-axis) and Per (y-axis), *Datura stramonium* L.; (a) 3D model; (b) model in the form of isoquants

Parameters considered to describe the leaves geometry in *Solanum nigrum* L. differentiated the variability of the leaves samples.

The length of the leaves (L) presented a high variability, rendered by the variation interval (table 1), the degree of dispersion (figure 4 (a)), but also through the value of the calculated variation coefficient $CV_L = 13.1813$. High variability was also recorded in the case of leaf width (w), table 1, figure 4 (b), $CV_w = 16.2707$

and in the case of perimeter (Per), table 1, figure 4 (c), $CV_{Per} = 14.6691$. The leaf area (SLA) in close dependence on dimensional parameters of the leaves (L, e, Per) registered the highest variability, table 1, figure 4 (d), $CV_{SLA} = 25.1231$.

Fractal dimension (D) is a parameter that expresses leaf geometry, and recorded the lowest variability, the lowest degree of dispersion, table 1, figure 4 (e), and $CV_D = 2.2802$. Thus, the fractal dimension (D) is the most stable parameter, among those considered, for the characterization of the leaf geometry in the *Solanum nigrum* L. species considered in the present study.

CONCLUSIONS

The study described in statistical safety conditions the variability of the foliar parameters taken into account (L, w, Per, SLA and D) related to the geometry of the leaves in the *Solanum nigrum* L. specie.

The parameter with the lowest degree of dispersion and the lowest variability was the fractal dimension (D), which was found to be the most stable and high fidelity parameter in describing the geometry of leaf samples in the specie considered in the study, in relation to geometric topology of leaves.

The variability of the analyzed parameters, in descending order was $CV_{SLA}=25.1231$, $CV_w=16.2707$, $CV_{Per}=14.6691$, $CV_L=13.1813$.

The regression analysis facilitated the obtaining of models in the form of equations, in statistical safety conditions, useful to describe the variation of some parameters. Based on the obtained equations and the specific coefficients, 3D models and in the form of isoquants were obtained, which graphically represented with high fidelity the variation of the SLA and D parameters in relation to the primary dimensional parameters of leaves (L, w and Per).

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