Impact of the wedge angle on the specific cutting energy of black radish during the exploitation of guillotine knife

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Abstract. The paper presents the influence of cutting conditions of black radish guillotine knife on specific cutting energy value. The tests were carried out using the texture meter: Texture Analyser TA.XTplus Stable Micro Systems. The structure of the black radish is heterogeneous and, therefore, in order to study the specific cutting energy of black radish its parenchyma was taken from a few specific places. The samples were cut with a longitudinal and transverse orientation of the fibers relative to movement of the working tool. The cutting process was carried at the knives wedge angles: 2.5°; 5°; 7.5°; 10°; 12.5°; 15°, the knives moved at the speed of 0.83 $mm \cdot s^{-1}$. The results were statistically analyzed using the program Statistica 8.0. The statistical analysis showed the impact of the place of sampling, direction of fibers in the black radish parenchyma samples and knife wedge angle on the specific cutting energy. The black radish parenchyma samples obtained from the core of the top layer showed the highest specific energy of cutting. Furthermore, the specific cutting energy showed higher value when the orientation of fibers was in the transverse direction rather than longitudinal. The highest value of the specific cutting energy was obtained for the cutting knife wedge angle of 15°, and the lowest for the knife with $\beta = 2.5°$ wedge angle.

Key words: cutting, specific cutting energy, knife wedge angle, place of sampling, the orientation of fibers

INTRODUCTION

The shredding is a process commonly used in the food industry. During the processing of fruit and vegetables a very common method of shredding is cutting, which aims at the obtainment of the product of desired shape and size. This is because of organoleptic, technological and performance requirements. A greater degree of fragmentation is required in vegetables for salads or juices, but smaller for the heat treatment [7, 8, 10].

The factors that have a significant impact on the process of raw materials cutting are primarily related to their mechanical properties, among others, morphology of plant and the individual characteristics of the variety, time and storage conditions [2, 4, 13, 15, 20].

Another group of factors are construction and exploitation parameters of shredding machines. The process of cuts depends on the configuration and shape of knife or knives, material supplying unit and operating parameters. The mechanism designed to crush has to be adapted to the characteristic properties and dimensions of the raw material [3, 9, 16, 21].

Shredding is an energy intensive process, and it creates the need to conduct research on the impact of various factors on energy consumption during the cutting of plant products. By the optimal selection of knife wedge angle, the specific cutting energy can be significantly reduced. Knife wedge angle should be chosen in such a way that during the cutting process the quality of the raw material is maintained. Too small knife wedge angle may lead to its rapid blunt and uncontrolled loss of the upper edge of the material being cut, while too large knife angle causes excessive area of cutting surface and the formation of large amounts of waste. The resulting shreds are often difficult to remove [1, 5, 11, 12, 17, 18, 19, 22, 23, 24, 25].

Despite many studies, there are still problems with the optimization of the cutting process of plant materials and operating conditions of cutting elements, because the plant materials are characterized by heterogeneity, anisotropy and they belong to diversified categories.

In recent years Poland has increased the consumption of black radish because of its high nutritional value and taste [6, 14], however, in the existing literature there are no reports of cutting and processing this vegetable for food purposes.

The aim of the study was to evaluate the influence of the place of sampling, direction of fibers in the black radish parenchyma sample as well as the knife wedge angle on the specific cutting energy.

MATERIAL AND METHODS

The raw material used for the study was the black radish variety Murzynka. The research material was taken from the second day after the date set for the seventh day. Vegetables stored in a ventilated room at the temperature of 4°C and relative moisture of 95%. Due to the different anisotropic structure of vegetables, the test samples were taken in a specific way. Figure 1 shows the appearance of black radish structure after cutting: a) longitudinally, b) transversely and indicates the place of sampling.

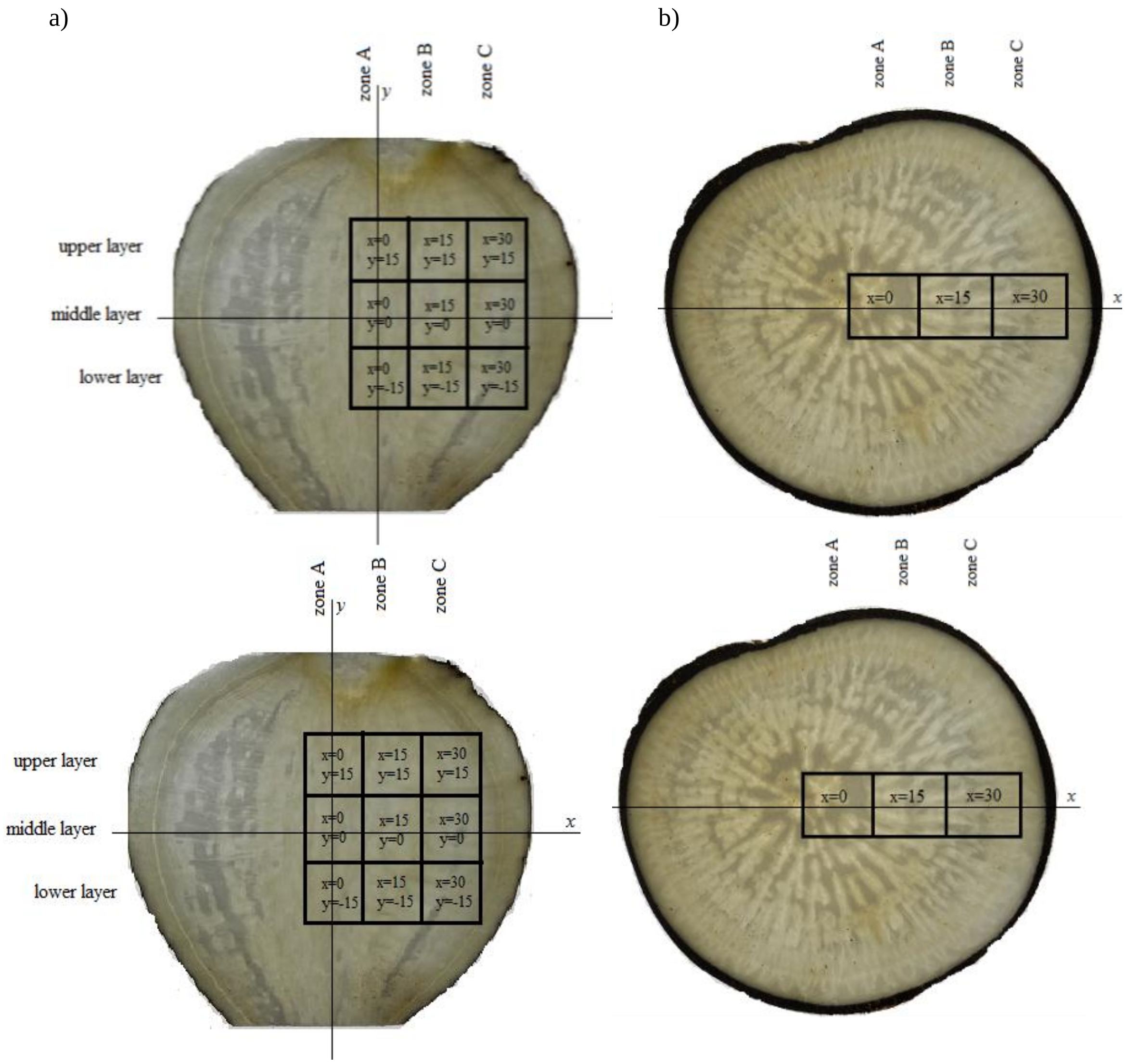


Fig. 1. The structure of black radish parenchyma and place of sampling after cutting: a) longitudinally, b) transversely to the fibers

Samples were prepared in the following way: each vegetable was partitioned into three layers (upper, middle and lower) with the thickness of 15 mm. Then, from each layer cuboids were cut out, sized 45x15x15 mm, which were partitioned into three zones A, B and C (15 mm wide). This resulted in cubes of 15 mm sides. To ensure the accuracy of cutting the samples were prepared on the metal template with four parallel-spaced knives with blades spaced 15 mm. Samples were cut by the knives of texture meter arranging them longitudinally and transversely to the fibers located in parenchyma and to the direction of the knife wedge.

In order to be able to carry out mathematical statistical analysis, the locations of the respective sample centers were determineded. Coordinate system *x-y* was assumed, which crossed at the point 0. The *y*-axis coincided with the vertical axis of the zone A, the *x*-axis with the horizontal axis of the middle layer. Vertical axis tests located in zone B and C spaced were the *y*-axis, respectively 15 and 30 mm, and the horizontal axes samples with upper and lower layers were spaced at 15 - 15 mm from the axis *x*. Coordinates *x* and *y* applied were related to the middle of cubes.

It was assumed that the black radish root was symmetric relative to the *y*-axis. Figure 1 shows that the structure of the raw material is heterogeneous. In the illustrated longitudinal section of the black radish (Fig. 1a) it is evident that there is a high fiber density in the top layer and the cross-section, which illustrates the radial distribution of fibers (Fig. 1b), in the middle of the vegetables.

The process of cutting the black radish was conducted on the texture meter Texture Analyser TA.XTplus Stable Micro Systems cooperating with the computer having software Texture Exponent 32. The machines used a starter, which included a set of replaceable knifes with holder for their attachment and the guide (Fig. 2). The cutting samples were laid longitudinally to the fibers (sample A) and transversely to the fibers (sample b).

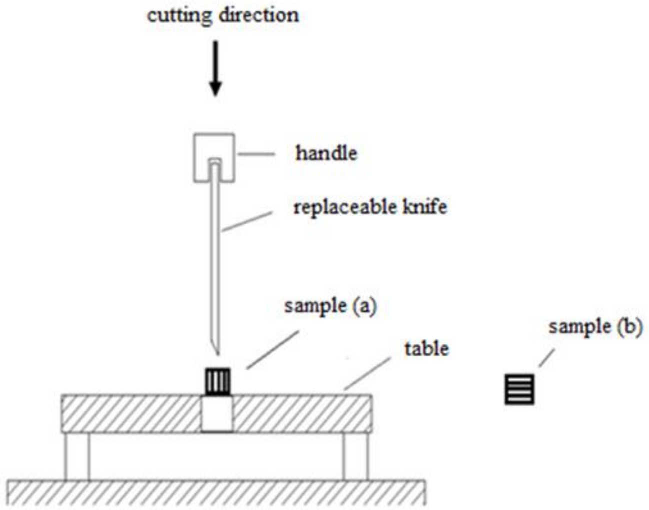


Fig. 2. Scheme of equipment for cutting

In the study straight guillotine knives were used made of steel NC6 with the following knife wedge angles: 2.5°; 5°; 7.5°; 10°, 12.5° and 15°. The angle of the knife was equal to 0°, and the cutting speed was 0.83 $mm \cdot s^{-1}$.

As a result of the measurement graphs were obtained showing the relationship between the force and displacement of the cutting knife, which defined the maximum value of the cutting force and, using the formula (1), the specific cutting energy was calculated, defined as the labor required to cut the specific area of the material:

$$Ej = \frac{L}{A} \quad (1)$$

where: Ej – specific cutting energy [$J \cdot m^{-2}$], L – work of cutting [J], A – surface area of the sample [m^2].

The studies were performed in ten replicates (for each sample position and the knife).

The results were statistically analyzed using the statistical package Statistica 8.0. In order to examine the significance of differences between the place of sampling and specific cutting energy, multivariate analysis of variance ANOVA was carried out. Inference was made with the significance level of 0.05. Detailed analysis of medium confidence intervals were made using Tukey's test. Using the regression analysis derived equations that describe the specific cutting energy depending on the place of sampling for the knives of various wedge angles on both directions of the fibers.

RESULTS AND DISCUSSION

Depending on the results of specific cutting energy, samples of the black radish parenchyma taken from specific locations, cut along and across the fibers, at the knives wedge angles 2.5°, 5°, 7.5°, 10°, 12.5° and 15° are presented in the form of graphs in Figures 3, 5, 7, 9 and 11. The different points included in the average values of the graphs indicate the presence of significant differences among them.

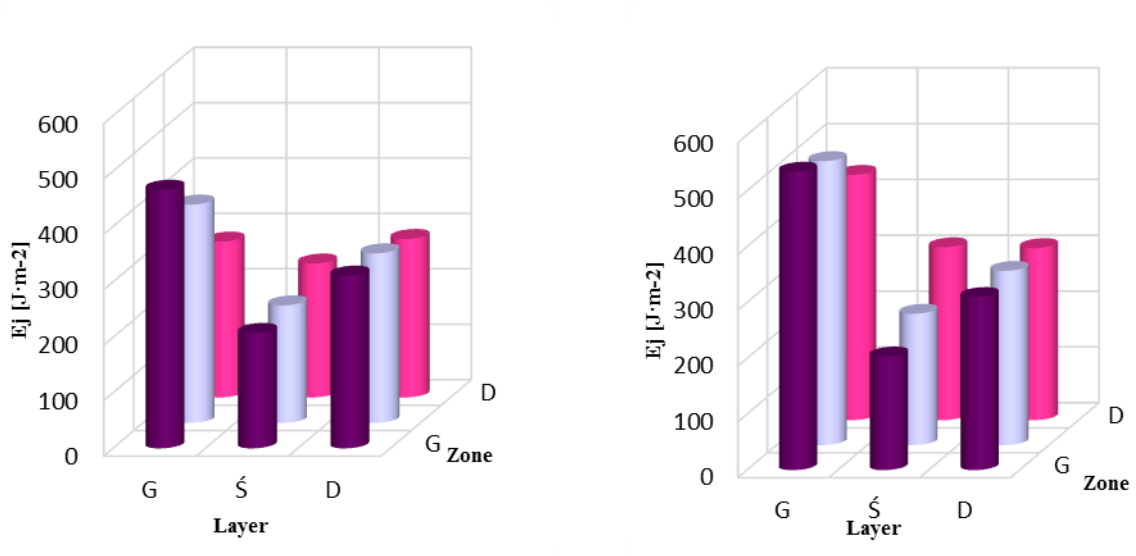
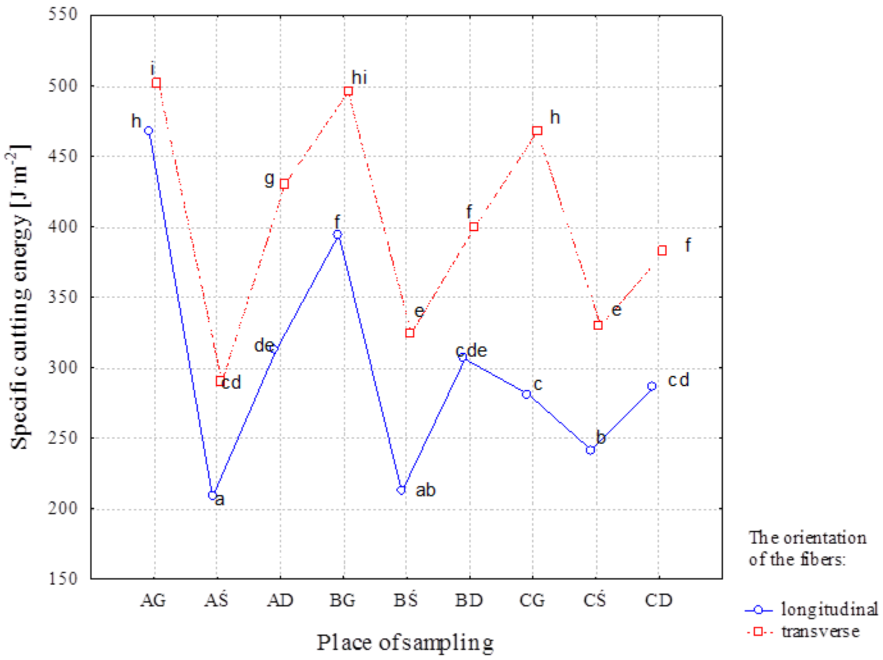


Fig. 3. Dependence of specific cutting energy of the black radish parenchyma at knife wedge angle β = 2.5° on the place of sampling at a) longitudinal b) transverse fibers orientation

Figure 3 contains the average of specific cutting energy samples taken from the parenchyma of black radish, cut with the knife at the wedge angle $\beta = 2.5^{o}$. Most of energy for cutting the parenchyma samples from the upper layer was used by black radish fibers arranged transversely. The average value of specific cutting energy for zone A was 500.61 $J \cdot m^{-2}$, zone B-495.37 $J\ m^{-2}$ and zone C-467.61 $J\ m^{-2}$. The lowest value of the specific cutting energy for samples of black radish arranged longitudinally and transversely was observed in the middle layer zone A. The determined values were, respectively: 208.25 $J \cdot m^{-2}$ and 289.66 $J \cdot m^{-2}$. Based on the Tukey test of the significance of differences, a significant effect was shown of the place of sampling and fibers orientation (Fig. 4).



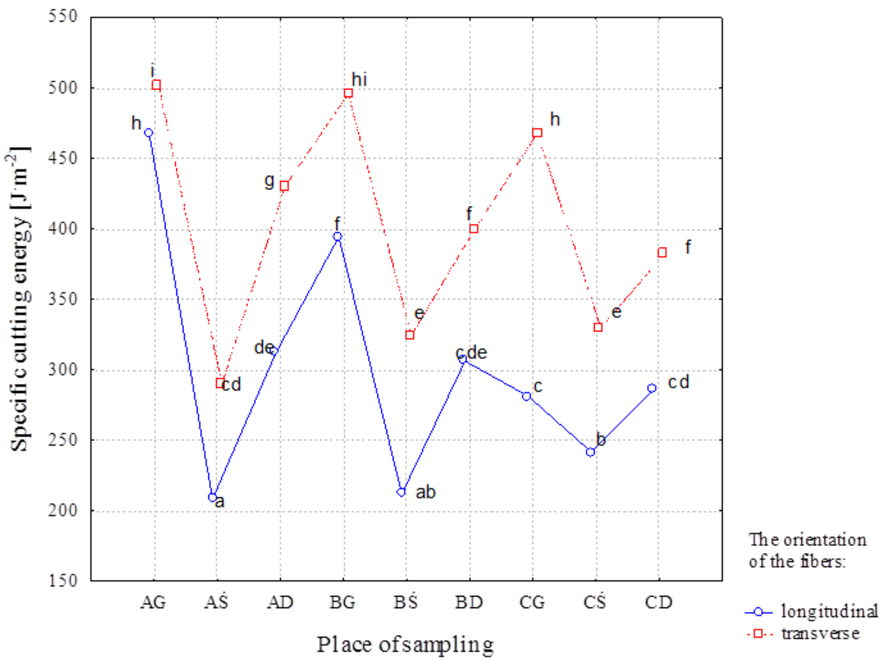


Fig. 4. The significance of differences Tukey test: specific cutting energy at knife wedge angle 2,5^{o} for samples of black radish parenchyma taken from specific places along the longitudinal and transverse direction of fibers

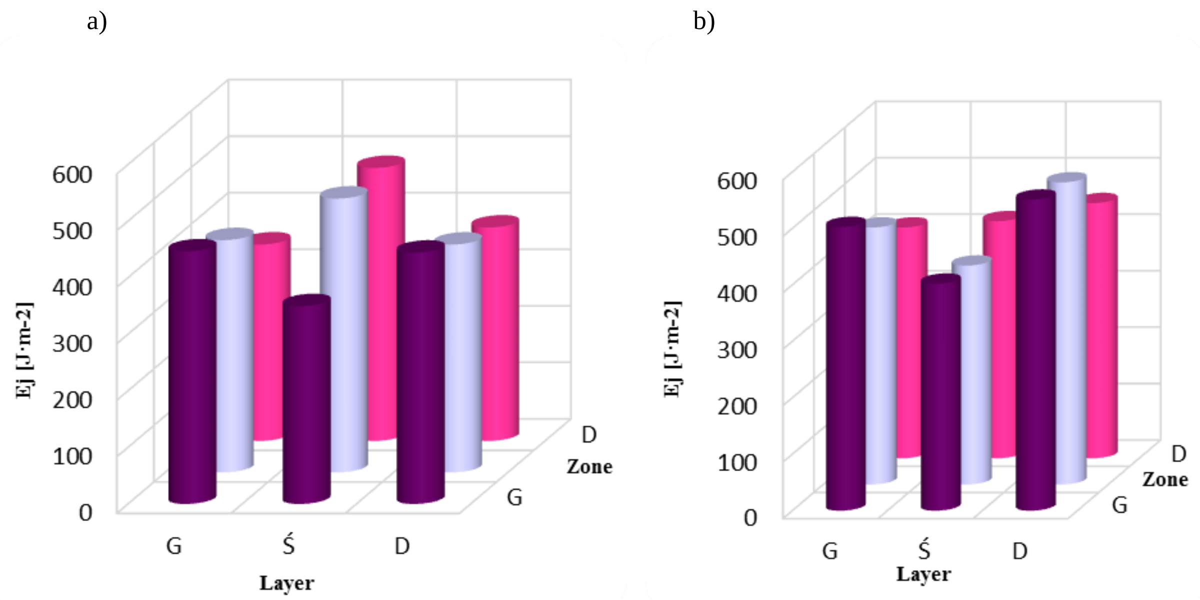


Fig. 5. Dependence of specific cutting energy of the black radish parenchyma at knife wedge angle $\beta = 5^{o}$ on the place of sampling at a) longitudinal b) transverse fibers orientation

Based on the results obtained during the cutting of the tissue of the root of black radish knife wedge angle β = 5° (Fig. 5), it was observed that the average of specific cutting energy are in the numerical interval from 347.33 to 492.06 $J \cdot m^{-2}$ for parenchyma samples a longitudinal orientation of the fibers, and from 387.8 to 550.96 $J \cdot m^{-2}$, the transverse orientation of the parenchyma fibers. The greatest value of the specific cutting energy samples of black radish arranged along the fibers observed in the middle layer zone C, and tissue arranged when cutting across the fibers in the lower layer zone A.

Comparison of average values of specific cutting energy of samples of black radish of the longitudinal and transverse orientation of the fibers of indication groups of uniformity is shown in Figure 6. The different points are included in the average values give rise to a significant difference between them.

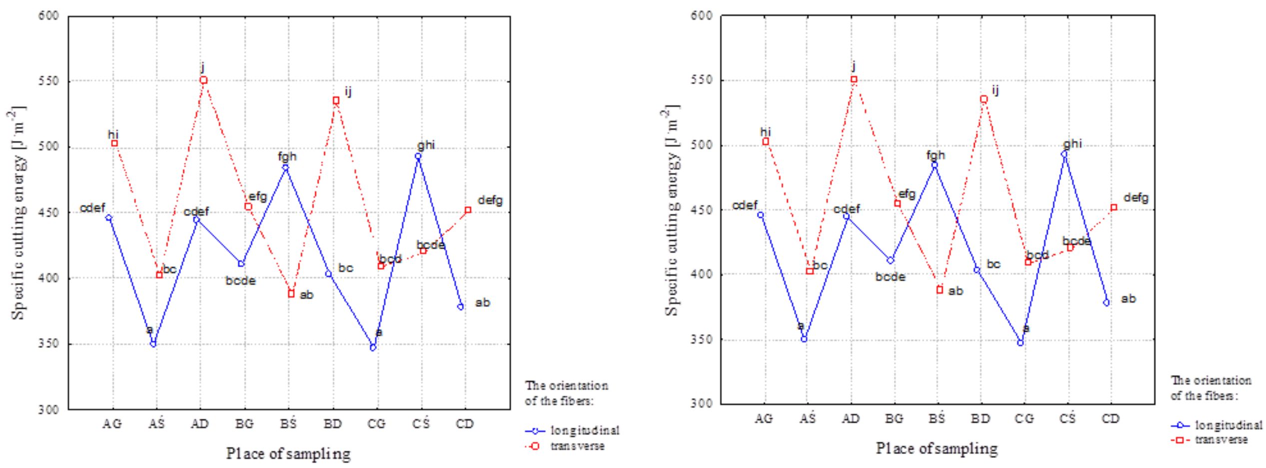


Fig. 6. The significance of differences Tukey test: specific cutting energy at knife wedge angle 5^{o} for samples of black radish parenchyma taken from specific places at the longitudinal and transverse direction of fibers

In the test of cutting the black radish parenchyma by knife wedge angle $\beta = 7{,}5^{o}$ when the sample was placed across the fibers (Fig. 7a), the highest specific cutting energy value was observed for the sample taken from the upper layer zone A - 608.99 $J \cdot m^{-2}$. With the longitudinal orientation of the fibers (Fig. 7b), the specific cutting energy of black radish parenchyma taken from the same place was by 19.55% higher. The lowest specific cutting energy was observed for the middle layer zone A cut across the fibers (416.22 $J \cdot m^{-2}$).

Comparison of mean values for both the aspects of black radish parenchyma samples indicating the uniformity of the groups is shown in Figure 8.

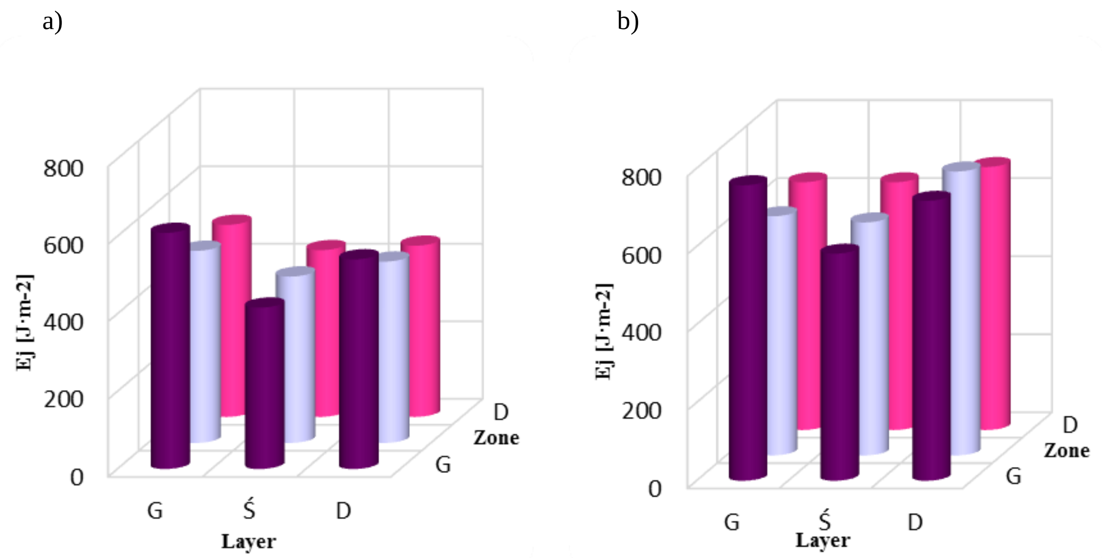


Fig. 7. Dependence of specific cutting energy of the black radish parenchyma at knife wedge angle $\beta = 7.5^{\circ}$ on the place of sampling at a) longitudinal b) transverse fibers orientation

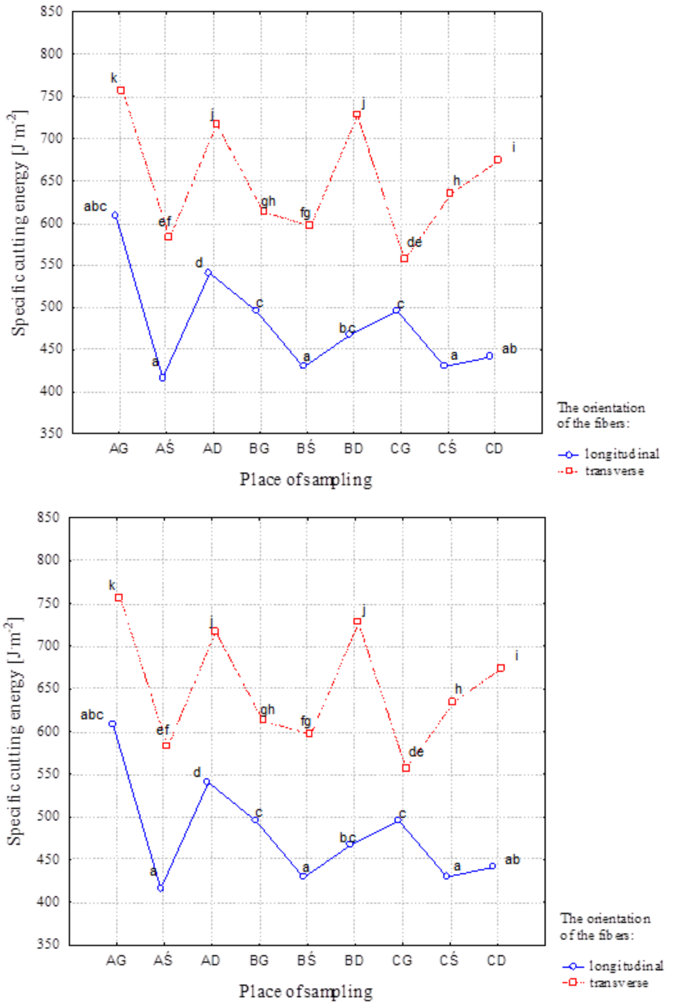


Fig. 8. The significance of differences Tukey test: specific cutting energy at knife wedge angle 7.5° for samples of black radish parenchyma taken from specific places at the longitudinal and transverse direction of fibers

Based on the results of cutting the root tissue at knife wedge angle $\beta = 10°$ (Fig. 9 and 10), it was observed that the average specific cutting energy values were in the numerical interval from 463 to 564.16 $J \cdot m^{-2}$ for samples with longitudinal orientation of the fibers, and from 532.52 to 739.11 $J \cdot m^{-2}$ for the transverse orientation of the parenchyma fibers. The highest value of the specific cutting energy of black radish samples located along and across the fibers was observed in the upper layer of the zone A.

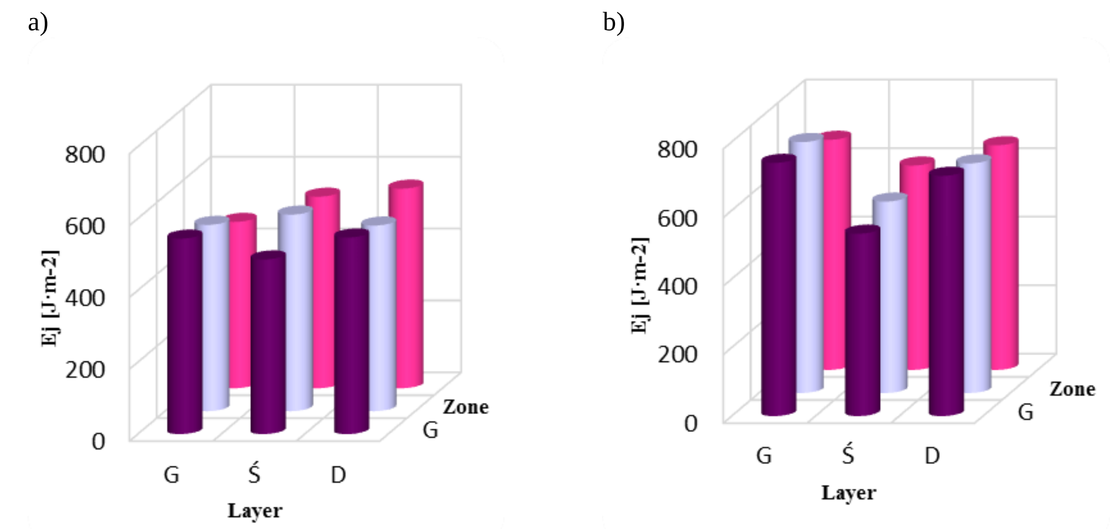


Fig. 9. Dependence of specific cutting energy of the black radish parenchyma at knife wedge angle β = 10^o on the place of sampling at: a) longitudinal b) transverse fibers orientation

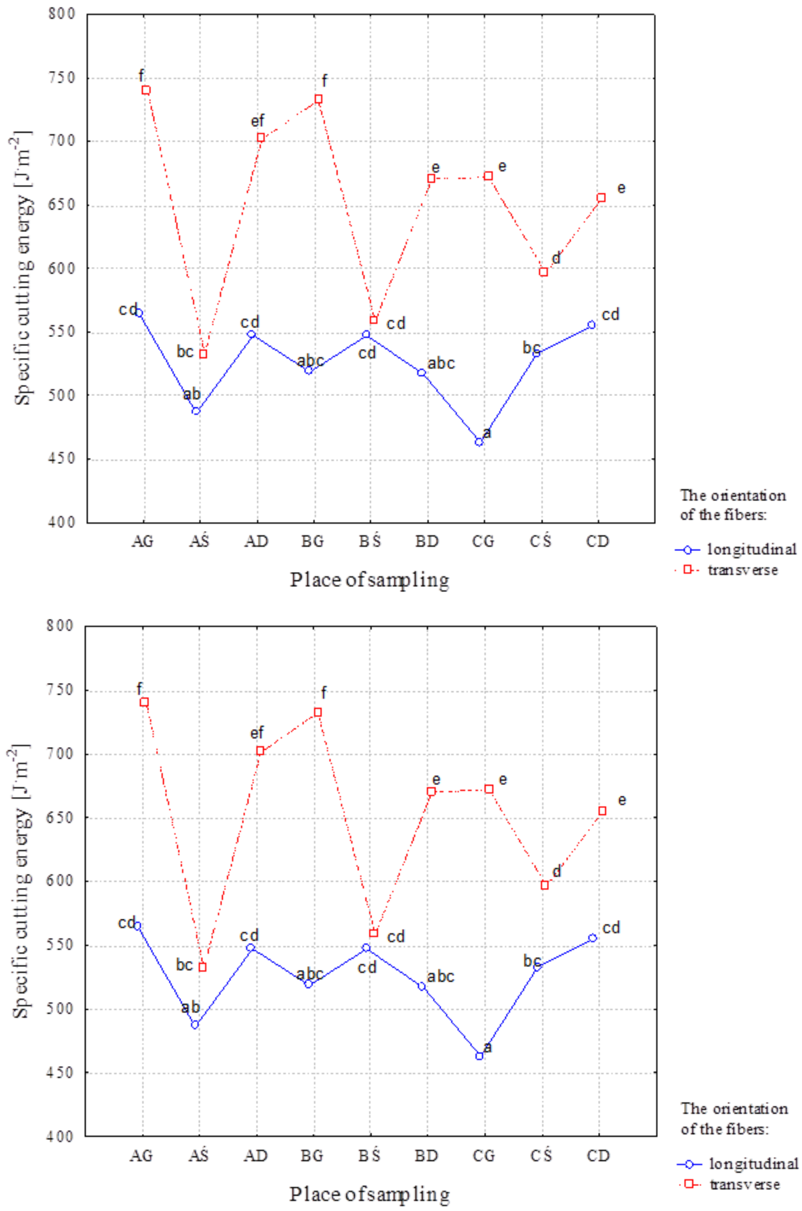


Fig. 10. The significance of differences Tukey test: specific cutting energy at knife wedge angle 10^o for samples of black radish parenchyma taken from specific places at the longitudinal and transverse direction of fibers

For black radish parenchyma of the longitudinal orientation of the fibers cut by a knife wedge angle β = 12,5^o observed the lowest values of specific cutting energy for the middle layer (Fig. 11). Based on the test the significance of differences Tukey (Fig. 12), there was no significant difference between the specific cutting energy samples of black radish taken from this place. The average value of the specific cutting energy for the zone A was 556.09 J·m^{-2}, zone B 554.45 J·m^{-2} and zone C 588.35 J·m^{-2}. The greatest value of the specific cutting energy observed at the transverse orientation of the fibers parenchyma samples taken from the black radish tissue upper layer zone A (851.58 J·m^{-2}). For the same measuring place, but a sample located along the fiber, this value was about 7.24% lower.

a) b)

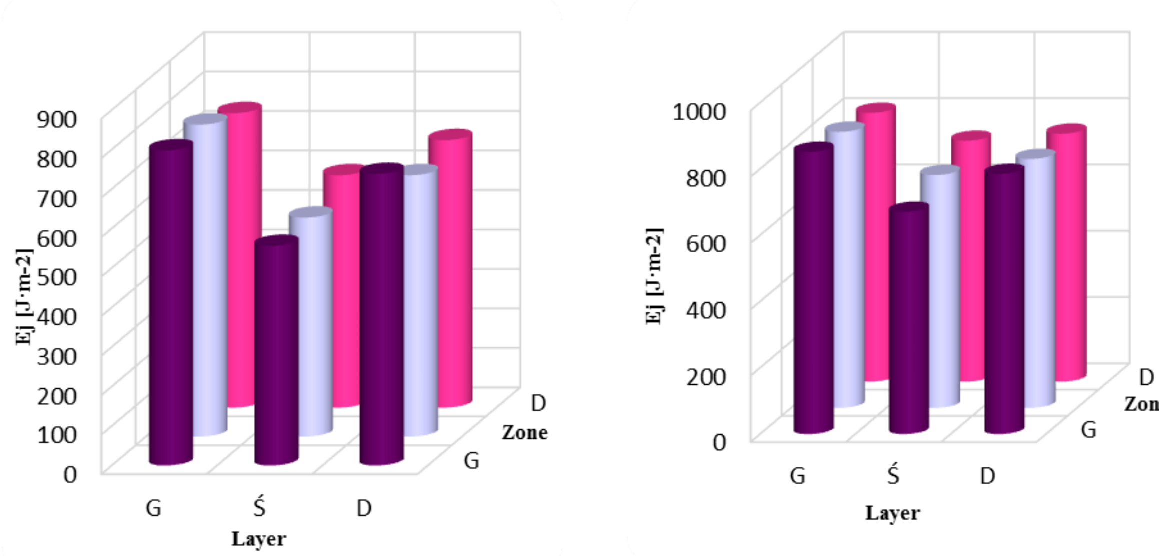


Fig. 11. Dependence of specific cutting energy of the black radish parenchyma at knife wedge angle β = 12.5^o on the place of sampling at: a) a longitudinal b) transverse fibers orientation

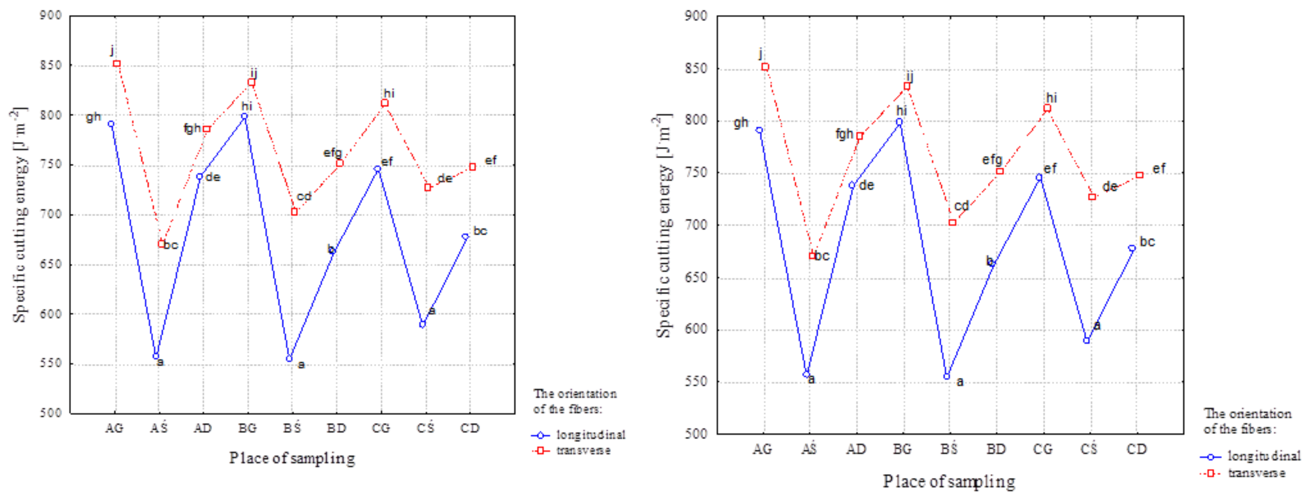


Fig. 12. The significance of differences Tukey test: specific cutting energy at knife wedge angle 12,5^o for samples of black radish parenchyma taken from specific places at the longitudinal and transverse direction of fibers

Analyzing the data in the graphs 13a, 13b and 14, it can be concluded that the highest specific cutting energy value was obtained for samples of black radish taken from its core (zone A). The highest specific cutting energy was required to cut the sample arranged transversely and taken from the top layer of the material (1033.43 J·m^{-2}). Its value when placed at longitudinal fibers was by about 182.33 J·m^{-2} lower. Based on the Tukey test of the significance of differences a significant effect was shown of the place of sampling, as well as of the orientation of fibers (Fig. 14).

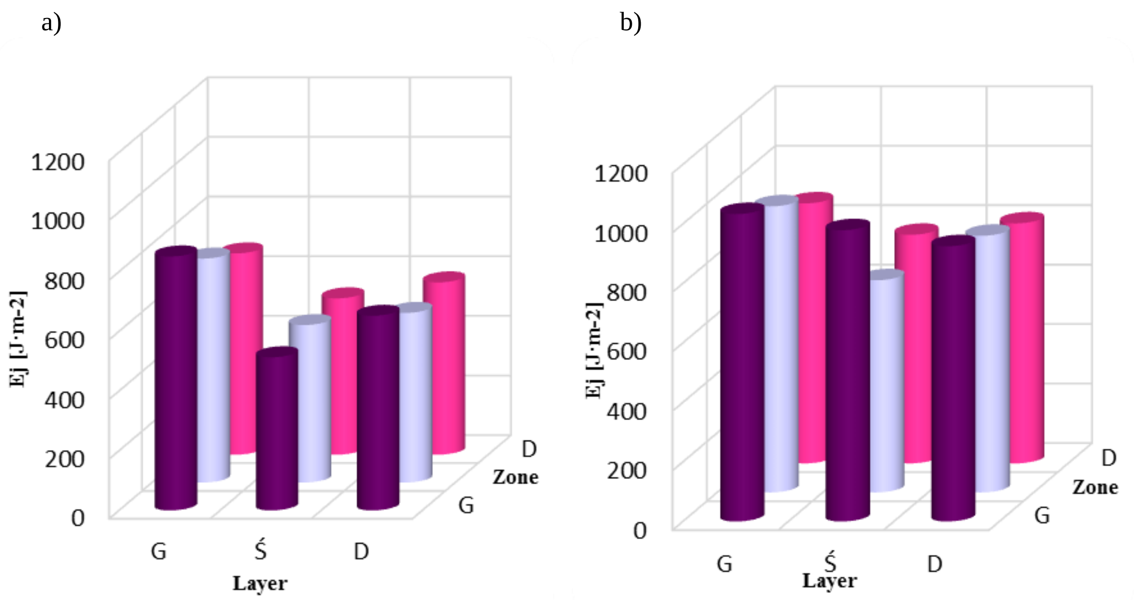


Fig. 13. Dependence of specific cutting energy of the black radish parenchyma at knife wedge angle β = 15^o on the place of sampling at: a) longitudinal b) transverse fibers orientation

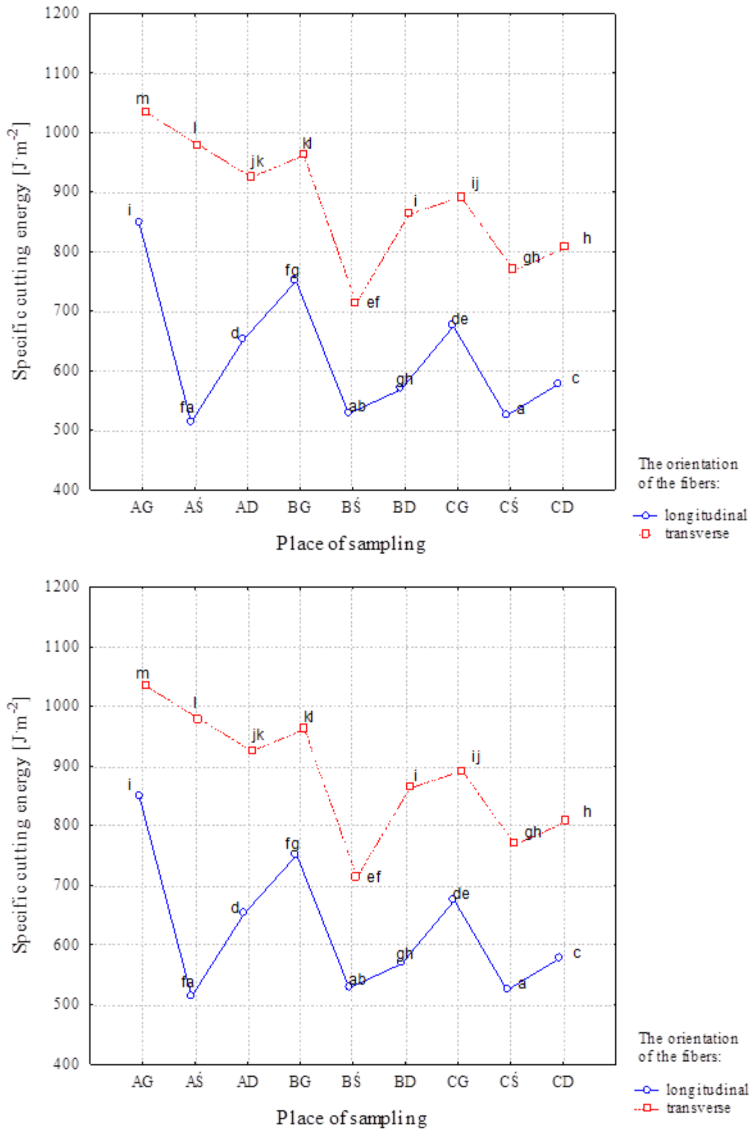


Fig. 14. The significance of differences Tukey test: specific cutting energy at knife wedge angle 15^o for samples of black radish parenchyma taken from specific places at the longitudinal and transverse direction of fibers

Table 1 presents the regression equation of specific cutting energy of the black radish parenchyma cut with guillotine knifes at various wedge angles in both the orientations of fibers depending on the place of sampling.

Location of samples, i.e. the distance from the *x*- and *y*-axis had a significant impact on the value of specific cutting energy.

Table 1. The regression equations and coefficients of determination R^2 describing the specific cutting energy of black radish parenchyma for the longitudinal and transverse orientation of fibers, knives wedge angles from 5° to 15° depending on the place of sampling

Knife wedge angle [°]	**Fiber orientation**	**Regression equation**	**Coefficients of determination R^2**
2,5	longitu	$Ej = 0{,}535y^2 - 1{,}976x + 2{,}647y + 250{,}271$	0,729
	transve	$Ej = 0{,}583y^2 + 2{,}808y + 314{,}58$	0,919
5,0	longitu	$Ej = -0{,}15y^2 + 436{,}046$	0,418
	transve	$Ej = 0{,}359y^2 - 1{,}945x - 1{,}909y + 432{,}414$	0,769
7,5	longitu	$Ej = 0{,}37y^2 - 2{,}21x + 1{,}668y + 458{,}269$	0,696
	transve	$Ej = 0{,}309y^2 - 2{,}125x - 2{,}141y + 636{,}298$	0,508
10,0	longitu	$Ej = -0{,}82y^2 + 528{,}916$	0,457
	transve	$Ej = 0{,}589y^2 + 1{,}289y + 562{,}552$	0,821
12,5	longitu	$Ej = 0{,}751y^2 + 2{,}848y + 566{,}295$	0,878
	transve	$Ej = 0{,}43y^2 + 2{,}348y + 699{,}934$	0,852
15,0	longitu	$Ej = 0{,}67y^2 - 2{,}677x + 5{,}311y + 561{,}83$	0,855
	transve	$Ej = 0{,}244x^2 + 0{,}415y^2 + 3{,}248y + 916{,}898$	0,828

where: *x* - distance of the point from the axis of ordinates [mm], and *y* - distance of the point from the abscissa [mm].

The equations are valid for the values of *x* (in the range of 0 ÷ 30 mm) and *y* (in the range of -15 to 15 mm) and are designated at the level of significance of differences $\alpha \leq 0.05$.

CONCLUSIONS

1. The knife wedge angle significantly affects the specific cutting energy of black radish.
2. The knife angle increase from 2.5° to 15° caused an increase of specific cutting energy of black radish from 347 to 851 $J \cdot m^{-2}$ (at the longitudinal orientation of fibers), and from 388 to 1033 $J \cdot m^{-2}$ (at the transverse orientation of fibers).
3. When cutting black radish tissue, the highest average value of specific cutting energy was obtained for the parenchyma sample from the upper layer (zone A), and the lowest from the zone C (upper layer).
4. At the transverse direction of the black radish parenchyma fiber the value of the specific cutting energy was significantly higher than at the longitudinal.
5. It is advisable to undertake research on cutting materials of plant origin with particular reference to their structural features, as these materials are characterized by anisotropy, which significantly affects the cutting process.

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