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A justification of the choice of parameters for the picking reel tooth on a lowbush blueberry harvester

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Abstract. The functional working tool on the blueberry harvester is its rotating picking reel. Its working element is the picking rake which is attached to the picking reel. A total of four rakes are attached to the picking reel. A picking rake includes an axis which is attached in an articulated manner between the reel's end discs, and pin-shaped teeth which are rigidly attached to it. The picking rake's tooth must be made of a fully flexible material to prevent damage to the blueberry plant. The aim of this research was to determine the flexure of test specimens (plastic rods) which have been constructed from a fully flexible material of different conditions, along with the suitability for use of such flexible material as the teeth on the picking rake. As a result of this study, it became clear that, based on the results from flexure, durability, and residual deformation tests, it is more expedient to choose Ertacetal C (POM-C) as the material for the picking reel's tooth, with a diameter of 4.3 mm.

Key words: blueberry harvester, elastic modulus, flexible tooth, picking reel.

INTRODUCTION

Blueberry plantations have been established on mineral lands, but also on exhausted milled peat fields (Peatland Ecology Research Group, 2009). Machinery has been created to take care of all technologically-involved operations, including harvesting, where medium and tall blueberry varieties are concerned which have been planted on mineral lands.

According to the available literature (Starast et al., 2007; Olt et al., 2013; Ali, 2016; Retamales & Hancock, 2018), blueberry cultivation consists of a series of technologically-involved operations, of which harvesting is one of the most labour-intensive-, and logistically-demanding operation. Harvesting can be done by machine or hand harvest, with machine harvesting optimizing harvest efficiency (Käis & Olt, 2010; Olt et al., 2013; Takeda et al., 2017).

With lowbush blueberries (*Vaccinium angustifolium* Ait.), which have a plant height of 10–20 cm and whose berries ripen more or less simultaneously (Noormets et al., 2003), it is common practise on mineral lands to harvest them commertcially using automated equipment (Fig. 1) and a horizontally-located rotating picking reel (Fig. 2, a, b), with its working element being a picking rake (Heinloo, 2007; Arak & Olt, 2014). The picking rake is of the parallelogram type, which means that a picking rake remains parallel to its initial position at any angle of rotation. The picking rake contains an axis which is attached in an articulated manner between the end discs, to which teeth are rigidly attached in parallel with each other. The teeth are attached to the axis of the picking rake with spacing that allows them to move between blueberry plants without damaging them, while separating the berries from the stalks. This format is also known as a coarse harvester, which means that any impurities (such as leaves, twigs, peat particles, etc) and crushed berries are not separated by the harvester. Therefore the harvester's technologically-involved operations involve separating the berries from the stalks without any damage and to direct them to the exchangeable berry boxes or containers during the operation by means of a chute.

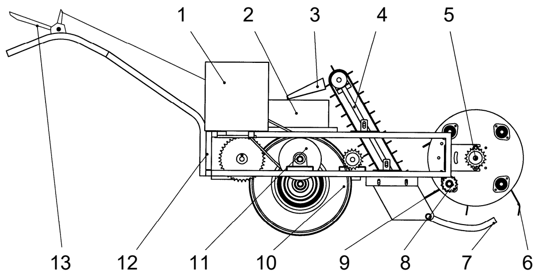


Figure 1. The main assemblies and parts of a motoblock-type harvester: 1 – engine; 2 – berry box; 3 – chute; 4 – conveyor; 5 – picking reel; 6 – hook spring-tine; 7 – copying unit; 8 – picking rake; 9 – rake tooth; 10 – wheels; 11 – transmission; 12 – frame; and 13 – steering levers.

The main disadvantage of the motoblock harvester for use with lowbush blueberries is the risk of damaging the plants, such as pulling them out of the ground. The process of damaging and tearing the plants occurs as follows: on a plant with long stems, where the stems are low to the ground in all directions around the centre of the plant due to the weight of the berries, those stems which mainly face in the same direction as the picking rake often get stuck between the picking rake's teeth as the picking rake moves downwards. The stems of a blueberry plant which are caught between three or more teeth are torn to shreds or are pulled out of the ground by the rotating picking reel when the wheel is equipped with rigid teeth (usually made from stainless steel). There is no problem with plants which have low stems of up to 15 cm long, as they mainly remain upright, but it is a serious problem for plants with stems which are longer than 20 cm. The problem comes from poor compatibility between variations in plant growth and the picking reel teeth in currently-available blueberry harvesters.

The simplest technical solution to the problem would be to replace the rigid picking rate teeth with flexible teeth. To accomplish this, a material with suitable properties must be selected for the production of the teeth.

According to Fig. 2, a, the operating elements of the picking reel 1 are horizontal picking rakes, which comprise picking rake teeth, 3, which are rigidly affixed to the axes, 2, which in turn are attached in an articulated manner between the side discs. The picking rake teeth, 3, are designed to be produced from a flexible material in order to prevent damage being inflicted on the blueberry plants. The picking rake teeth, 3, can be located positions 3a and 3b. The berries are separated from the stalks by means of the teeth, 3, which are moved through the blueberry stalks. In the initial position, 3a, with this being the unloaded position, the picking rake is straight; in the loaded position, 3b, the picking rake is bent (Fig. 2, a). If a picking rake's elastic tooth, 3, gets stuck behind a plant stem or if a plant stem located on the picking rake's path gets stuck between the ends of the teeth, the rotation of the picking reel, 1, places an additional load on the teeth, 3, with the tooth bending and assuming position 3b. When the teeth, 3, bend this means the plant stems are released from between the ends of the teeth and tooth moves past the plant without damaging the stem. After being released from the plant stems, the teeth, 3, reassume their initial shape, as in position 3a. The picking rakes are connected according to the parallelogram principle and the angle γ of the tooth, 3, is adjustable.

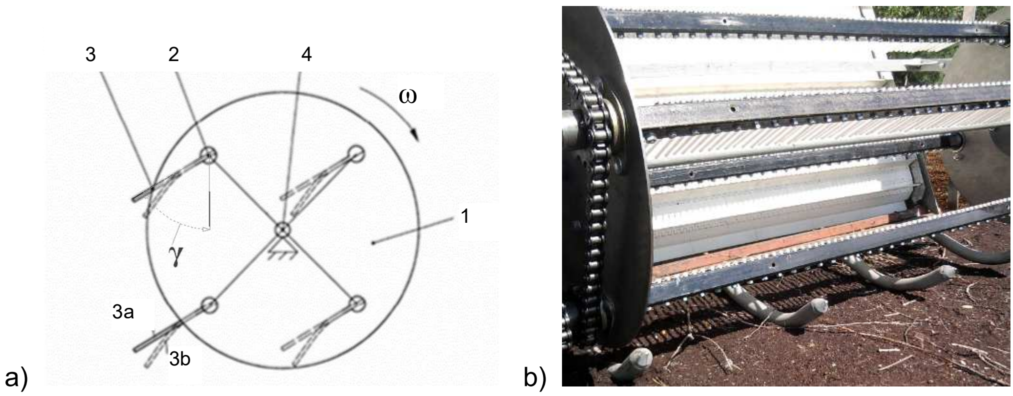


Figure 2. The blueberry harvester's picking reel: a) the principal schematic; b) prototype, with 1 – picking reel, 2 – picking rake, 3 – rake tooth, 3a – straight tooth, 3b – bent tooth, and 4 – spindle.

The aim of this work was to determine the flexure and durability of test specimens (plastic rods) which have been produced from elastic material which have differing general parameters, ie. observing and testing their suitability for use as picking rake teeth. The modified harvester with the flexible picking teeth may improve harvest efficiency and reduce plant damage, but requires testing to determine the feasibility of using this new harvester technology. Additionally, picking teeth conditions need to be studied to optimize harvest.

MATERIALS AND METHODS

In the case of lowbush blueberry harvesting, the system's elements are the blueberry plant, namely its berries, ie. the crop, along with the plant stalk which supports the berries, and the plantation and working harvester, which together form the blueberry cultivation system and subsystems. When the values of the relationships between the elements are known, it is possible to design harvesting technology in such a way that the requirement of preventing plant and berry damage during harvesting is ultimately fulfilled.

The Fig. 3 describes the forces exerted by the tooth on the berry and the plant during berry picking, where F_c is the connection force between the berry and the stem, F_s is the tensile strength of the plant's stem, and the connection force F_a between the stem and the soil, F_l is the lifting force, F_g is the gravitational force, E_m is elastic modulus of rake´s tooth material and E_s is tensile strength of plant's stem. It is evident from Fig. 3 that, in order to avoid damaging the crop or blueberry plants during harvesting, the harvesting machine must be designed in such a way that the following condition are fulfilled:

$$\left.\begin{matrix} F_{a,min} > F_{s,min} > F_l > F_{c,max} \\ E_m > E_s \end{matrix}\right\} \quad (1)$$

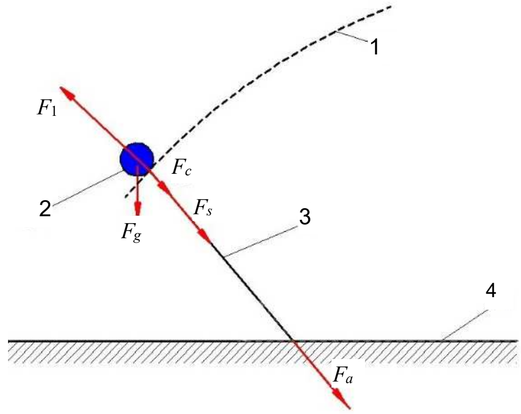


Figure 3. Those forces which are applied to a blueberry plant by the harvesting machinery flexible picking teeth: 1 – the picking reel's teeth; 2 – the berry on the blueberry plant; 3 – the blueberry stem; 4 – the field surface.

When taking these variables (Arak & Olt, 2017; Arak et al., 2018) into account, the material to be selected for the picking elements or the picking rake's teeth should be able to separate the berries, but should do no damage to the plant, or crush it, or tear it from the ground, and neither should it bruise the berries. Test work was carried out to select suitable material for rake tooth. Any description of those forces which are applied in the blueberry harvester's picking reel should be based on the coordinate system $O_1X_1Z_1$ (Fig. 4, a), as related to the berry that is to be removed, where the origin O_1 is located at the connection point between the berry and the stem, axis Z_1 is parallel to the blueberry plant, and the positive direction of the axis is directed towards the berry's surface and mainly forms a right angle with the non-deformed tooth.

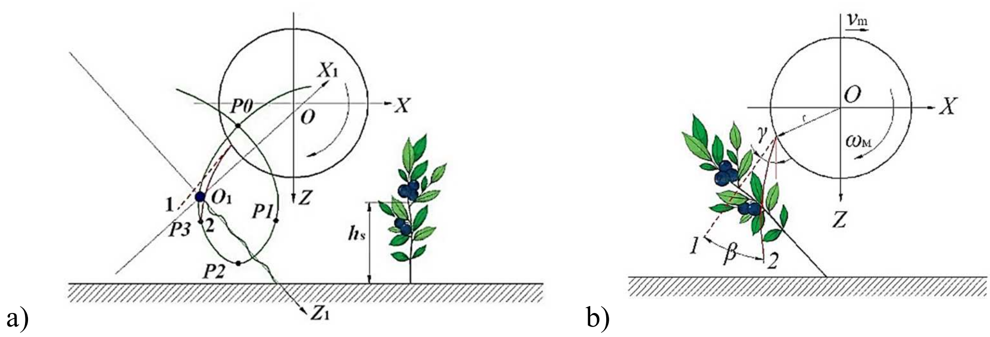


Figure 4. A diagram which characterises the work of a picking tooth: a) stages (*P1-P4*) of work of picking tooth; b) angles characterizing the work process for an elastic tooth.

The following forces are applied to the connection point between the berry and the tooth (Fig. 4, a).

In order to separate the berry from the stem, the force F_x which is applied to the connecting stem must be greater than the connection force $F_{c,\ max}$ between the berry and the stem.

The tooth of a picking reel is straight in the unstressed position (Fig. 4, position 1). Due to force F_c, the stressed tooth attains position 2, which forms a flexure in comparison to the straight tooth, as expressed by the angle of inclination β. The angle of inclination γ of the blueberry harvester's prototype can be changed within the range of 40°–70°.

The extent of any bending is determined by the value of connection force F_c.

The berry is removed from the stem when the inequality (1) and following condition (2) is fulfilled:

$$\beta < \gamma, \quad (2)$$

where γ is the angle between the non-deformed tooth and the vertical direction.

The calculation of the force being applied to the tooth is based on the following assumptions:

1. The maximum yield of the blueberry plantation: 17,000 kg ha^{-1}, or 1.7 kg m^{-2} (Siliņa & Liepniece, 2020);
2. The mass of an individual berry: 0.14–3.40 g (Soots et al., 2017);
3. Therefore, about a thousand berries grow over one square metre;
4. The blueberry harvester's prototype (Arak et al., 2018) has teeth that are placed 21.5 mm apart, with a length of 125.0 mm. The maximum working area for one pair of teeth is 0.27×10^{-3} m^2.

As arising from assumptions 1-4, there are three berries for one pair of teeth during a working cycle (Fig. 4, a, *P1-P3*). When we apply a reserve factor of three, a pair of teeth will pick about ten berries during one working cycle.

According to Arak & Olt (2017), the connection force of berries that are ripe for harvesting was 0.17–0.83 N and 0.89–1.93 N for unripe berries. The numerical ratio between ripe and unripe berries during harvesting season is 80% and 20% respectively. Therefore, the maximum force to be applied to one pair of teeth is 12 N.

The gravitational force which results from the tooth's mass itself is small (0.025 N for a tooth diameter of 4.3 mm and 0.038 N for a tooth diameter of 5.3 mm), and may be dismissed. Likewise, the gravitational force which results from the berry's mass may be dismissed as its maximum value is 0.034 N.

Selecting the materials for the teeth: an engineering plastic Ertacetal C (Acetal Copolymer, POM-C) was chosen as the material for the flexible teeth as it is characterised by its great mechanical strength, its impact strength, and its ability to be treated by cutting in manufacturing process of tooth (Olt & Arak, 2012).

Selecting the diameter of the teeth: two choices of material were selected so that the test could be carried out, with a round cross-section of the diameters of 4.3 mm and 5.3 mm.

The following tests were carried out when it came to selecting the diameter of the materials being used on the picking reel teeth, *D*:

1) Determining the plastic deformation of the teeth by systematically bending the material at various diameters (4.3 mm and 5.3 mm);
2) The resistance of the teeth to breaking-in so-called semi-aggressive and aggressive bending modes.
3) Measuring the flexure of teeth at various loads.

Describing teeth flexure theoretically

To investigate the flexure of the picking reel, we consider the tooth as being a cantilevered homogeneous beam (Fig. 5). This beam is characterised by the modulus of elasticity E_m and the moment of inertia I.

The finite element method, FEM, has been used to study tooth flexure (Logan, 2007). The picking reel's tooth (Fig. 5) is rigidly attached at point 1 (Fig. 5), and is loaded at point 2 by force F. The beam is now modelled using two elements, I and II, with nodes 1, 2, and 3.

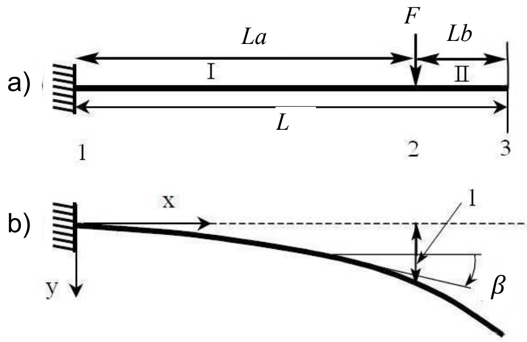


Figure 5. Cantilever beam being subjected a concentrated load: a) unloaded beam; b) loaded beam.

The local stiffness matrices for the elements I and II are K_1 and K_2 respectively.

$$K_1 = \frac{E_m I}{La^3}\begin{bmatrix} 12 & 6La & -12 & 6La \\ 6La & 4La^2 & -6La & 2La^2 \\ -12 & -6La & 12 & -6La \\ 6La & 2La^2 & -6La & 4La^2 \end{bmatrix}, \qquad (3)$$

$$K_2 = \frac{E_m I}{Lb^3}\begin{bmatrix} 12 & 6Lb & -12 & 6Lb \\ 6Lb & 4Lb^2 & -6Lb & 2Lb^2 \\ -12 & -6Lb & 12 & -6Lb \\ 6Lb & 2Lb^2 & -6Lb & 4Lb^2 \end{bmatrix}. \qquad (4)$$

The total stiffness matrix K is the result of assembling K_1 and K_2.

$$K = K_1 + K_2 \qquad (5)$$

Through direct superposition and considering (3) and (4), the governing equation for this cantilever beam is:

$$\begin{Bmatrix} F_{1y} \\ M_1 \\ F_{2y} \\ M_2 \\ F_{3y} \\ M_3 \end{Bmatrix} = K \begin{Bmatrix} d_{1y} \\ \beta_{t1} \\ l_t \\ \beta_{t2} \\ d_{3y} \\ \beta_{t3} \end{Bmatrix}. \qquad (6)$$

Considering the boundary conditions at node 1, we have:

$$\beta_{t1} = 0 \qquad (7)$$

and:

$$d_{1y} = 0. \qquad (8)$$

The momentum of inertia I for the beam with a circular cross-section can be described (Mäkelä et al., 2011):

$$I = \frac{\pi D^4}{64}. \qquad (9)$$

Due to the initial task (Fig. 5), we get:

$$F_{2y} = F. \qquad (10)$$

Solving the equation (6) by conditions (7), (8), and (10), the displacement at node 2 is:

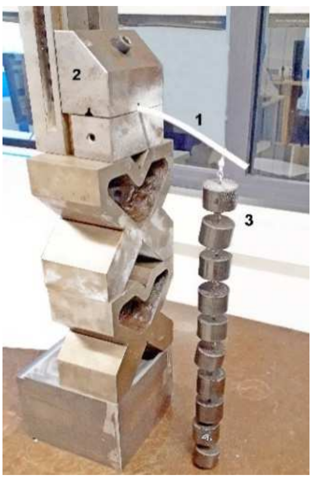
$$l_t = \frac{{L_a}^3 F}{3 E_m I} \tag{11}$$

where L_a – distance of the attachment point from the point at which the force F was applied and the slope (in radians) at node 2 can be calculated as:

$$\beta_{t2} = \frac{2{L_a}^2 F}{E_m I}. \tag{12}$$

Experiments for studying the flexure of the teeth

Tests were carried out with tooth materials of two different diameters: D_1 = 4.3 mm and D_2 = 5.3 mm (these values have been chosen based on theoretical calculations and material availability). Tooth (1) was connected to the stand (2) as a cantilever (Fig. 6, a). The tooth was stressed with plastic weights (3) which were connected to a point that was 20 mm from the free end. The loads were connected to the tooth (1) using a hinge (4) which ensured that the applied force was vertical. The room temperature was 22 °C and relative humidity was at 26% during the tests (the value of the material's modulus of elasticity E_m was determined under the temperature and humidity conditions of 23 °C and 50%).

a) 

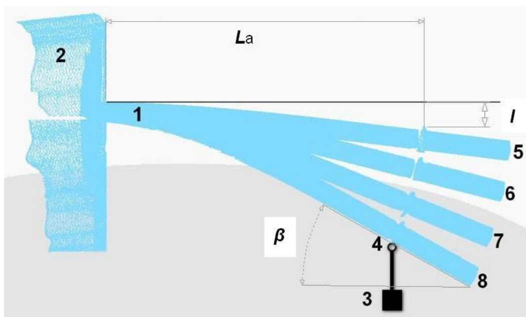
b) 

Figure 6. Test stand for measuring the tooth's flexure, a): and a digital model of the tooth's flexure b): with three weights (position 5), six weights (position 6), nine weights (position 7), and twelve weights (position 8), where l is the flexure of the cantilever beam and L is the distance between the cantilever attachment point and the weight attachment.

The flexures of the tooth (1) under various loads were scanned using a Nikon MCAx20/MMD50 portative laser scanner. After scanning, the resultant data was processed, a digital model was prepared, and flexure measurements were carried out using the software package, ANSYS SpaceClaim 2017.

A universal lathe was used to carry out the durability test on the tooth test specimens. The test equipment contained a fragment of a picking rake to which two tooth specimens were rigidly attached, one with a diameter of 4.3 mm and the other with a diameter of 5.3 mm. The fragment of the picking rake was installed on the lathe's jaws. A roller acting as an artificial obstacle was attached to the lathe's blade holder to simulate the passage of teeth between blueberry plants and their effect on the teeth in the test. Its distance from the axis of rotation of the picking rake fragment was less than the length of the tooth, while the tooth flexed upon its passing the artificial obstacle. The rotation of the lathe mimicked the work of the teeth upon blueberries being harvested, creating repeated bending cycles. The total number of revolutions for the test piece and therefore also the number of flexings in the teeth was 23,300.

During a field test, a blueberry crop (a mixt of several varieties) was harvested from a 0.1 hectare test plot. The test was carried out on Marjasoo Farm in Tartu County, South Estonia. The aim of the test was to check the durability of the flexing teeth in a commercial setting. The picking reel of used harvester has four rakes (Fig. 2, a), every rake has 66 tooth. The length and diameter of the tooth was controlled with the digitaal caliper ((Mitutoyo 200 mm) during of the installation of them, rotational speed of picking reel was controlled with rotational speed measuring device (ТЧ 10-Р). The flexure of teeth (5 randomly selected teeth on each rake) was measured before and after harvest of test plot with digital angle meter (ADA 20).

RESULTS AND DISCUSSION

The theoretical flexures l_t and β_t and the measured flexures l_m and β_m for materials of various diameters are given in Table 1 and Fig. 7, where l_m and β_m. are the arithmetic means of the three series of measurements. The calculations were carried out in the Mathcad 15.0 environment. For the theoretical calculations, the value of E_m was selected to be 3,000 MPa (Mitsubishi, 2020).

The teeth's work in passing through a blueberry plant and in removing the berries from the stem was simulated by loading the teeth with weights.

Table 1. Calculated and measured flexures of a tooth with diameters of 5.3 mm and 4.3 mm

F, N	D = 5.3 mm		D = 4.3 mm	
	l_t, mm	l_m, mm	l_t, mm	l_m, mm
3.0	8.5	8.8	19.7	23.1
6.0	17.2	17.8	39.6	44.5
9.0	25.7	27.7	59.3	59.3
11.9	34.3	36.7	79.1	69.0

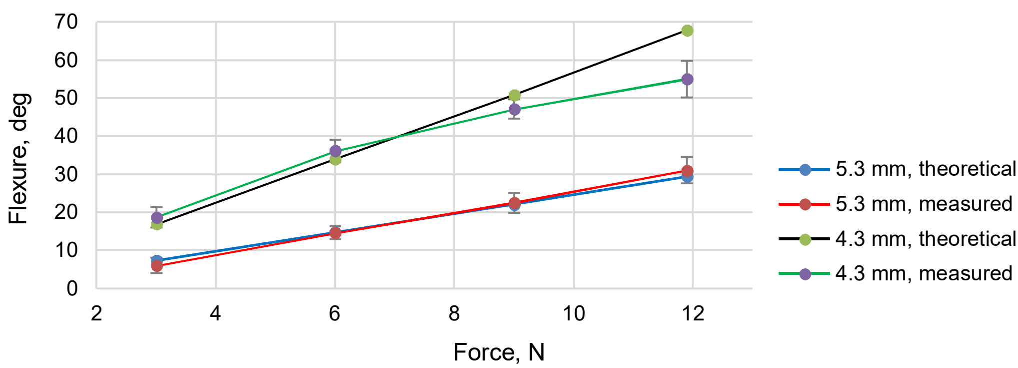


Figure 7. Calculated and measured (with standard deviation) flexures (in degrees) of a tooth with diameters of 4.3 mm and 5.3 mm.

Theoretical calculations (Eq. 11 and 12) and test results (Table 1 and Fig. 7) showed that the following results:

1) at maximum load (12 N), the flexure of the 4.3 mm diameter tooth test piece was at 70°;

2) at maximum load (12 N), the flexure of the 5.3 mm diameter tooth test piece was at 35°;

3) the differences between the theoretical and test results for materials with diameters of 4.3 mm and 5.3 mm are 10.1% and 5.1% respectively.

The results show that selected material with both diameters are suitable as materials for a picking reel's teeth as they both fulfil the condition under maximum load which was stipulated by Eq. (2).

The durability tests for the teeth revealed that, upon the long-term loading (23,300 flexings cycles) of the teeth, the residual deformation of a tooth with a diameter of 5.3 mm is up to three times higher than is the residual deformation of a tooth with a diameter of 4.3 mm (Olt & Arak, 2012).

No teeth were broken during the field test, but a flexing effect was observed in the tooth material (in the form of spring-back). The number of revolutions of the teeth during this test was 2,300. The average deviation of the free ends of the teeth from the longitudinal axis was 1.2 mm. After being left at a standstill for three days at a temperature of $T = 20–22$ °C, a new set of measurements were carried out with the following results: the permanent deformation in the 4.3 mm diameter teeth had disappeared and they had resumed their original position.

CONCLUSIONS

As a result of the flexure as the material for the picking reel's teeth, both 4.3 mm and 5.3 mm diameter test specimens were found to be suitable for the production of teeth, with the difference between theoretical and test results for 4.3 mm and 5.3 mm diameter materials being 10.1% and 5.1% respectively.

The flexing teeth do not tear the stem apart and neither do they pull the plants out of the ground, instead bending when an obstacle is encountered and regaining their original shape after clearing the obstacle.

Based on the results of all three tests - the flexure, durability, and residual deformation tests - the Ertacetal C with a diameter of 4.3 mm was shown to be a suitable replacement for standard teeth made from (stainless) steel, that led to reduced plant damage. This diameter was preferred over the 5.3 mm diameter because it has less residual deformation and the initial position recovers faster.

Further research should be done, such as larger field testing that evaluates long-term durability, harvest efficiency, economics of the proposed system, and impacts on berry quality. Also the length of tooth of picking rake and kinematic parameters (rotation speed of picking reel and working speed of the blueberry harvester) are also affect blueberry harvesting and should be additionally studied.

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