FEASIBILITY ANALYSIS OF FLUTED ROLLER DISPENSER APPLICATION FOR PRECISION FERTILIZATION

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SOONRULLDOSAATORI RAKENDATAVUS TÄPPISVÄETAMISEL

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ABSTRACT

With depleting resources, it is essential to increase the application of Agriculture 4.0 principles and technologies. Blueberry cultivation includes various operations, one of them being fertilization. To precisely discharge the correct amount of fertilizer, a volumetric dispenser utilizing a straight fluted roller could be considered as an option. The aim of this research is to verify whether such a dispenser could be used for precision fertilization with solid granular fertilizers. The output of the dispenser was measured on different conditions with three NPK fertilizers. Based on statistical analysis, the required 10% discharge uniformity cannot be achieved and it is necessary to modify the dispenser or use another one.

LÜHIKOKKUVÕTE

Järjest kahanevate ressurssidega on ülioluline tõsta ja kiirendada Põllumajandus 4.0 põhimõtete ning tehnoloogiate rakendamist. Kultuurmustikate kasvatamine kätkeb endas mitmesuguseid operatsioone, üks neist on väetamine. Soovitud koguse täppisväljutamiseks võib võimalikuks lahenduseks pidada sirgsoonrulliga mahtdosaatorit. Antud uurimuse eesmärk on selgitada välja, kas tuntud väljakülviseade on kasutatav granuleeritud väetisega täppisväetamiseks. Dosaatori väljundit mõõdeti erinevatel tingimustel kolme NPK väetisega. Statistilise analüüsi põhjal saab väita, et väljakülvi ühtlust 10% piires ei võimalik saavutada ning dosaatorit on tarvis kas modifitseerida või kasutada teist.

INTRODUCTION

Cultivation of low-bush blueberries (Vaccinium angustifolium Ait.) on depleted peat fields is seen as an economically profitable way to reduce greenhouse gas emissions (*Vahejõe et al., 2010*). However, the peat fields are commonly located in remote areas where workforce is scarce. Therefore, the mechanization and automation of technological operations is essential. Traditional agricultural machinery is intended to be used on mineral soils, which restricts its use on peat fields, as the traditional machinery may be too heavy (*Olt et al., 2013*). This creates a need for autonomous robots which are manufactured for use on peatlands. Notably the automation of the technological operations is also more efficient than mechanization (*Virro et al., 2020*).

Cultivation of blueberries requires several technological operations (*Olt et al., 2013*): soil preparation, planting, plantation maintenance, fertilization, plant protection, harvesting, post-harvesting processing, and cutting back the plants or carrying out rejuvenation pruning. From the list of technological operations above, fertilization is particularly important, as it may increase the yield from 3 to 8 times (*Vahejõe et al., 2010*). In order to achieve high yield, one must consider the issues of economic loss and potential environmental pollution due to excessive fertilization and plant’s nutritional disorders due to excessive or insufficient fertilization (*Chang et al., 2016*). Thus, precision agriculture plays an enormous role in the sustainable development of the cultivation system (*Chen et al., 2014*) and furthermore, precision fertilization is a key to economic and environmental success.

For effective and sustainable fertilization, suitability of machinery is essential. Evolution of machinery used for fertilization has been significant and in constant improvement. This has narrowed down the acceptable tolerances for fertilizer spread and discharge uniformity. Initially commonly used centrifugal spreaders provided approximately 30% uniformity (*Boson et al., 2016*).

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After improvement and further development of such spreaders, 15% uniformity has been achieved (*Bulgakov et al., 2021*). Major improvements have been done based on mathematically modelling the trajectory of fertilizer particles (*Olt & Heinloo 2009*). With computer-aided engineering software, which are based on discrete element method, more complex and precise simulations are being introduced (*Liedekerke et al., 2009*). This results in centrifugal disc spreaders providing less than 10% deviation from the target discharge rate (*Bulgakov et al., 2021*). This is acceptable for example for grain cultivation, but in some cases, such as blueberry cultivation, regardless of improved uniformity and enhanced control over discharge, broadcast fertilization with centrifugal-type disc spreader is not feasible and is unacceptable in terms of sustainable cultivation. Blueberry bushes are cultivated in rows (*Arak et al. 2020*), which means that applying fertilizer only for a row would have significant advantages compared to broadband spreading. More suitable is a spreader based on roller with outer grooves, often referred as a fluted roller dispenser, which has gained significant popularity and is considered very efficient when cultivating in rows (*Lv et al., 2012).* Such dispensers are simple, easy to manufacture, lightweight and compact (*Kuş et al., 2021*), capable of providing discharge uniformity usually between 10% and 20%, where better than 20% is considered acceptable and better than 10% is considered good (*Huang et al. 2018*). Due to the plantation pattern on the blueberry field, there are bare spots (*Soots et al. 2021*) between plants. Applying fertilizer to such spots would not only encourage weed growth on the field but also contaminate and simply waste fertilizer (*Olt et al., 2013*). Instead of simply applying fertilizer for the whole row, spot application has a significant effect to save up fertilizer costs, increase yield and decrease weed growth (*Chang et al., 2016*).

On the global scale the recommended fertilization rate for low-bush blueberries varies to a large extent. The recommended rate of nitrogen (N) in Canada (*Lafond, 2000)* is significantly higher than rates that have shown highest yield in Estonia (*Albert et al., 2011*). These locations differ by their latitude which implies differences in the length of vegetation period and climate condition. Moreover, meteorological conditions have shown to have the greatest impact on low-bush blueberry yield (*Parent et al., 2020*) and fertilization should take the length of vegetation period into account, as excessive amount of nitrogen during autumn fertilization may impede the lignification of shoots, which then are susceptible to frost damages (*Paal et al., 2004*). Therefore, the dispenser must allow fertilization rate adjustment while maintaining precision. However, the variety of granular fertilizers with significant differences in granule shape and size (*Lillerand et al., 2021)* add further complexity to the technical requirements of dispensing automation.

The aim of this paper is to clarify suitability of a common straight fluted roller dispenser for precision fertilization application by evaluating its precision in terms of agrotechnical and economic requirements, fulfilling 10 % discharge deviation criteria from determined target fertilization rate, while using three widely available granular fertilizers for low-bush blueberry.

MATERIALS AND METHODS

A commercially available volumetric dispenser was selected (Fig 1.), based on fluted roller design. Such a dispenser was considered due to its fairly simple construction, low price, versatility and longevity (*Huang et al., 2018, Bangura et al., 2020, Kuş et al., 2021*). In addition, such dispensers have proven themselves to be accurate enough in the grain seed sowing applications (*Kuş et al., 2021*). The roller is divided into grooves, with volume dependent on the radius of the flute and length of the roller. Rotating the roller by corresponding number of degrees results in output of a single groove while a revolution results in output of single grooves multiplied by number of grooves.

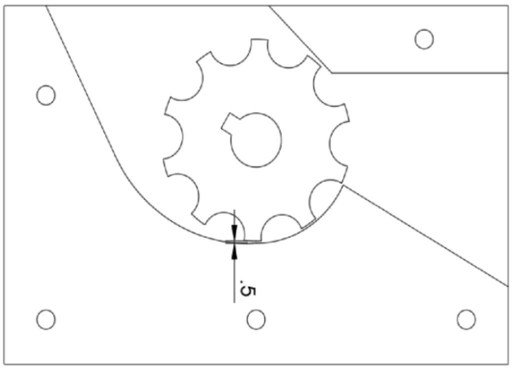
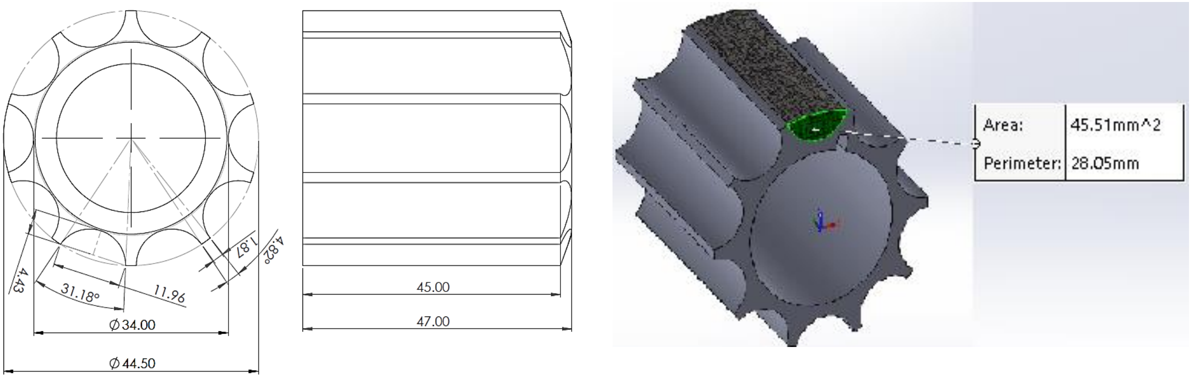


Fig. 1 - Simplified cross-section of the volumetric dispenser

In the study, a straight fluted roller (Fig 2.) was selected with 10 grooves, each of them with volume of 2.048 cm^3. With altering roller parameters such as flute diameter, shape, length and angle, the discharge rate is affected (*Liping et al., 2018, Kuş et al., 2021*). Using an optimal roller that ensures uniform discharge can result in saving up to 40% from fertilizer costs (*Bangura et al., 2020*). The number of flutes and their diameter is selected according to required discharge rate in time and considering size of the particles *(Gujar et al., 2018*).



(**a**) (**b**)

Fig. 2 - The selected fluted roller (Lillerand et al., 2021)

(a) measurements of the roller; (b) cross-section area of its groove

As seen in Fig. 3 and Fig. 4 the groove is never fully filled due to irregular placement and granulometric variations of fertilizer particles. In this case, the empty volume should be defined as porosity, where the porous part consists of the empty gaps between the fertilizer granules. Porosity is variable not only between different fertilizers but also within a single fertilizer and therefore, average porosity must be taken into account. It must be assumed that the fertilizer particles are spherical (*Valius & Simutis, 2009*). To express porosity:

$$\Phi=\frac{V_p}{V_s}=\frac{V_s\text{-}V_f}{V_s}=1\text{-}\frac{V_f}{V_s} \tag{1}$$

where:

V_p – volume of pores; V_s – volume of a groove; V_f – volume of granules in groove, with m_f.

Equation 1 reveals that by knowing discharged volume V_0, e.g. volume of groove and measured weight of discharged fertilizer m_f from it, the porosity can be easily found. To presume that granular fertilizer particles are with similar diameter spheres, then porosity is expressed:

$$\Phi=1\text{-}\frac{V_t}{V_s}=1\text{-}\frac{\pi}{6}n\left(\frac{d}{a}\right)^3 \tag{2}$$

where:

n - number of granules in cube with side length of a; d – diameter of granules.

It can be presumed that the number of granules in volume V_s = a^3 depends on their positioning. Theoretically it can be expressed if their placement is regular:

$$n=\frac{a}{x}\cdot\frac{a}{y}\cdot\frac{a}{z}=\frac{a^3}{xyz} \tag{3}$$

where:

x, y, z on Eq.3 is distance between granules in direction according to their X, Y and Z axis.

By combining equation 3 with 2:

$$\Phi=1\text{-}\frac{\pi d^3}{6xyz} \tag{4}$$

When observing two situations, with dense and sparse positioning, then porosity can be expressed:

$$\Phi_s=1\text{-}\frac{\pi}{6}\approx 0.48=48\% \tag{5}$$

$$\Phi_d=1-\frac{\pi\sqrt{2}}{6}\approx 0.26=26\% \tag{6}$$

This indicates that theoretically the porosity doesn't depend on the size of particles, but only on how they are positioned. From measuring the length, width and thickness of fertilizer granules, it is clear that the dimension is not constant and varies greatly. Therefore, to define the diameter of the particles, geometric mean d_m is used. To measure porosity directly in the dispenser, computed tomography device Yxlon FF35 CT was used. The porosity was measured from the corresponding groove, straight before discharging the fertilizer in 10 repetitions for each fertilizer, resulting in mean average porosity 48% for Substral, 59% for Agro NPK and 68% for Agro Organic.

The output of such dispensers is affected not only by the parameters of the roller or the granulometric parameters of a specific fertilizer, but also by the gap between the roller and dispensers' bottom flap (*Huang et al., 2018*). Every time the roller is being rotated, the moving particles can be divided in two separate layers: forced moving layer and influenced layer. Particles in the first layer rotate along with the roller while particles in the influenced layer are being dragged along by friction and interlocking between the particles (*Huang et al., 2018*). In addition, motion of the particles in the influenced layer is affected by friction between particles and the dispenser shell, including the adjustable bottom flap. Adjusting the gap to minimum, it results in less drag but too small gap can result in seized dispenser, crushed particles or even damaged dispenser. Too large gap creates greater drag, which decreases discharge uniformity (*Huang et al., 2018*). Therefore, the optimal gap was chosen based on granulometric properties of 3 fertilizers in this research scope (*Lillerand et al. 2021*), considering the mean average of the geometric mean diameters of the particles in the sample sets. Using the Industrial Computed Tomography device Yxlon FF35 CT, the measured gap was 4.38 mm (Fig 4.) which was fixed and remained the same through all the experiments carried out.

Fig. 3 - Straight fluted roller with a filled groove

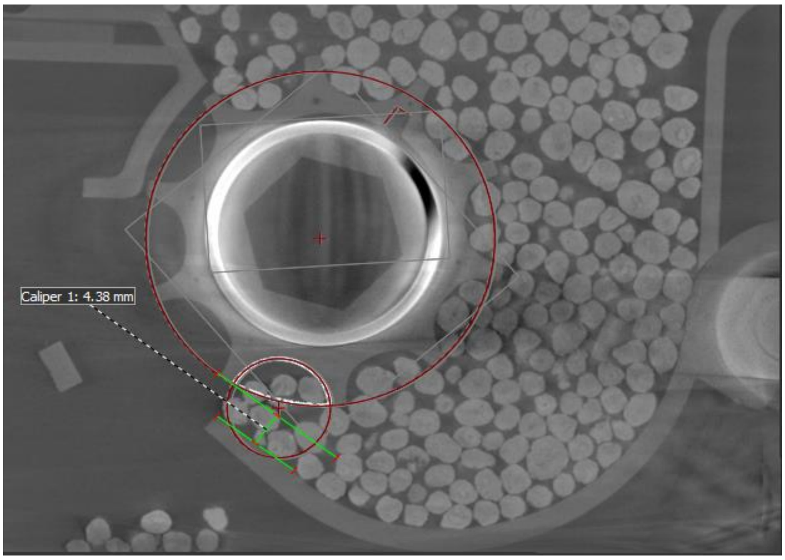


Fig. 4 - Dispenser cross-sectional view

4.38 mm gap measured between the roller and adjustable bottom flap

The necessity of using different fertilizers during the vegetation period comes from that for spring and autumn fertilization, different fertilizers are required due to different concentration of minerals, where in spring growth is stimulated and in autumn the plant receives minerals to enhance its resistance against the cold (*Paal et al., 2004*). As provided in table 1, concentration of nitrogen can vary up to 3 times. Taking examples from other similar research papers (*Bangura et al., 2020, Huang et al., 2018.*), the size of a sample set was 100 granules per fertilizer. For all three fertilizers, length, width and thickness of 100 particles were measured with a digital caliper Mahr 16 EWRi. Mean geometric diameter of 100 particles varies by 15%, sphericity varies by 21% and bulk density varies by 25%. This creates an additional requirement for the dispenser to be simultaneously suitable for three significantly different fertilizers (Fig 5.).

Table 1

Properties of blueberry fertilizers in scope

Fertilizer	**N**	**P**	**K**	**E_f**	**d_m,100**	**φ**	**γ**
	[%]	**[%]**	**[%]**	**[€·g^{-1}]**	**[mm]**	**[-]**	**[kg·m^{-3}]**
Agro NPK	12	6	24	0.0026	4.29	0.90	1030
Agro Organic	4	3	8	0.0016	3.64	0.74	775
Substral	5	15	30	0.0062	3.68	0.93	950

Fig. 5 - Examples of used fertilizers

(a) Agro Oranic; (b) Substral and (c) Agro NPK

Opposed to other similar research where the fertilizer discharge on field is measured in time (*Gujar et al., 2018, Huang et al., 2018, Bangura et al., 2020, Kuş et al., 2021*) in this study a different approach has been selected due to spot application. The number of discharged grooves is controlled by the feedback from the encoder attached to the fluted roller. Therefore, it is essential to clarify and establish the best possible discharge uniformity from a single groove. The output of the selected 10 groove fluted roller dispenser with bottom flap gap adjusted to 4.38 mm was measured respectively: output of single groove in 10 repetitions, output of full revolution in 10 repetitions, for each fertilizer. Each time the output was weighted with analytical scale Kern ABJ 220-4NM (Fig 6.), creating a dataset that was used for predicting the output based on the required number of grooves to be emptied.

Fig. 6 – Kern ABJ 220-4NM analytical scale (*Lillerand et al., 2021*)

Average groove discharges ($\underline{m_g}$) of a single groove and the full revolution of the grooved roller were compared in order to understand if the mass of multiple consecutive groove discharges differs from the mass of a single groove discharge. As the grooved roller had 10 grooves, the discharged mass of a full revolution was multiplied by the factor of 0.1 in order to make the values comparable with the discharge mass of a single groove. Normality of data was evaluated with Shapiro-Wilk test. As the distributions did not significantly differ from normal distribution ($p > 0.171$ in all cases), two-sample t-test was used to compare the $\underline{m_g}$ of the single groove and full revolution conditions.

A novel approach was used to determine the discharging precision. Usually discharge uniformity in time unit is used to evaluate the discharging precision (*Gujar et al., 2018, Huang et al., 2018, Bangura et al., 2020, Kuş et al., 2021*). In the current study discrete values of single grove discharges were combined to calculate the distribution of fertilization rates. Discharging precision was evaluated by setting the target fertilization rate Q_t [g·plant $^{-1}$], calculating the number of groove discharges η_c, and then calculated fertilization rates Q_c were found using η_c and measured m_g values.

Nitrogen rates resulting in high yield in an Estonian low-bush blueberry fertilization experiment (*Albert et al., 2011*) were used to set Q_t value. The average of the two N rates with highest yield, Q_{tN} = 1.6 g plant $^{-1}$, was then divided by the fertilizer's N concentration (table 1) to calculate the Q_t for each fertilizer (table 2).

The number of groove discharges η_c was calculated:

$$\eta_c=\frac{Q_t}{\underline{m_g}} \tag{7}$$

The η_c values were rounded to the nearest integer and are denoted as η_t. Then, the number of possible combinations C that can be obtained with η_t and the quantity of m_g data was found:
if $\eta_t < 10$, then:

$$C=\frac{n!}{(\eta_t!(n-\eta_t)!)} \tag{8}$$

if $\eta_t > 10$, then:

$$C=\frac{n!}{(x!(n-x)!)}\cdot\frac{n!}{(y!(n-y)!)} \tag{9}$$

where: $n = 10$, $10x + y = \eta_c$, $x = \{1, 2, ..., 9\}$ and $y = \{0, 1, ..., 9\}$.

For each fertilizer all C combinations of m_g data were obtained with a custom MATLAB script. Combinations of m_g data, denoted as m_c, were then used to calculate Q_c:

$$Q_{c_i}=m_{c_i}\cdot\eta_t,\ \left[g\cdot plant^{-1}\right] \tag{10}$$

where: $i = \{1, 2, ..., C\}$.

Table 2

Parameters of discharging precision evaluation

Fertilizer	**Q_t**	**$\underline{m_g}$**	**η_t**	**C**
	[g·plant $^{-1}$]	**[g]**	**-**	**-**
Agro NPK	13.3	2.705	5	252
Agro Organic	40.0	1.730	23	5400
Substral	32.0	2.664	12	450

Targeted (E_t) and calculated (E_c) fertilizer expenses were calculated as follows:

$$E_t=Q_t\cdot E_f,\ [€] \tag{11}$$

$$E_c=\underline{Q_c}\cdot E_f,\ [€] \tag{12}$$

where:

$\overline{Q_c}$ is the average calculated fertilization rate, and E_f is fertilizer's unit expense €·g^{-1} (table 1).

RESULTS

In the case of Agro NPK the differences of average groove discharges between the single groove ($\underline{m_g}$ = 2.705 g) and full revolution ($\underline{m_g}$ = 2.672 g) conditions were not statistically significant, t(18) = 0.21, p = 0.836. Similarly, in the case of Agro Organic the differences of average groove discharges between the single groove ($\underline{m_g}$ = 1.730 g) and full revolution ($\underline{m_g}$ = 1.955 g) conditions were not statistically significant, t(18) = 1.64, p = 0.119. In contrast, in the case of Substral the differences of average groove discharges between the single groove ($\underline{m_g}$ = 2.664 g) and full revolution ($\underline{m_g}$ = 2.377 g) conditions were statistically significant, t(18) = 2.97, p = 0.008.

In all cases the Q_c values fall in the range of the minimum and maximum fertilization rates (Fig 7.) providing the highest yield in the experiment of Albert et al. (*Albert et al., 2011*). However, in the case of Agro Organic and Substral the calculated rate is significantly different from the target, where with Organic the fertilizer is potentially wasted and with Substral, the fertilization is significantly below target rate. With fertilizer Organic the actual cost per plant is also higher than the target is. The fertilization rates provided in the experiment of Albert et al. (*Albert et al., 2011*) do not consider modern agricultural machinery capabilities or the precision fertilization principles and simply provide the data for fertilization rates that the plant can handle without damaging and providing the greatest yield.

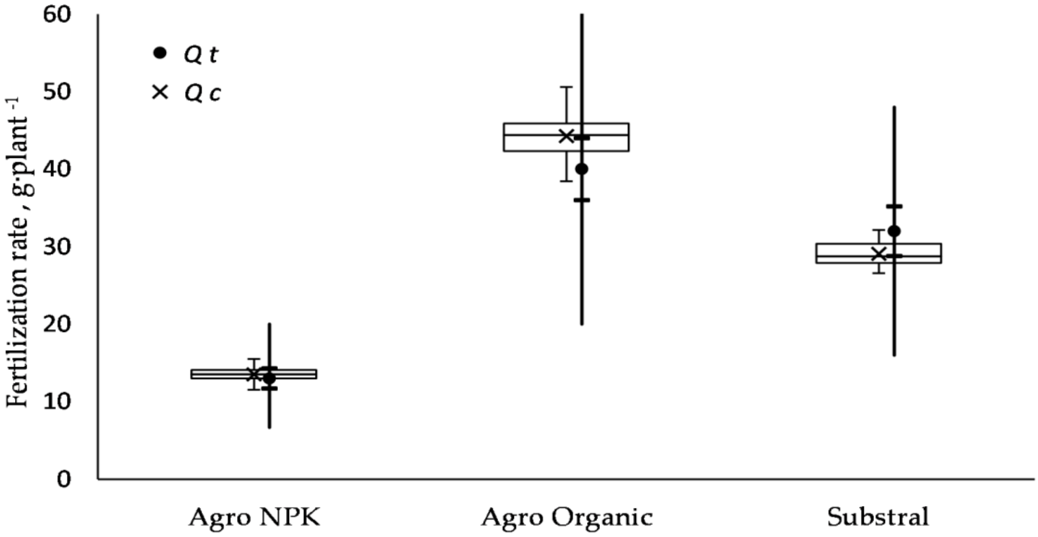


Fig. 7 - Targeted (Q_t) and calculated (Q_c) fertilization rates

Boxplots represent distribution of Q_c, the lines next to boxplots cover the range of two highest yielding fertilization rates in Albert et al., (2011) with target rate Q_t and 10% deviation tolerance for it

By adding the 10% discharge deviation requirement to the target fertilizer rate, only with Agro NPK the dispenser meets the requirements. For Agro Organic, the calculated discharge rate is rather near the upper 10% limit from the target rate and for Substral, the calculated discharge rate is near the bottom 10% limit. In some cases, the discharge rate is out of the 10% tolerance limits. This indicates that in terms of precision farming and precision fertilization, the dispenser is not meeting the requirements (*Huang et al., 2018*).

Discharging excessive fertilizer has effect on increased weed growth and environmental contamination, which both inhibit yield and profit from the blueberry cultivation (*Olt et al., 2013*). Provided in the research of Albert et al. (*Albert et al., 2011*) and Paal et al. (*Paal et al., 2004*)., it is rather preferred to fertilize below the target than above it, as over-fertilization has greater effect on the yield than under-fertilization.

In addition to plant health, yield and environmental aspects, there is also an economical aspect. Due to the vast increase in the prices of available fertilizers, the significance of precision in fertilization process becomes progressively dominant. On a blueberry field of 25 ha area and 1 by 1 m^2 plotting, with technological paths and infrastructure, fertilization of over 200 000 plants can result in excessively spent 1400 € when using one of the three fertilizers (Organic) studied in the paper. Moreover, in the long run additional issues may rise from the inability to predict precise quantity of fertilizer for the whole vegetation period (table 3). This is especially important considering the instabilities in supply chains.

Table 3

Target of fertilizer cost per plant, calculated cost, difference between target and calculated

Fertilizer	E_t	E_c	E_c - E_t
	[€·plant $^{-1}$]	[€·plant $^{-1}$]	[€·plant $^{-1}$]
Agro NPK	0.035	0.035	-0.001
Agro Organic	0.065	0.072	-0.007
Substral	0.197	0.179	0.018

The suitability of a selected common straight fluted roller dispenser for precision fertilization, using three widely available granulated low-bush blueberry fertilizers, is assessed by corresponding to agrotechnical and economic requirements. Firstly, the agrotechnical requirements are met, as these are robust and perhaps outdated. The agrotechnical requirements reflect the capabilities of the previous generations of agricultural machinery and do not allow to apply the full potential of machinery in the Agriculture 4.0 framework, as the paradigm of precision has obtained stricter tolerances. Further research is needed to determine the agrotechnical requirements for precision fertilization in the context of increased potential of the machinery. Secondly, the economic requirements are heavily influenced by fertilizer's parameters (unit cost, nutrient composition, granulometric and mechanical parameters) and agrotechnical requirements (need to adjust the fertilization rate during the vegetation period). The selected common fluted roller dispenser managed to achieve acceptable fertilization rate only in the case of one of the three fertilizers (Fig 7.). This is an insufficient result, as the dispenser is expected to achieve precision regardless of the fertilizer's parameters. Fertilizer must be chosen considering the needs of the plant not by the capabilities of the dispenser, therefore the dispenser design needs to be altered to support precise discharging of various fertilizers.

The total deviation of a fluted roller dispenser's output is incremental and depends on the number of required grooves (*Bangura et al., 2020*). By reducing the necessary number of dispensed grooves, decreasing porosity in a groove and increasing discharge uniformity, better results can be expected. The design and optimization are advised to be done by using discrete element method-based simulation software, as trial and error approach is ineffective and time consuming and may require over 20 iterations considering a single fertilizer (*Huang et al., 2018*). Alternative design, verified by discrete element method simulations is most likely to enhance the results and provide a design fulfilling the requirements for all three fertilizers.

CONCLUSIONS

Due to the fact that different fertilizers with different chemical, mechanical and granulometric properties are used during the vegetation period, key requirement to the dispenser is compatibility with all the fertilizers simultaneously, providing accurate and consistent output. The aim of this paper was to clarify suitability of a commercially available common straight fluted roller dispenser for precision fertilization application. This was done by evaluating its precision in terms of agrotechnical and economical requirements while using three widely available granular fertilizers for low-bush blueberry. It was found that the selected dispenser when used with one of the three fertilizers is suitable and accurate enough to support both, the agrotechnical and economical requirements. While in the case of the remaining two fertilizers, the agrotechnical requirements are met, but the conceptual requirements and economic aspects involve risks due to inability to precisely meet the targeted fertilization rates. In conclusion, practical tests and data analysis revealed that in current state, the commercially available dispenser is not suitable for precision fertilization applications and further development is required by mainly designing a suitable roller for the fertilizers in the scope.

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