FEASIBILITY OF SCREW DOSING SYSTEM FOR LOW-BUSH BLUEBERRY FERTILIZATION

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Abstract. Analysis of recent studies has shown that automation in agriculture presents significant opportunities to improve efficiency and reduce labour dependency in modern farming. One area of focus is the precise and automated dosing of granular or powdered materials, such as fertilizers, using field robots, in particular blueberry fertilizing robots. This article introduces the design and development of a screw dosing system intended for integration with an agricultural robot. The machine employs a screw-type mechanism for material dosing. The aim of this article was to explore the accuracy, and feasibility of the proposed screw dosing system for agricultural applications. Design parameters, including the screw geometry and multiple threads, are discussed. Based on past research, the rational amount of the fertilizer for this case is found, and material properties like size distribution and shape characteristics determined by several tests. Theoretical validation using DEM analysis and experimental validation of the dosing accuracy tests with a 3D printed prototype were conducted, resulting in a system that dispenses within tolerances in 90% of the cases and underdoses in 9.2% of the cases. A viable solution regarding the parameter set was created. Design parameters such as the dosing amount, accuracy and form factor are constrained by an existing project, where the system would be used. Similar dosing systems are analysed and possible improvements are proposed. This study contributes to the development of automated solutions that enhance the precision and sustainability of agricultural processes, particularly in resource-constrained environments.

Keywords: discrete element method, precision agriculture, smart farming, berry cultivation.

Introduction

The cultivation of low-bush blueberries (Vaccinium angustifolium Ait.) on depleted peatlands is recognized as a sustainable agricultural practice with potential climate benefits, such as reducing greenhouse gas emissions [1]. However, due to the remoteness of these areas and the limited availability of labour, there is a pressing need to automate cultivation processes. Conventional machinery, designed primarily for mineral soils, is often unsuitable for peat-based fields due to excessive weight and compaction risks [2] and field robots could be one possible solution [3]. This situation highlights the necessity for lightweight, autonomous systems specifically adapted for soft soil, such as plantations that are established on depleted milled peat fields. Cultivation of blueberries requires several technological operations, one of them being fertilizing.

Fertilization is of high importance because accurate fertilizer dosing could lead to 3-8 times higher yield [1]. Traditional fertilization methods often suffer from inconsistencies which could lead to over fertilizing which in turn results in wasted fertilizer and potential environmental pollution. [4] Machinery suitability for fertilizing can be evaluated based on precision. Advancements have been made in the field of the fertilising technology. Disc spreaders initially provided 30% of uniformity [5], after developments 15% of uniformity has been achieved [6]. Advancements in simulations [7] and understanding of materials has improved the accuracy of disc spreaders to a deviation of less than 10% from the target discharge rate [6]. Disc spreaders are suitable for cereals, not for cultivated blueberries.

Blueberry bushes are cultivated in rows [8] which makes fertilizing the entire field unreasonable. Fertilizing only the individual blueberry bushes is more economical and leads to less environmental pollution. Fertilizing uncultivated spots between blueberry bushes leads to weed growth, which adds to labour costs, contaminated soil and significant economic inefficiency from the fertilizer losses [2]. Fertilization rate for lowbush blueberry depends on the location of the plantation and the size of the plants. For example, nitrogen rates that show the highest yield in Canada [9] are significantly higher from nitrogen rates that show the highest yields in Estonia [10], this makes universal dispensers impractical.

Different types of dosing systems have been analyzed for this purpose. Flueted roller dispenser is one possible solution as this has been used for fertilizing rows of plants. [11] The accuracy of such systems has been analyzed in the past with results indicating a suitability based on the fertilizer and its properties [12]. A dosing system that could be made compatible with a specific fertilizer by 3D printing important elements of the dosing system would make custom dosing systems more economical and precision fertilizing more accessible. Fused deposition modelling (3D FDM) results in a part that is not uniform in strength [13]. The screw geometry does not have large overhanging features that makes 3D FDM a suitable option. The prototype helps understand if it is even feasible for short term use, longer tests should be done to evaluate reliability in the long term and choose the optimal manufacturing method.

The aim of the article is to evaluate the screw-based dosing system suitability for this type of fertilizer and for the fertilization process in general.

Materials and methods

Design parameters

Design of any dosing system depends on the required accuracy, speed and efficiency. This article mostly focuses on accuracy of a screw dosing system. The fertilizer used is Yara Mila Cropcare NPKS-8-11-23-29 [14]. Manufacturer specification for the granule size is to be within 2-4 mm in 88% of the granules. The required amount of fertilizer per plant is calculated based on the nitrogen content C_N in the fertilizer, for this fertilizer C_N = 8% [14]. The required amount of nitrogen per plant m_{gn} = 1.6 g [10]. To find the specific amount of this fertilizer for each plant the following formula was used [10]:

$$Q_{tN} = \frac{m_{gn}}{C_N} = \frac{1.6}{0.08} = 20 \text{ g}, \tag{1}$$

where Q_{tN} – required amount of fertilizer per plant (g);
m_{gn} – required nitrogen for each plant (g);
C_N – percentage of nitrogen in the fertilizer.

Precision of the system is evaluated in relation to the target dosage. Firstly, a single dose of the system is found, and the standard deviation calculated. Fertilizing accuracy of the system should be within 10% of the targeted value, so ± 5% is considered [15]. As brought out in the studies regarding lowbush blueberries, for berry yield it is better if the system slightly underdoses, rather than overdoses.

Material characterization

Accurate representation of fertilizer granules is essential for modelling their behaviour in the discrete element method (DEM) simulation. The physical properties of granular materials significantly influence their interaction with the screw dosing mechanism, affecting the dosing accuracy. This section presents the methodology and results of material characterization, including the particle size distribution, shape analysis, and bulk density measurements.

To determine the distribution of particle sizes, a sieve analysis was conducted. The fertilizer granules were passed through a series of sieves with each mesh size d_s being 0.2 mm smaller than the one before, then the retained fractions were weighed to establish the percentage distribution across different size ranges. This was done in batches of 100 g, to ensure the sieves did not become blocked. In total 500 g were analysed. The results are given in the version that DEM software expects, cumulative passing. This allows the software to construct the particles based on the distribution of the sizes. This method provided an overview of particle size variability, which is critical for understanding how the granules will interact within the screw dosing system. For all weight-based measurements a Kern ABJ 220-4NM analytical scale was used. Fig. 1 shows how the test was conducted, visual inspection was used to verify that all particles that could pass, had passed. Fig. 2 shows what percentage of material passed each of the sieve sizes. This method of representation is required by the simulating software. The following formula was used to calculate the percentage of particles that passed the sieve [16]:

$$100\% - \%\ retained(C)(Current\ sieve) = C_p\ (Current\ sieve). \tag{2}$$

The simulation software can model particles as spheres, polyhedrons, sphero-cylinders or sphero-polygons. In this study spherical or sphero-cylindrical representation is relevant. To decide between the two representations, 200 granules were measured with the Insize 1103-200 digital caliper for length, width and thickness. The resulting equivalent diameter was calculated using the following formula [12]:

$$D = \sqrt[3]{LWT}\ , \tag{3}$$

where D – equivalent diameter;
L – length;
W – width;
T – thickness.

With the D found, sphericality ϕ of the granule can be calculated with formula [12]:

$$\phi = \frac{D}{L} \tag{4}$$

Based on the measurements and calculations, the following characteristics were found:

- arithmetical average equivalent diameter D_{avg} = 3.64 mm;
- mean equivalent diameter D_{mean} = 3.68 mm;
- arithmetical average sphericality φ_{avg} = 0.92;
- mean average sphericality φ_{mean} = 0.93.

Fig. 1. **Fertilizer particles in the sieve**

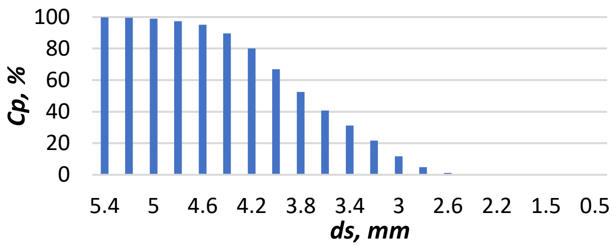

Fig. 2. **Material distribution based on sieve size, cumulative passing method**

Based on these results the material representation that was chosen was sphere.

The bulk density ρ was found using a graduated container and the fertilizer in an uncompacted state. Fifteen measurements were carried out and the calculated average bulk density is ρ_{avg} = 1152.1 kg·m^{-3}.

Design of the screw dosing system

The screw dosing system consists of multiple parts and based on the design the number of parts can differ, but the basic parts are indicated in Fig. 3, and dimensions of the screw in study are shown in Fig. 4.

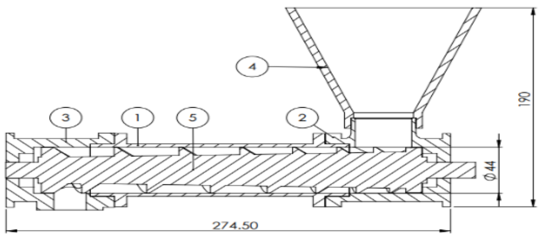

Fig. 3. **Screw dispenser components:** 1 – body; 2 – inlet housing; 3 – outlet housing; 4 – hopper; 5 – screw

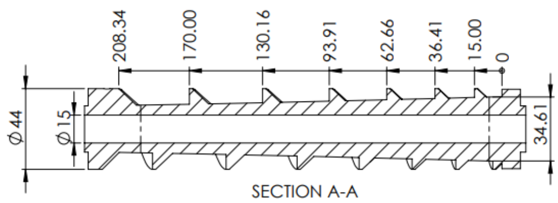

Fig. 4. **Screw geometry**

This system was designed to be manufactured by 3D FDM. This mainly affected the screw design. To help with manufacturability, the screw thread was designed with a 45° incline, this allowed the screw to be 3D printed standing on its end. To prevent blocking of the screw, the helix is designed with a variable pitch, whereas the screw goes on, the pitch becomes larger. The shaft of the screw is tapered. The idea behind this design is to take as much load off the screw as possible, to ensure that the volume of the space between the screw and the body increases from the inlet side to the outlet side. Horizontal alignment is beneficial for integrating it into existing designs, as the dispenser is placed below the hopper, it does not affect the ground clearance of the system significantly. The screw moves the material horizontally to a position where it can be accessed by application devices, for example, by a robotic arm.

Simulation setup

Open-source DEM software was used to simulate the particles or granules flowing in and flowing out. Material inlet and outlet geometries were created and the material flow defined by $Q_{m} = g \cdot s^{-1}$. For the screw to rotate a motion frame was created, with the centre of the screw as the axis of rotation, and a speed $\omega_{s} = 5$ rad $\cdot$ s^{-1}. No acceleration was applied. The timeline for the simulation is as follows: 1-5 s the inlet provides the material at the specified rate. The screw starts rotating from the third second, as this allows for the material to accumulate. The entire simulation duration is $t_s = 57$ s. The simulation environment is shown in Fig. 5. To verify the simulation results, a 3D printed prototype showcased on Fig. 6 was tested. All the parts were manufactured from PLA material, by using Creality K1 MAX and assembled at the rapid prototyping lab at the Estonian University of Life Sciences.

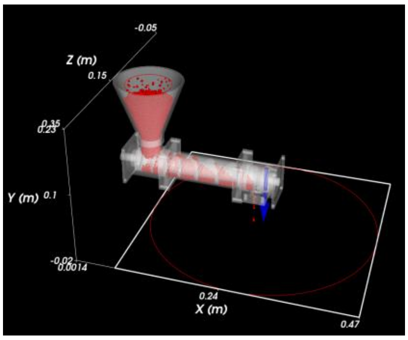

Fig. 5. **Simulation environment**

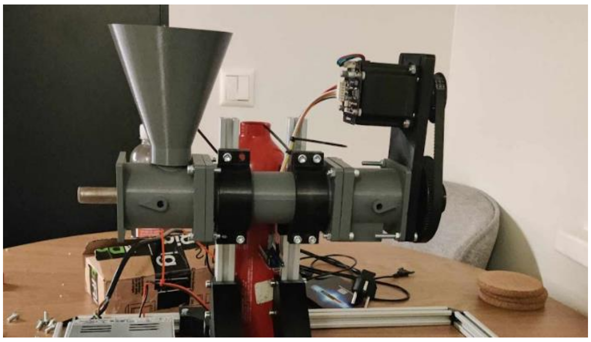

Fig. 6. **3D Printed and assembled prototype**

Results and discussion

The results are verified by rotating the screw by one cycle *T*, of which one chamber empties completely, and the material of that chamber is weighed. It should be noted, that wear of the flight screw was not noticed after the testing and the screw remained usable after multiple tests. The results are presented in Fig. 7 and Fig. 8 where the orange line represents the mean dose value. For the simulations the mean dose is $M_{mshs} = 6.34$ g and standard deviation $\Delta_{mshs} = 0.49$ g, for the measured values $M_{mshm} = 6.56$ g and $\Delta_{mshm} = 0.28$ g accordingly.

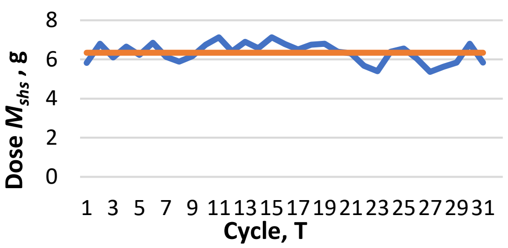

Fig. 7. **Single helix DEM simulation results**

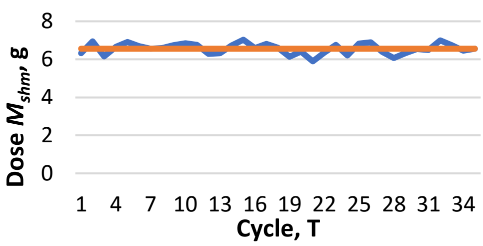

Fig. 8. **Single helix measurement results**

A double helix screw was designed to test, if lower dose per cycle yields better accuracy. This lowered the volume that the fertilizer could fall into, and cycle *T* was now only half of a turn. The simulation parameters and measurement methodology were maintained. The results (Fig. 9 and Fig. 10) indicate peak values which rules out the usage of this specific screw design. A single helix screw was tested further. The acquired data was analysed with Microsoft Excel Descriptive Statistics package and the resulting data is presented in Table 1. It should be noted that the sample variance smooths out peak values which are important in this scenario. The double helix screw standard error values are lower, but it also requires roughly five times as many cycles to complete the same dosage, so the total error should be considered.

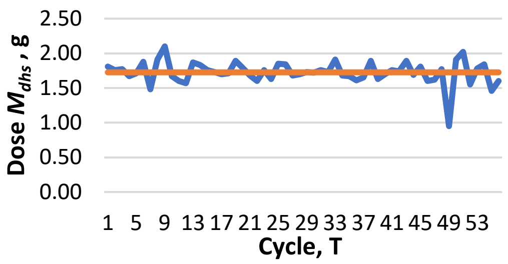

Fig. 9. **Double helix screw simulation results**

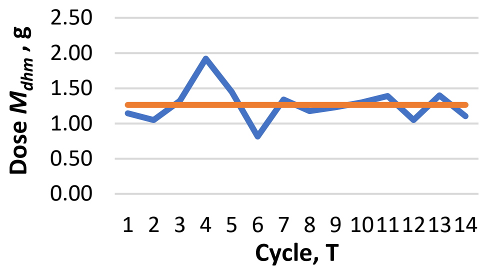

Fig. 10. **Double helix screw measured results**

Table 1

Data analysis results

Parameter	Single helix DEM	Single helix measured	Double helix DEM	Double helix measured
Mean, g	6.34	6.56	1.73	1.26
Standard error, g	0.09	0.05	0.02	0.07
Median, g	6.39	6.59	1.73	1.26
Standard deviation, g	0.49	0.28	0.16	0.26
Sample variance	0.24	0.08	0.03	0.07
Range, g	1.76	1.14	1.15	1.11

1000 doses were synthetically generated (Fig. 11). As the target value is 20 g, with a M_{mshm} = 6.56 g, three turns should be done for a synthetic dose M_{shg}, between limits of 21 g and 19 g. The limits are set according to desired accuracy of 10%, allowing maximum under– and overdose by 5%.

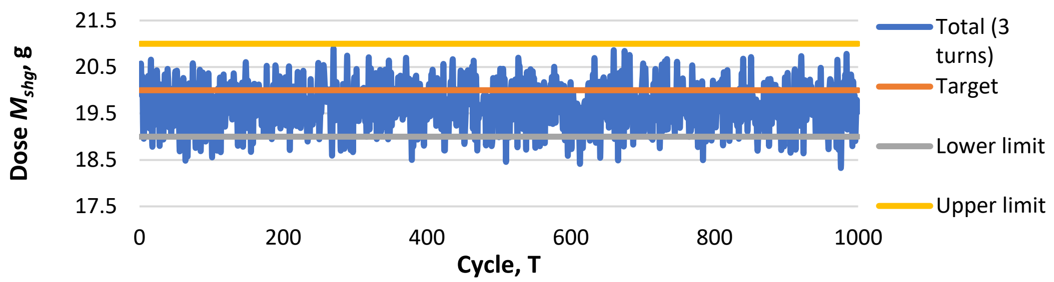

Fig. 11. **Synthetically generated doses**

The single helix screw dispenser tested in this study doses within the set limits in 90% of the cases, 9.2% cases it under- and only 0.8% cases it overdoses. The dosing system is considered accurate if it dispenses within 10% of the target value [15], which this system does not always achieve. As overfertilization is harmful to the environment and leads to economic losses [2], the proposed system in this study is a viable solution. There are dispensing systems such as for powdered materials and coffee beans, which provide higher accuracy, but due to their technical limitations they cannot be used with granulated fertilizers [17-18]. A belt-pin fertilizer dispensing system has been tested with 6.1 - 9.3% of dispensing uniformity, but it is intended for fertilizing fields, not plantations [19]. In future work, adding weight based feedback and pregrinding larger granules could possibly result in better dispensing uniformity.

Conclusions

1. The results show suitability of the studied dispenser for the given fertilizer and dosing parameters.
2. In the given case, the single helix screw had better discharge uniformity and accuracy.
3. The proposed system achieves the desired accuracy in 90% of dispensing cases and has a tendency to under dose.

Author contributions

Conceptualization, T.L.; methodology, K.K. and T.L.; software, K.K.; validation, K.K. and T.L; formal analysis, K.K.; investigation, K.K. and T.L.; writing – original draft preparation, K.K.; writing – review and editing, T.L.; visualization, K.K.; project administration, T.L.; funding acquisition, T.L. All authors have read and agreed to the published version of the manuscript.

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