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Granulometric Parameters of Solid Blueberry Fertilizers and Their Suitability for Precision Fertilization

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Abstract: For precise fertilization of blueberry plants, it is technologically the easiest and most suitable option to use a volumetric filling, for which it can be presumed that it is possible to precisely dose the fertilizer for each plant by grams. For setting up a volumetric filler, it is necessary to know parameters such as the size of the fertilizer particles and their bulk density. The aim of this research is to determine the granulometric parameters and their effect, which is done by measuring up three different fertilizers (SQM Qrop K, Memon Siforga, Substral): width, height, and length of 100 randomly selected fertilizer particles as well as the volumes and weights of 100 particles in 10 repetitions. According to the measurements, the average diameters of fertilizer particles were found as well as the average mass, volumes, and bulk density. A Mahr Digital Caliper 16EWRi 0–150 mm was used to measure the diameters of the fertilizer granules. A Yxlon FF35 computer tomograph was used to accurately scan particles. The analytical scale, Kern ABJ 220-4NM, was used to determine mass. The volumes were measured, using measuring glasses, with one having a maximum volume of 10 mL in 0.2 mL increments and another having a maximum volume of 100 mL in 1 mL increments. Descriptive statistics analysis was performed in Microsoft Excel. It turned out that the average diameters (3.68 vs. 3.64 vs. 4.29 mm) and bulk densities (0.928 vs. 0.631 vs. 0.824 g cm^{-3}) of the three fertilizers differed far from each other, meaning that the given volume could be filled with different amounts of fertilizer. Equations between mass and weight were formed according to the measurements. As a result, it was found that a volumetric filler can be used for fertilizing blueberry plants precisely, but it demands adjusting the filler each time in the situation, which is defined by the variety of blueberry plants: their age, size, and health.

Keywords: agricultural robotics; berry plantation; dosing; product design and development

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1. Introduction

According to several authors who have been involved in applied research and the development of cultivated blueberries; i.e., [1–4]; the system for blueberry cultivation includes fertilization during the growing season, in addition to other technological operations (such as soil preparation, planting, plantation maintenance, plant protection, harvesting, post-harvest processing, and plant culling, i.e., rejuvenation pruning). This paper is dedicated to the precision fertilization of cultivated blueberry plantations which have been established on depleted milled peat fields.

The mechanical cultivation of berries, including blueberries, in which all technological operations are mechanized [2,5], can be made even more efficient by using precision cultivation methods [6], and by automating its technological operations. In the introduction of precision farming, unmanned platforms [7,8] and field robots [9] are increasingly being used in various technological operations.

The start of the process of automating—or robotizing—blueberry cultivation can reasonably be assumed to begin with the work of fertilizing the plantation. For this purpose, a fertilization robot has already been modeled [5]. Something that must be taken into account in terms of any berries, including blueberries, is the fact that the availability of nutrients from the soil will significantly affect plant productivity [10,11]. Higher fertilization rates (up to 150 kg ha^{-1} N) significantly improve plant growth and yield [12], especially in nutrient-poor soils [13,14]. A strong positive correlation has been found between the availability of nutrients and the vegetative parameters of the blueberry plant: plant height and leaf area [15,16].

Within that context, fertilization depends upon the characteristics of the specific soil and the age of the plant, which is why a specified fertilization dosage has been set for each fertilizer. With regard to the age of the plant, the fact should be taken into account that the root of the plant expands every year, so the area around the plant that needs to be fertilized increases accordingly. In the first year, the fertilizer should be spread around the plant in a somewhat smaller area of approximately 20 cm × 20 cm, but at an age of between 6–8 years, when this shrub-type plant has acquired its maximum dimensions in the plantation, that area has already increased, being approximately 100 cm in diameter. It depends primarily upon planting density. If the distance between plants in a row is 1.5 m, then the size of the fertilized area is 1.5 m in diameter.

In a blueberry plantation, the plants are fertilized two or three times during the vegetation period, i.e., in spring, summer, and autumn [1]. This can be done both with mineral and liquid fertilizers. The fertilization rate depends upon the age of the blueberry plants; it is lower at first but higher later as the plants grow. In the first few years, when using NPK 10-20-20 complex fertilizer, the dose is about 20–30 g per plant, while it reaches up to about 60 g for each plant in later years [5,13].

Fertilizers. Three mineral fertilizers that are commercially available for fertilizing blueberry plants on plantations were chosen; these are Agro NPK SQM QROP TOP K, Substral, and Agro Organic Memon Siforga. This article focuses mainly on the granulometric characterization of these fertilizers and the problems that arise with it. Table 1 shows the chemical comparison information for the blueberry fertilizers, along with the bulk density, which is indicated on the packaging by the fertilizer's manufacturer.

Table 1. The properties of blueberry fertilizers.

Fertilizer	Color	N (%)	P (%)	K (%)	Bulk Density γ (kg m^{-3})
Agro NPK (SQM Qrop Top K)	green	12	6	24	1030
Substral	white	5	15	30	950
Agro Organic (Memon Siforga)	brown	4	3	8	775

Table 1 shows that blueberry fertilizers differ in their chemical composition and therefore in their areas of use. The different composition also indicates that the amounts in grams per plant will vary between the fertilizers. The Agro NPK fertiliser has a high nitrogen (N) content (12%), which activates the plant's growth and is therefore more suitable for spring fertilization when the plants need to be stimulated to grow. It is certainly not wise to fertilize blueberry plants with this fertilizer in the autumn.

Substral fertilizer has a low nitrogen (N) content but is high in phosphorus (P) and potassium (K), which makes it more suitable for autumn fertilization, as P and K help the plant to prepare for winter. Substral could be given to plants in early August. Of course, such fertilizer can also be applied in spring if the soil has a low P and K content [1].

Agro Organic is a fertilizer that contains organic material (chicken manure). It actually contains all three elements but in a relatively low concentration. It can be used for spring, summer, and autumn fertilization. Consequently, all of the fertilizers shown in Table 1 are included in the list of fertilizers, which according to the producers and retail sellers of the fertilizers are suitable for blueberry cultivation.

Technology. A centrifugal disc spreader [17–19], while widely used in agriculture and intended for the full fertilization of fields, is not suitable for the accurate dosing of mineral fertilizer in blueberry plantations. It is instead expedient to use precision fertilization technology in a blueberry plantation because, due to the planting scheme, a disc spreader in full fertilization mode fertilizes larger or smaller plant-free areas between the plants where weeds may start to develop intensively, possibly causing an unnecessary increase in weed control costs. In turn, this increases the specific costs involved in technological operations for blueberry growing and, consequently, the cost price of blueberries and their sales price on the market.

According to the authors of this paper, volumetric dosing is the most technologically suitable and simplest way in which to use precision fertilization. There is reason to assume that, with the use of this technique, the volumetric doser is able to dispense the prescribed amount of fertilizer (in grams) to each blueberry plant. In order to set the volume metering unit, it is necessary to know the mechanical properties of the material that is to be dosed, i.e., the fertilizer granules, including their granulometric properties, meaning the size of the fertilizer's particles (granules) and its bulk density.

The size and mass of the fertilizer particles (granules) are also important when spreading with a disc spreader, as these parameters affect the uniformity of fertilizer spreading [20–23]. According to the available literature [24,25], the particles of granulized fertilizers are not all of the same size. Particle size is estimated by the median diameter of those particles, d_{50} [26]. Typically, the experimental determination of the granular composition involves the screening of a fertilizer sample using a set of sieves [26,27]. In the case at hand, this method of determination is unsatisfactory, because it is not the fractional composition and surface uniformity of the application that are important for volumetric dosing but the uniformity of the (individual) amounts to be dosed per plant.

The aim of this research was to determine and characterize specific blueberry fertilizers through their granulometric properties and to evaluate the possible accuracy of dosing the blueberry fertilizers when using a volumetric doser.

2. Materials and Methods

2.1. The Particle Size of Blueberry Fertilisers

Although the fertilizer particles are depicted as spherical [28], the fertilizer granules are rather ellipsoidal on visual inspection. In any case, the fertilizer particles are three-dimensional and can be characterized in the approximation of a sphere by three diameters, which are measurable in three transverse planes (Figure 1). It is more convenient to evaluate different fertilizers according to the mean size of these granules, i.e., their mean diameter. In order to characterize the size of the granules, this parameter is quite approximate, whereas the mean diameter d_m of the fertilizer granules must be understood as the geometric mean dimension, which can be determined as follows:

$$d_m = \sqrt[3]{d_1 \cdot d_2 \cdot d_3}, \quad (1)$$

where d_1, d_2, and d_3 are the diameters of the granules according to the scheme (Figure 1), with d_1 being the largest diameter and d_3 being the smallest.

To determine the mean diameter d_m of the blueberry fertilizer granules, ten random samples were taken from several different layers of each 1000 kg large bag of said mineral fertilizer; the diameters d_1, d_2, and d_3, for the hundred random granules from the sample were measured according to Figure 1. The mean diameter d_m of each granule was found according to Formula (1). Then, the mean statistical diameter of the hundred granules $d_{m,100}$, and the lower and the upper limits were determined: $d_{m,min}$ and $d_{m,max}$ respectively. All fertilizer samples were collected in separate cups. A Mahr Digital Caliper 16EWRi 0–150 mm was used to measure the diameters of the fertilizer granules with an accuracy of ± 0.01 mm. The caliper was connected to a computer, and the software used was MarCom Professional.

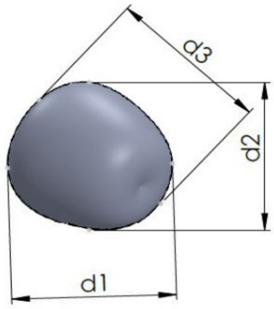


Figure 1. Schematic for measuring the geometrical parameters of a fertilizer granule.

2.2. *Shape of the Fertilizer Particles*

To see if there is a significant difference in the shape of fertilizer particles between the different producers, a sample set was selected and scanned by using Industrial Computed Tomography Yxlon FF35 CT and FXE Direct Beam tube. The CT scan provides to get a detailed model of the fertilizer particles. Differences in the shapes and roughness of particles could affect how the particles move in the doser and have a direct impact on the desired outputs.

2.3. *Bulk Density of the Blueberry Fertilizers*

Although the fertilizer manufacturers have indicated the bulk density of the fertilizer on the packaging for those fertilizers, it was appropriate for the sake of accuracy to specify it further within the context of this research. To be able to determine bulk density, the mass of a hundred fertilizer granules m_{100} was measured by weighing them. Their volume, V_0, was measured by means of a measuring glass; then, their bulk density $\gamma_{f,i}$ was determined as follows:

$$\gamma_{f,i} = \frac{m_{100}}{V_0}. \tag{2}$$

The mass m_{100} of a hundred granules of each fertilizer was determined in ten replicates, and their statistical mean was calculated. The analytical scale, Kern ABJ 220-4NM, was used to determine mass (Figure 2).

Figure 2. Kern ABJ 220-4NM analytical scales.

Then, the volume V of a hundred fertilizer granules was determined in ten replicates. The volumes were measured, using measuring glasses that had been manufactured to the GOST 1770-74 standard, with one measuring glass having a maximum volume of 10 mL in 0.2 mL increments and another having a maximum volume of 100 mL in 1 mL increments (Figure 3).

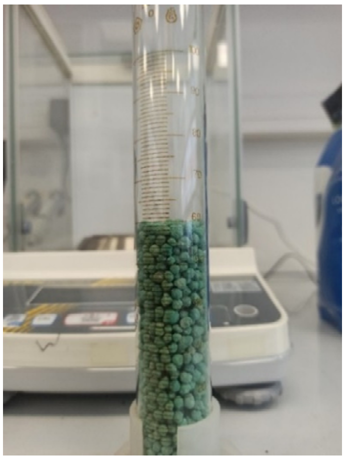


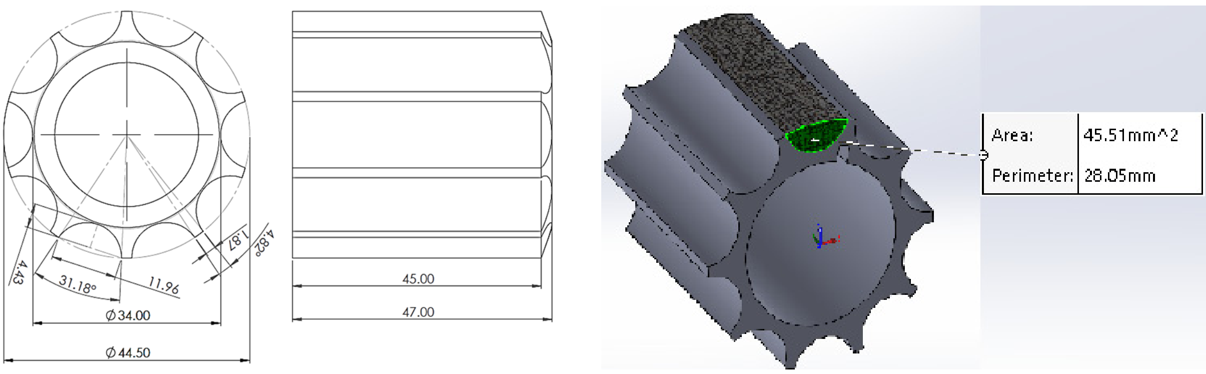
Figure 3. Measuring glass for volume measurement.

2.4. The Mass-to-Volume Dependency of the Fertilizers

According to the fertilizer dose Q, the fertilizer is precision-dosed by mass, within the range of Q = 20–60 g per plant. Based on this and the measurement results, the mass-to-volume dependency was determined for the fertilizer. For this purpose, a corresponding graph was prepared, which contained approximation functions.

2.5. A Determination and Setting of the Dosing Mass for the Volumetric Dosing Unit

A grooved roller doser was chosen as the volumetric doser to be used due to the simplicity of its construction and operation. The granulized fertilizer is metered in terms of the amount of fertilizer that is inside one or more of the grooves in the grooved roller (Figure 4a), according to the fertilizer dosage; therefore, it is important to first determine the groove's volume V_r.



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

Figure 4. Fertilizer doser's ten-groove roller: (**a**) parameters of doser; (**b**) cross-section of groove.

It is theoretically possible to dose a maximum of $m_g = V_r \cdot \gamma_{f,i}$ of granulized fertilizer in grams with the help of one groove, and since $V_r = A_s \cdot l$,

$$m_g = A_s \cdot l \cdot \gamma_{f,i} \tag{3}$$

where:

A_s—the cross-sectional area of the fertilizer quantity in the groove, in mm^2;
l—working length of the groove in mm;
$\gamma_{f,i}$—bulk density.

Since the cross-sectional area of the groove roller's groove is A_s = 45.51 mm^2 (Figure 4b), and the maximum working length of the groove is l = 45 mm, the total volume of the groove is V_r = 45.51 mm^2 × 45 mm= 2048 mm^3 = 2.048 mL, whereas the groove's volume is $m_g = A_s \cdot l \cdot \gamma_{f,i}$ = 2.048 · $\gamma_{f,i}$ g fertilizer.

If the cross-sectional area of the fertilizer in the groove is A_s = constant, and the specific fertilizer's bulk density $\gamma_{f,i}$ = constant, the prescribed fertilizer rate in grams depends upon the groove's working length l and the number of groove discharges η_c. If we know the fertilization rate Q [g plant^{-1}], then the number of grooves η_a can be found as follows:

$$\eta_c = \frac{Q}{m_g} = \frac{Q}{A_s l \gamma_{f.i}}. \tag{4}$$

For setting the groove doser, it is recommended that the number of groove discharges η_t be selected as an integer that is higher than or equal to the calculated η_c, in order to satisfy the following condition:

$$\eta_t \geq \eta_c. \tag{5}$$

To simplify the setting of the doser, it can be considered reasonable to choose an equally reasonable constant number of groove discharges, i.e., η = constant. In this case, the groove's working length l remains adjustable; l is calculated from Equation (4):

$$l = \frac{Q}{\eta A_s \gamma_{f.i}}. \tag{6}$$

For example, if the fertilizer rate is Q = 50 g plant^{-1}, the number of grooves is η = 30 or three full revolutions of the ten-groove roller, A_s = 45.51 mm^2, and the fertilizer being used is Substral with its bulk density being $\gamma_{f,}$ = 950 kg m^{-3} = 0.00095 g mm^{-3}; then, the working length of the grooves must be set to l = 38.55 mm.

For a practical test of the doser, the fertilizer hopper was filled with fertilizer, the groove roller was rotated, and the actual mass was measured in terms of grams and volume in milliliters for fertilizer, which was exiting the roller's ten grooves, providing the figures for a full rotation.

3. Results and Discussion

3.1. Granule Size in Blueberry Fertilizer

A total of a hundred granule samples from various blueberry fertilizers were placed in different cups (Figure 5), which were assembled into a stand for testing purposes.

Figure 5. A hundred granule measuring cups: (**a**) Agro NPK; (**b**) Substral; and (**c**) Agro Organic.

The summary results are given in Table 2 for the measurement of the blueberry fertilizer granule diameters.

Table 2. Geometrical parameters of blueberry fertilizer granules.

Parameter/Fertilizer	Substral	Agro NPK	Agro Organic
Diameter of granule d_1	3.98	4.82	5.11
Diameter of granule d_2	3.65	4.32	3.18
Diameter of granule d_3	3.45	3.82	2.64
Mean diameter of granule $d_{m,100}$, mm	3.68	4.29	3.64
Minimum diameter $d_{m,min}$, mm	2.52	3.08	2.66
Maximum diameter $d_{m,max}$, mm	4.86	6.09	5.07
Sample variance	0.22	0.28	0.19
Standard deviation	0.47	0.53	0.44
Standard error	0.047	0.053	0.044

The information in Table 2 is illustrated in Figure 6, which shows that different blueberry fertilizers have different mean diameters and also apply under normal distribution. While the mean diameters of the Agro Organic and Substral fertilizers are relatively similar, i.e., 3.64 mm and 3.68 mm respectively, the mean diameter of the Agro NPK fertilizer is about 15% larger, or 4.29 mm.

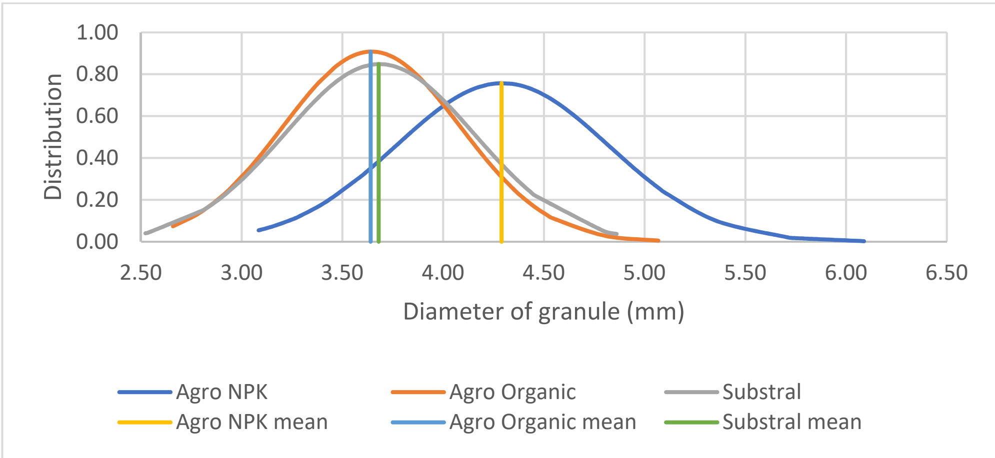


Figure 6. Distribution curves for the mean diameters of fertilizer granules.

In addition, the Agro Organic fertilizer contains a good deal of smaller granule debris inside. Knowing the granule diameter alone does not help us to set the doser so that it can dose the prescribed fertilizer amount; for that, we also need to know the bulk density of the fertilizer in question.

3.2. *The Shape and Roughness of Fertilizer Particles*

The computer tomograph scan provided accurate 3D models of fertilizer particles. As seen in Figure 7, the differences in the shape and roughness are significant.

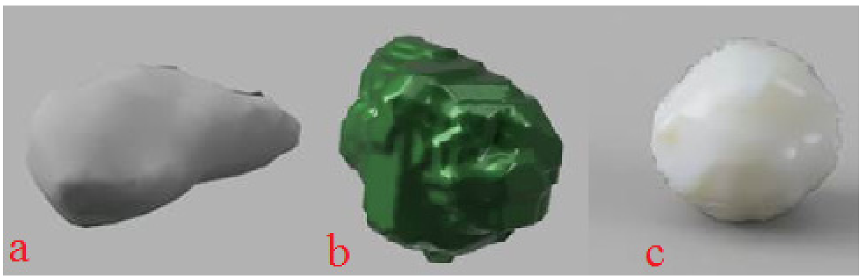


Figure 7. Examples of CT scanned fertilizer particles, (**a**) Agro Organic; (**b**) Agro NPK; (**c**) Substral.

Such significant differences supposedly have direct impact on how the particles move and fit in the doser, affecting the desired output. Roughness may increase the friction between the granules, and the complex shape will definitely affect how the granules will fit next to each other. Rougher and more non-uniform particles may increase porosity, which also might not be constant but very variable.

3.3. The Bulk Density of Blueberry Fertilizer

The masses and volumes of a hundred pellet samples were determined in ten replicates in order to be able to identify the bulk density of the blueberry fertilizers. The measurement results are summarized in Tables 3–5.

Table 3. The hundred-granule sample mass, volume, and bulk density for the Agro NPK fertilizer.

Parameter	**Mass m, g**	**Volume V_{avg}, mL**	**Bulk Density γ_{avg}, g cm^{-3}**
Mean	5.21	5.61	0.928
Standard error	0.22	0.22	0.007
Median	5.20	5.63	0.928
Standard deviation	0.70	0.68	0.022
Sample variance	0.49	0.47	0.0005
Range	2.18	2.20	0.073
Minimum	4.02	4.53	0.886
Maximum	6.20	6.73	0.959
Count	10	10	10

Table 4. The hundred-granule sample mass, volume, and bulk density for the Agro Organic fertilizer.

Parameter	**Mass m, g**	**Volume V_{avg}, mL**	**Bulk Density γ_{avg}, g cm^{-3}**
Mean	2.37	3.76	0.631
Standard error	0.11	0.17	0.003
Median	2.40	3.80	0.631
Standard deviation	0.35	0.53	0.010
Sample variance	0.12	0.28	0.0001
Range	1.16	1.73	0.033
Minimum	1.73	2.80	0.616
Maximum	2.88	4.53	0.649
Count	10	10	10

Table 5. The hundred-granule sample mass, volume, and bulk density for the Substral fertilizer.

Parameter	**Mass m, g**	**Volume V_{avg}, mL**	**Bulk Density γ_{avg}, g cm^{-3}**
Mean	3.31	4.01	0.824
Standard error	0.11	0.14	0.004
Median	3.34	4.03	0.820
Standard deviation	0.34	0.44	0.013
Sample variance	0.12	0.19	0.00017
Range	1.03	1.27	0.042
Minimum	2.69	3.27	0.809
Maximum	3.71	4.53	0.851
Count	10	10	10

The information in Tables 3–5 shows that the masses and volumes for the hundred granule samples in all three fertilizers, as well as their bulk density, are clearly different. Statistical data processing shows that the results that were obtained are indeed reliable.

Figure 8 shows that according to measured weights on given volumes, for all of the fertilizers that are under consideration, the volume increases linearly with mass. If, for example, we need to apply a dose of 50 g of fertilizer for each plant, the volumetric doser must be set to 50.6 mL for Substral, 54.9 mL for Agro NPK, and 66.35 mL for Agro Organic; i.e., the volumetric doser must be adjustable and must also ensure that dosing is possible for the prescribed amount of fertilizer in grams for each plant.

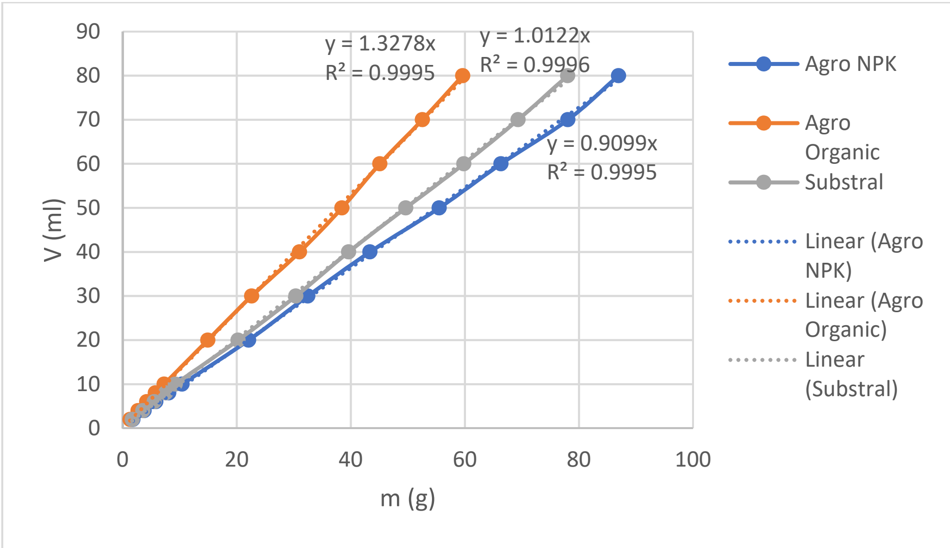


Figure 8. The mass-to-volume dependency of blueberry fertilizers.

3.4. Mass Dosing by Volumetric Doser

Results are given in Table 6, which have been obtained in terms of the practical testing of the volumetric doser for each full revolution or ten grooves of discharging from the grooved roller, i.e., the dosed masses and volumes.

Table 6. Dosing results at one full revolution of the grooved roller.

Test No.	Agro NPK		Agro Organic		Substral	
	Mass g	**Volume mL**	**Mass g**	**Volume mL**	**Mass g**	**Volume mL**
1	24.76	23	21.06	29	21.78	23
2	25.79	23	21.91	31	22.55	23
3	27.29	25	17.45	24	23.04	24
4	27.02	25	21.60	30	22.28	23
5	26.09	24	19.09	26	26.01	26
6	28.14	26	18.59	25	23.50	24
7	26.29	24	21.98	30	25.14	26
8	27.50	25	17.75	24	23.90	25
9	27.44	25	19.17	27	23.48	24
10	26.88	24	16.89	23	26.00	26
Mean	26.72	24.4	19.55	26.9	23.77	24.4
Calculated	19.00	20.5	13.70	20.5	16.87	20.5
Difference	1.41	1.19	1.43	1.31	1.41	1.19

The experimental data that are presented in Table 6 show that the results that have been obtained during practical dosing tend to differ from the calculated results; i.e., the dosing masses exceed the calculated masses by 1.41–1.43 times, and the dosing volumes exceed the calculated volumes by 1.19–1.31 times. Consequently, the volumetric doser's grooved roller draws the fertilizer along as it rotates; this must be taken into account when setting the doser and creating an equation for estimated output.

4. Conclusions

Granulated fertilizers with different chemical properties (NPK) are used in berry cultivation. It turns out that these fertilizers also have different granulometric parameters, resulting in very different particle sizes and shapes. In the precision fertilization of blueberry plants, the fertilizer must be dosed at the prescribed fertilization rate, in grams per plant. The aim of this research was to determine the granulometric parameters: the mean diameter d_m and the bulk density $\gamma_{f,i}$ of Agro NPK, Agro Organic, and Substral fertilizers. It was found that it is expedient to carry out the dosing by mass, using a simple volumetric doser, and in particular a doser with a grooved roller that rotates around its horizontal axis. A mass-to-volume dependency was determined for three different blueberry fertilizers, which can be used to set the volumetric doser for dosing granular fertilizers that have significantly different size and shape. Practical testing of the volumetric doser revealed that the actual results differed significantly from the calculated ones; this must be taken into account when setting the volumetric doser and requires a fertilizer-specific experimental approach.

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