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INNOVATIVE EQUIPMENT FOR THE APPLICATION OF GRANULATED BIOCOMPOSITES IN GRAPEVINE AND FRUIT TREE CROPS

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Abstract: The paper presents the CAD–CAE–assisted design and experimental validation of an innovative technical equipment for dosing and applying granular biocomposites, intended to stimulate the plant microbiome between rows of grapevines and fruit trees, and to prevent soil structure degradation. The mechanical system enables the controlled application of biocomposite powders, granules, and pellets of various sizes and shapes for experimental and laboratory use. CAE analyses confirmed the structural integrity and functionality of critical subassemblies, while field tests showed high distribution uniformity (average deviations below 1%), demonstrating the performance and reliability of the equipment. The results are relevant for researchers, teachers, students, and farmers, providing a practical solution for improving soil fertility and optimizing bioremediation in grapevine and fruit tree crop.

Keywords: granular biocomposites, CAD–CAE, agricultural equipment, grapevine, fruit tree

1. INTRODUCTION

Modern agriculture faces the challenge of optimizing soil fertility and reducing soil structure degradation in perennial crops such as grapevines and fruit trees. The controlled application of organic and mineral-organic materials represents an effective strategy for bioremediation of modified soils and stimulation of the plant microbiome. [1, 2].

Biocomposites resulting from the combination of mineral amendments with secondary agricultural materials (grape marc, wine yeast) and minerals (dolomite, slag) have soil-improving properties, contributing to increased humus content, pH stabilization, and improved water retention capacity. [3, 4].

These materials can be administered in granular or liquid form, allowing for controlled application in the inter-row spaces between perennial plants, avoiding excessive soil compaction and structural degradation. [5, 6].

A critical aspect of biocomposite efficiency is distribution uniformity. Uneven application can lead to areas of excessive nutrient accumulation, where the microbiome can be disrupted, or deficient areas, where plants suffer from a lack of nutrients [7, 8].

Therefore, dosing equipment must ensure precise control of flow rate and application depth, adapting to soil type and moisture conditions [3, 7].

In particular, application between rows of grapevines and fruit trees requires particular care to avoid soil degradation.

Rows of perennial plants have deep roots and variable soil density, and equipment traffic can cause localized compaction. Recent studies show that maintaining an adequate row spacing and adjusting the application depth of the granules prevents negative effects on soil structure while maintaining fertilization efficiency and stimulating the microbiome. [9, 10].

The objective of this work is to design, test, and validate innovative equipment for applying granular biocomposites to rows of grapevines and fruit trees, with a particular focus on:

- ensuring uniform distribution of granular and liquid material;
- minimizing soil structure degradation between rows;
- stimulating plant microbiome and improving soil fertility through controlled application;
- monitoring application parameters in experimental and laboratory studies [2, 3, 6, 9]

Given the importance of soil bioremediation and the need to develop equipment adapted to perennial crops, capable of ensuring the precise and sustainable application of biocomposites, within INMA, an innovative technical equipment for dosing granular biocomposites was designed and developed through a research project that meets the requirements for preventing soil structure degradation.

The innovative technical equipment for dosing and distributing granulated biocomposites consists of several subassemblies, of which the central element is the biocomposite distribution box in the form of granules or powder.

The distribution box ensures the administration of materials in the form of:

- powders;
- granules with vermicular, spherical, or cylindrical shapes;
- pellets with an individual mass of 0.2–0.3 g.

2. MATERIALS AND METHODS

Materials used

To verify the operation of the distribution system of the innovative equipment designed for the application of granulated biocomposites, an amendment in the form of granules was used, with physical and granulometric characteristics comparable to those of the biocomposites developed within the research project. This material was selected to ensure representative testing conditions, similar to those encountered during actual operation n of the equipment.

The amendment used, Minerals Lawn™ Smart (Figure 1), is a product formulated based on alkaline-activated clinoptilolite minerals, with a microporous structure, and is 100% natural and environmentally friendly. Its granulometric properties, bulk density, and flow behaviour enabled accurate assessment of distribution uniformity, flow stability, and dosing system performance under controlled conditions.

Figure 1. Amendment used to verify the functioning of the distribution system for dosing granulated biocomposites

The use of this amendment allowed functional validation of the equipment in the absence of major variations generated by the heterogeneity of biocomposites, thus ensuring the reproducibility of the tests and the correlation of the experimental results with the numerical analysis performed.

3D modeling of subassemblies

In the first stage of the study, a three-dimensional geometric model of the biocomposite distribution box subassembly was created. The modeling was performed on an HP Z4 G4 workstation equipped with an Intel® Xeon® W-2123 processor, using SOLIDWORKS® Premium 2023 SP5.0 parametric design software.

The 3D model was designed in accordance with the actual construction dimensions and functional relationships between components, allowing both the evaluation of subsequent mechanical behavior and the correct integration of the subassembly into the complete equipment. The geometry included all elements relevant to the operation of the distribution system, such as the box housing, the feed and discharge areas, and the material-guiding elements.

Figures 2–5 show different perspectives of the subassembly: general 3D view, front view, side section, and section detail, highlighting the internal structure, component positioning, and material flow inside the distribution box for biocomposites in the form of small or large granules or powder. These representations formed the basis for defining working conditions and identifying critical areas used in subsequent stages of structural and functional analysis.

Structural analysis using FEM

The shaft subassembly with distributors is the most mechanically stressed component of the equipment and, consequently, was subjected to a structural analysis using the finite element method (FEM). The components of the subassembly were designed individually in three-dimensional format and subsequently assembled using the SOLIDWORKS® Premium 2023 SP5.0 design environment.

The three-dimensional model used in the FEM analysis includes the screw-type distributor, equipped with an our-start spiral auger (Figure 6). The geometry was discretized using tetrahedral solid elements, with local refinement in the stress concentration areas, particularly at the interface of the screw equipped with a four-start spiral smoothing element, to ensure an adequate representation of the stress and deformation fields.

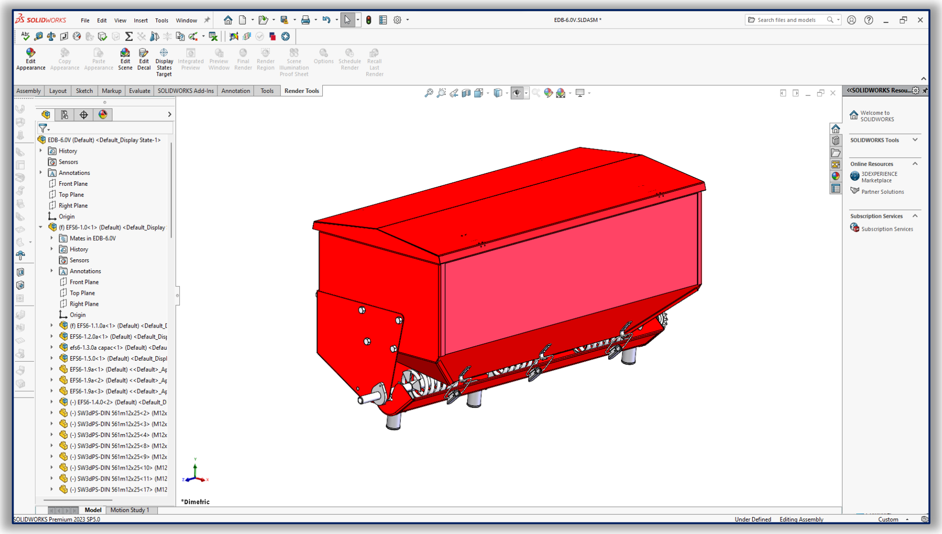

Figure 2. Box for distributing biocomposites in the form of small or large granules or powder – 3D view

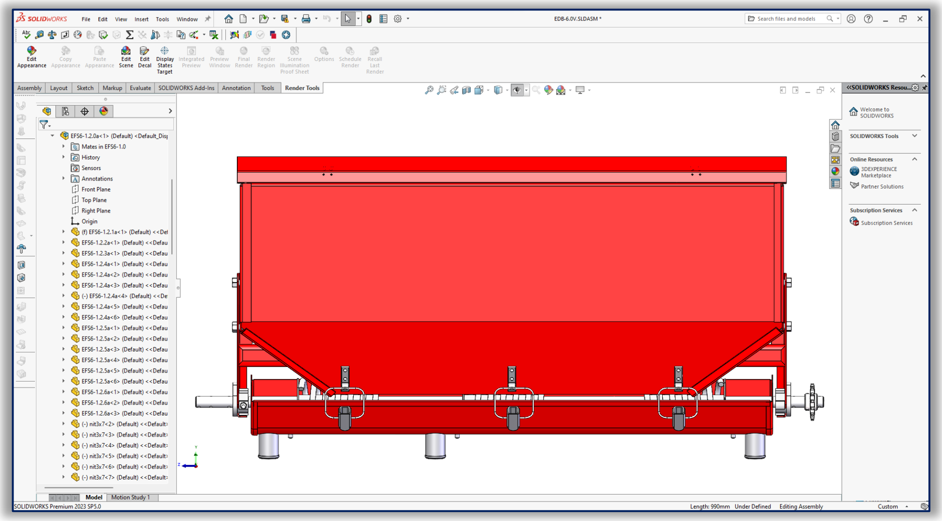

Figure 3. Box for distributing biocomposites in the form of small granules, large granules, or powder – front view

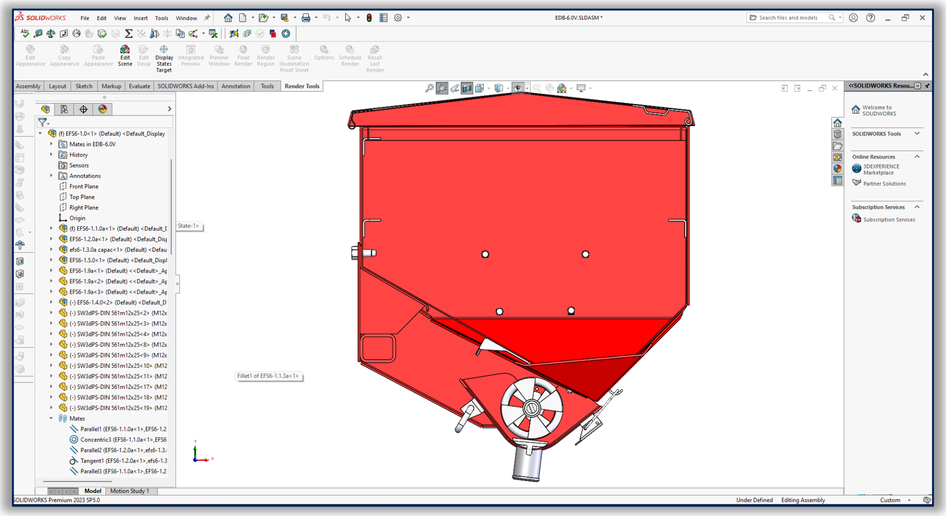

Figure 4. Box for dispensing biocomposites in the form of small or large granules or powder – side view

The materials were defined based on linear isotropic elastic behavior, as follows:

- distributor: steel;
- four-start spiral auger: steel.

The analysis was performed in linear static simulation mode, an assumption justified by the quasi-stationary operating mode of the equipment during the dosing process.

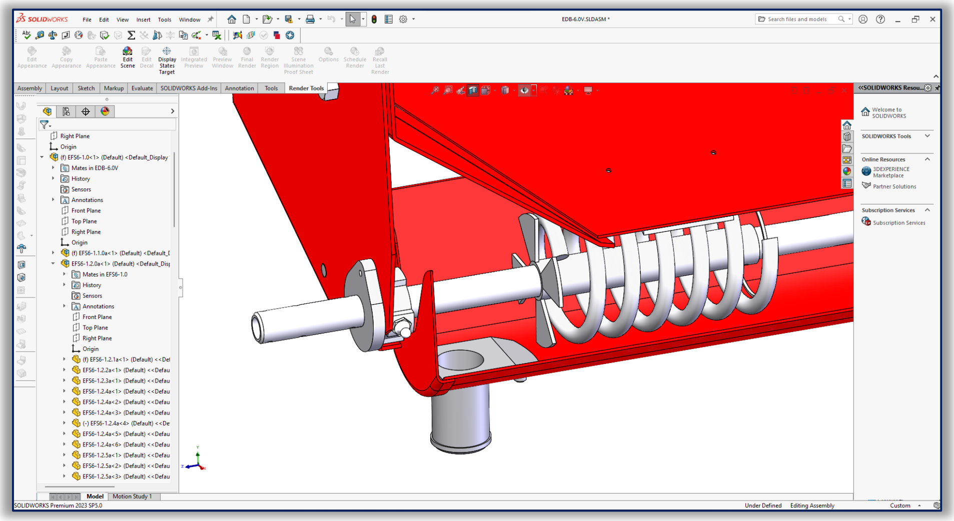

Figure 5. Box for distributing biocomposites in the form of small or large granules or powder—detailed section

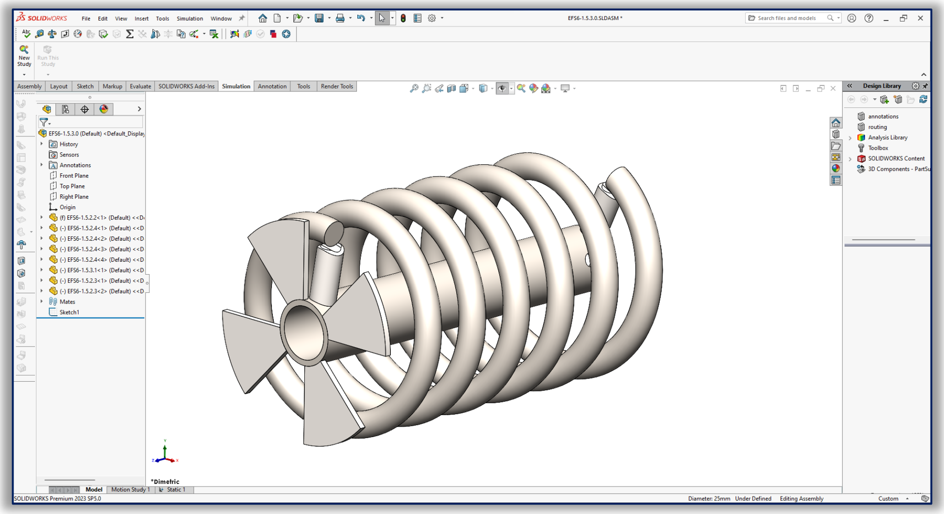

Figure 6. Distributor equipped with a spiral–type uniformizing element with four ends for biocomposites in the form of small or large granules or powder

Load conditions representative of normal operation were applied, namely:

- gravitational loads corresponding to the mass of the components and the material being transported;
- torque applied to the shaft, corresponding to the nominal operating conditions;
- boundary conditions at the bearings, modeled as support constraints, to simulate the fixing of the shaft in the support.

The contacts between the distributors and drive shaft were considered bonded, assuming full transmission of loads without relative slippage.

The results of the FEM analysis enabled the evaluation of:

- distribution of equivalent stresses according to the Von Mises criterion;
- maximum deformations, expressed as the total resulting displacement URES (mm), indicating the maximum displacement of the critical points of the subassembly;
- safety factor, used to assess structural safety and load-bearing capacity.

This analysis identified structurally critical areas, and the results obtained formed the basis for optimizing the design solution and validating reliable equipment for the precise and controlled dosing of granulated biocomposites.

3. RESULTS

▦ Distribution of stresses

Structural analysis using the finite element method of the shaft subassembly with distributors highlighted the areas with maximum equivalent stress (Von Mises) located mainly in the vicinity of the interfaces between the shaft and the screw -type distributors, as well as in the areas of contact with the plastic bearings (Figure 7).

This distribution is characteristic of rotating systems with transport elements and results from the combination of torsional moments with applied gravitational loads.

The maximum stress values were compared with theoretical estimates and were below the permissible limit for the material used (structural steel for the shaft and screw distributors), indicating elastic behavior of the subassembly under normal operating conditions.

The results indicate no risk of structural failure under the operating conditions analyzed.

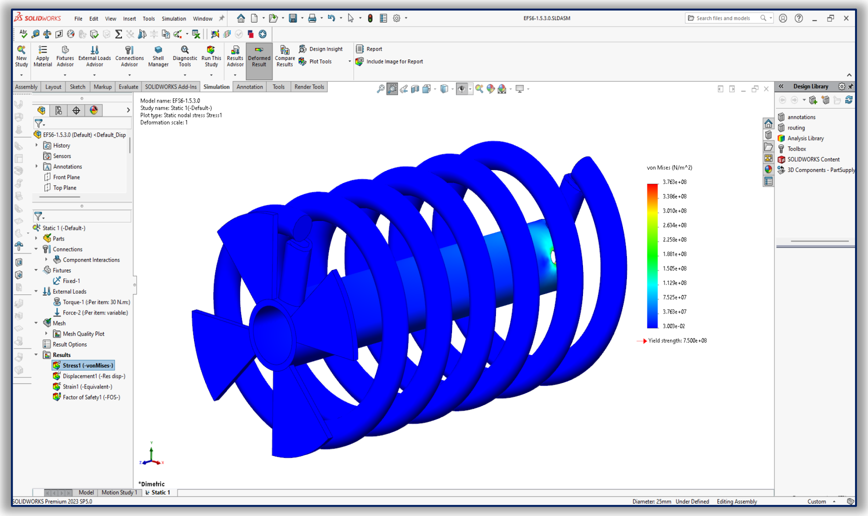
Model name: EFS6-1.5.3.0
Study name: Static 1(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 1

Figure 7. Equivalent stress map (Von Mises) for distributor

Maximum deformations

The static simulation allowed determination of maximum deformations, evaluated based on the total resulting displacement (URES). The highest deformation values were identified at the ends of the screw-type distributors (Figure 8), areas characterized by increased stresses generated by the interaction with the distributed material and the transmission of the rotational moment.

However, the resulting deformation values remain below critical thresholds that could affect the proper functioning of the equipment, ensuring that the shaft alignment and proper contact with the biocomposites are maintained during the dosing process.

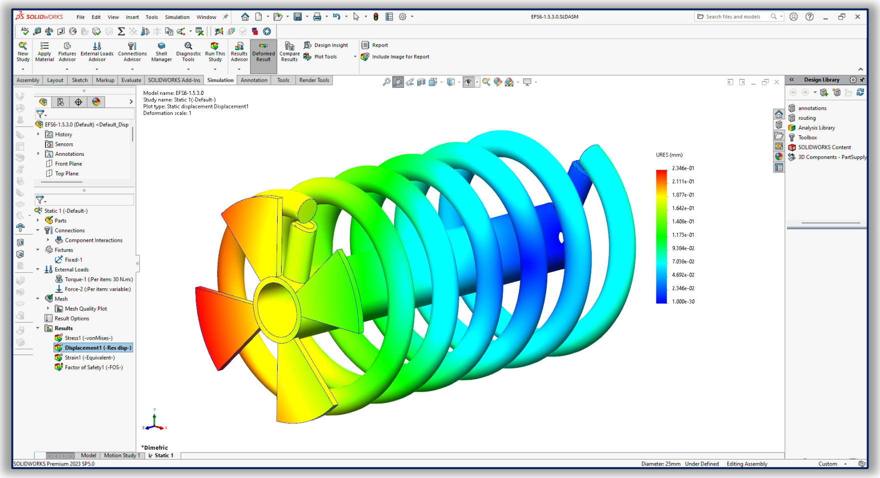
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Figure 8. Map of maximum deformations (URES) for distributor

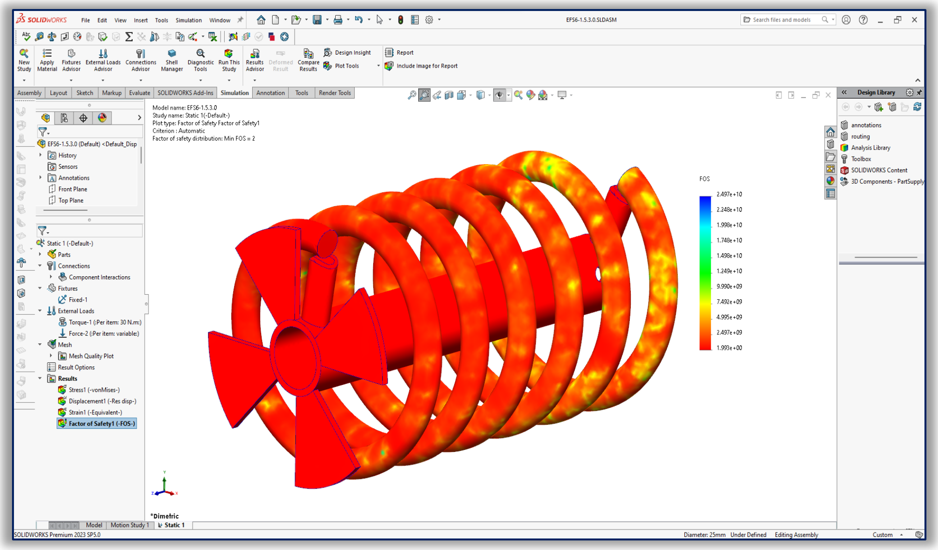
Safety factor

The safety factor assessment, based on the distribution of equivalent stresses, indicates values above the minimum threshold accepted for agricultural applications. These results confirm that the shaft and distributors are adequately dimensioned to withstand the moderate static and dynamic loads typical of granular biocomposite dosing.

The distribution of the safety factor highlights an adequate structural reserve in critical areas, contributing to the reliability and durability of the equipment in long-term operation (Figure 9).

Interpretation of results

The results of the FEM analysis confirm that the design solution for the shaft subassembly with distributors and equalizing elements exhibits mechanical behavior that meets the functional requirements of the equipment. The refinement of the finite element mesh in critical areas allowed for an accurate assessment of stress and strain fields, highlighting the consistency between numerical results and theoretical estimates.



Model name: EFS6-1.5.3.0
Study name: Static 1(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Automatic
Factor of safety distribution: Min FOS = 2

Torque-1 (:Per item: 30 N.m:)
Force-2 (:Per item: variable:)

Figure 9. Safety factor chart for distributor

The uniform distribution of stresses and low deformation levels support the subassembly's ability to operate under real operating conditions without compromising the accuracy of biocomposite dosing or the structural integrity of the equipment. In addition, the FEM methodology used enables for the rapid evaluation of possible design changes, such as optimizing the shaft geometry or using alternative materials for bearings, facilitating performance improvement and adaptation of the equipment to various operating conditions.

Determination of distribution uniformity and application rate

To assess the uniformity of distribution of the granular biocomposites, flow tests were conducted at a distributor speed of 24 rpm, with a duration of 30 s for each sample. The tests were performed simultaneously on the three distribution units of the equipment, under identical operating conditions.

Three repeated tests were performed for each trial, and the average flow rate DDD was calculated from the values obtained. The deviation of each test from the average value was determined according to the following equation:

$$\mathbf{a} = \frac{\mathbf{D_i - D}}{\mathbf{D}} \times \mathbf{100}, (\%) \tag{1}$$

where: D_i – the flow rate measured at sample i, D – the average flow rate of the three samples, a – percentage deviation from the average.

The condition for acceptability is that the percentage deviation must be less than 10% (a<10%), a criterion that confirms the satisfactory uniformity of distribution and the correct functioning of the equipment. The experimental results are presented in Table 1.

Table 1. Results

Auger distributor No.	Trial 1 (g)	Trial 2 (g)	Trial 3 (g)	Average flow rate D (g)	Percentage deviations a_1 (%)	a_2 (%)	a_3 (%)	Average deviation $\bar{a}$ (%)	Acceptability condition (a < 10%)
1	657,5	660,4	659,6	659,17	0,25	0,19	0,07	0,17	Acceptable
2	668,8	650,5	660,6	659,97	1,33	1,44	0,10	0,96	Acceptable
3	688,4	680,8	685,9	685,03	0,49	0,62	0,13	0,41	Acceptable

The results obtained indicate very good uniformity of the distributed flow, with average deviations between 0.17% and 0.96%, well below the permissible limit of 10%. This confirms that the equipment operates stably and ensures uniform distribution of the granular biocomposites at a speed of 24 rpm. The tests were performed simultaneously on the three distribution units of the equipment, under identical operating conditions (Figure 10).

During the tests, visual observations and photographs were made of the distribution of the material according to the distribution organ (Figure 11).

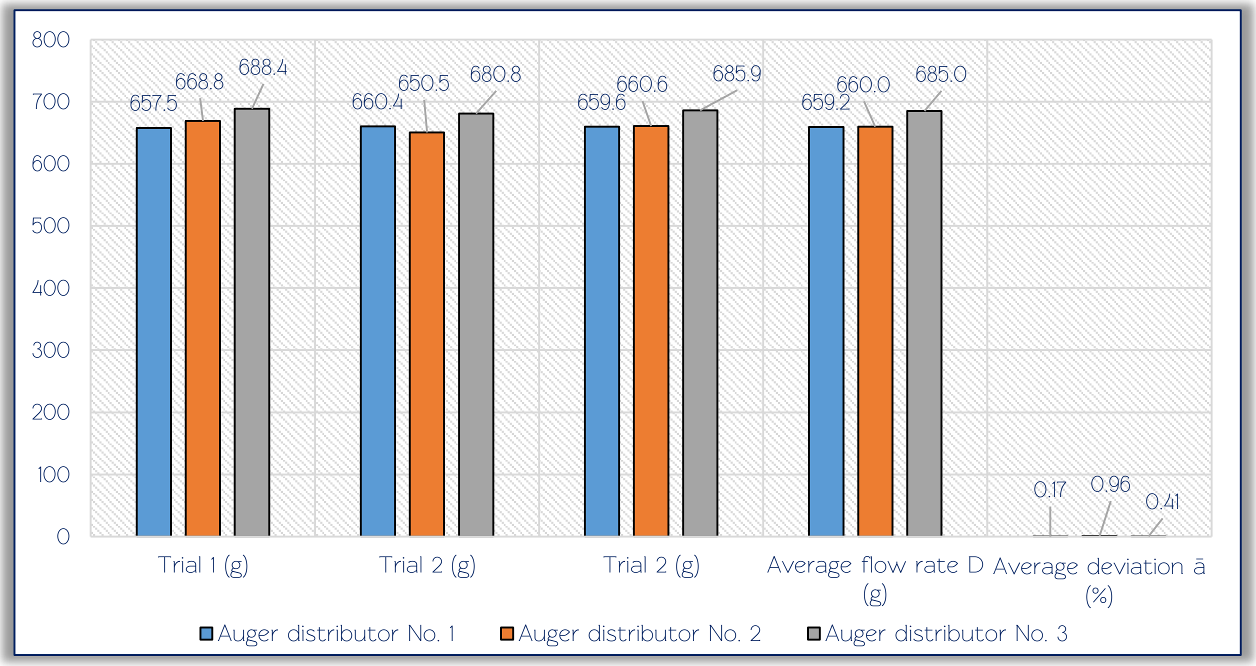


Figure 10. Uniformity of distribution between the three distribution bodies, highlighting differences in flow and deviations from the average

Figure 11. Aspects of determining distribution uniformity under field conditions

4. DISCUSSION

The structural analysis of the shaft subassembly with distributors, performed using the finite element method (FEM), highlighted the typical distribution of stresses and strains for a rotating system with transport elements. The areas with maximum equivalent stress (Von Mises) were concentrated at the interfaces between the shaft and the screw-type distributors, as well as at the contact with the plastic bearings. This is explained by the combination of torsional moments with the gravitational loads of the components and the distributed material. The maximum values recorded remained below the permissible limit of the structural steel used, indicating elastic and reliable behaviour of the subassembly under normal operating conditions.

Maximum deformations (URES) were identified at the ends of the distributor augers, in areas of intensive interaction with the granular material. However, the values remain below critical thresholds, ensuring that the shaft remains aligned and in uniform contact with the biocomposites. These results demonstrate that the equipment can operate without clogging or material losses, maintaining the efficiency of the dosing process.

The safety factor analysis confirms an adequate structural reserve, suitable for the moderate static and dynamic loads encountered in agricultural operations. Thus, the dimensions and geometry of the components have been validated for continuous and long-term operation without degradation of critical structures.

Experimental tests on distribution uniformity and average application rate showed excellent system performance. The average percentage deviations between the three distribution bodies were between 0.17% and 0.96%, well below the acceptable threshold of 10%. This confirms the stability and accuracy of the dosing system, ensuring uniform distribution of the granular biocomposites and preventing deficient or overloaded areas, which are critical for uniform stimulation of the plant microbiome.

The correlation between FEM results and experimental observations indicates a high degree of agreement between numerical predictions and the actual behavior of the equipment. This validates the CAD-CAE design methodology and demonstrates that the proposed construction solution is optimal from mechanical and functional perspectives.

In addition, the methodology adopted allows for rapid evaluation of design changes, such as shaft geometry optimization, worm size modification, or the use of alternative bearing materials, providing flexibility for adapting the equipment to different types of biocomposites and field conditions. This is essential in soil bioremediation applications, as it allows operating parameters to be adjusted to maximize efficiency and minimize impact on soil structure.

In conclusion, the equipment for dosing granular biocomposites ensures both the structural integrity of critical subassemblies and the uniformity of material distribution in the field. The results obtained support its applicability in soil bioremediation between rows of grapevines and fruit trees, providing a robust, accurate, and sustainable solution for optimizing soil fertility and stimulating the plant microbiome.

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