Scientific Papers. Series A. Agronomy, Vol. LXVIII, No. 2, 2025
ISSN 2285-5785; ISSN CD-ROM 2285-5793; ISSN Online 2285-5807; ISSN-L 2285-5785

# RESEARCH ON THE REALIZATION AND OPTIMIZATION OF EQUIPMENT FOR SUSTAINABLE SOIL BIOREMEDIATION

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***Abstract***

*The mobile equipment developed and tested by INMA Bucharest performs sustainable in-situ soil bioremediation, including a dosing device for biocomposites obtained from recycled resources, based on slag, dolomite, grape marc and wine yeast. The optimization consisted in determining the optimal combination between the speed of the biocomposite dosing devices and the working speed of the equipment. To simulate the dosing and distribution process of biocomposite materials, Altair EDEM$^{TM}$ software, was used. In order to validate the theoretical simulation method, the results obtained from the simulation were compared with the experimental results which was carried out according to SR ISO 5690-2:1995. The relative error between the results obtained by simulation and experimental had small values and it could be concluded that the theoretical simulation method has a good predictive capacity. The quantities of biocomposite that the equipment can distribute per hectare at two working speeds indicated in the current regulations were calculated and the optimal combination between the speed of the dosing devices (28 rpm) of the biocomposite materials and the working speed of the equipment (1.5 m/s) was determined.*

***Key words****: biocomposites, dosing device, mobile equipment.*

## INTRODUCTION

Soil health is essential for sustainable agriculture. Soil is essential for life, providing nutrients, water and oxygen and supporting plants. It is a non-renewable resource. An assessment of the state of soils in the EU found that around 60-70% of them are in poor health due to current management practices (*European Commission, Retrieved from https://commission.europa.eu/index_en*).

Excessive use of nutrients, including manure, on agricultural land in the EU also has a negative impact on water quality and biodiversity (*EU Mission Soil Deal for Europe, 2022. Retrieved from https://mission-soil-platform.ec.europa.eu/living-labs/lighthouses*; *European Court of Auditors, 2023. Retrieved from www.eca.europa.eu*).

Soil or sediment remediation depends on several factors, such as the type of soil, its physical properties, the nature of the contaminants, the possibility of their isolation, the degree of handling required, and the costs involved (Wuana et al., 2011).

The traditional methods available for soil remediation can be grouped into three categories, namely chemical, physical, and biological methods, the latter being carried out either in the polluted place (*in situ*) or outside it (*ex situ*) (Sales da Silva et al., 2020).

These methods are widely used to treat contamination with heavy metals and other toxic substances. Although effective in some cases, they have a high cost and a negative impact on the environment. Also, these methods do not restore soil fertility, but only focus on removing contaminants. In addition, they do not contribute to the circular economy and have a high carbon footprint.

Biological methods can significantly alter soil chemical properties by adding chemicals and nutrients to stimulate microbial growth. Also, in situ soil washing techniques or land use restrictions can lead to groundwater contamination (Dermon et al., 2008).

A simpler and more economical solution, especially for land intended for horticultural and agricultural use, is to cover the surfaces with a superficial layer of clean or uncontaminated soil (Khan et al., 2018; Yang et al., 2021).

Bioremediation refers to the use of microorganisms to degrade contaminants that pose risks to environmental quality and human health. Phyto- and bioremediation have recently been intensively studied because they are ecofriendly, are able to quickly remove various contaminants and have a relatively lower cost compared to pre-existing techniques (Soleimani, 2014; Kumar et al., 2018).

On the Romanian and international market, competition in the field of soil remediation comes mainly from two directions: traditional physico-chemical methods and alternative bioremediation solutions developed by other companies or research institutes.

In this context, the partners within the CeSoh complex project funded by the PNRR (National Recovery and Resilience Plan) have developed innovative and emerging bioremediation solutions, which will significantly contribute to the ecological restoration of soils, by valorizing waste from various industries (metallurgical/iron and steel, construction materials, viticulture, etc.) and obtaining biocomposites with potential for use in the remediation of soils contaminated with potentially toxic elements (www.cesoh.ro). The project responds to an urgent need for cost-effective and efficient solutions for the regeneration of soils affected by industrial and agricultural activities.

In this study, the optimization of mobile equipment for *in situ* soil bioremediation carried out by INMA Bucharest, consisted in determining the optimal combination between the speed of the biocomposite materials dosing devices and the working speed of the equipment, so that the quantities applied to the soil comply with the regulations in force and the doses currently used in agricultural practice. For this purpose, the behavior of the biocomposite material in the dosing and distribution process was simulated, using the Altair EDEMTM software, and the data were validated experimentally.

## MATERIALS AND METHODS

Recycled materials such as slag, dolomite, grape pomace and wine yeast were used to obtain biocomposites. The advantages of using recycled materials are the low costs and the ecological character of the obtained biocomposites. While traditional competition focuses on short-term and often destructive solutions, biocomposites offer a holistic solution, which not only eliminates contaminants, but also restores the structure and health of the soil.

Following the granulometric analysis of the material obtained by mixing the components, it was found that it falls into granulometric class 4, with grain sizes between 1.7 and 4 mm (SR ISO 5690-1, Annex A). These physical parameters are important for the design of mobile equipment for in-situ soil bioremediation and especially for the design of dosing and distribution devices.

Since the amount of biocomposite material obtained in the laboratory at this stage of the CeSoh complex research project was insufficient to perform dosage and distribution tests with mobile equipment for in-situ soil bioremediation, a commercially available Smart mineral amendment was chosen, which has characteristics similar to those of the Biocom-posites made within the project (Figure 1).


Figure 1. Amendment used to verify the operation of the biocomposite dosing and distribution device

Smart Minerals is generally used to improve the physical structure of the soil, but also to degrade harmful chemical elements, balance pH, improve biological properties, helping to promote healthy plant growth.

Within the CeSoh project, the team of the partner INMA Bucharest designed, built and tested a mobile equipment for in-situ soil bioremediation, by applying solid or liquid biocomposites, which is presented in Figure 2.

The mobile equipment for in-situ soil bioremediation consists mainly of a frame with rubber wheels, on which a spur roller is mounted that creates alveoli on the soil surface, three devices for spreading granulated biocomposites, a smooth roller for covering the biocomposites and compacting the soil, a 100 l granulated biocomposites hopper, three spiral-type dosing devices with propellers driven through a chain transmission by an ECM070/030U electric gear motor powered by 12 V and an installation (optional) for administering liquid biocomposites (100 l tank, ARAG ProFlo 12V pump, filter, nozzle, hoses).

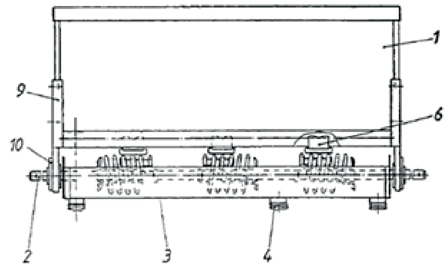

Figure 2. Mobile equipment for in-situ soil bioremediation - experimental model

For this study, a complex design and simulation process was developed, starting with the creation of the biocomposite hopper - chute - dosing devices assembly, using the SolidWorks modeling software. The SolidWorks program was chosen due to its ability to generate precise and detailed models, facilitating the design of the assembly under study.

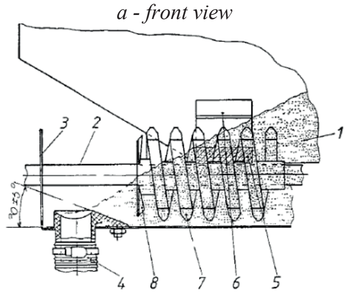
The biocomposite hopper *1* has a prismatic shape with flow angles for all types of biocomposites, powders, granules (vermicular, spherical, cylindrical fragments) or pills (prepared in spherical form with a weight of 0.2-0.3 grams). It is equipped with screens to prevent the biocomposites from agglomerating and a sieve to prevent lumps or other hard materials from entering the hopper when feeding, which could damage or prevent the operation of the equipment. The biocomposite hopper is provided at the bottom with slots *5* for feeding the dosing devices, which can be closed by adjustable shutters *6*. Below these slots are the dosing devices *7* mounted on the shaft *2* and the chute *3* provided with some discharge openings *4*, positioned at a slope of 30° ± 5°, to limit the free flow of the biocomposite. The dosing devices are of the auger type equipped with uniforming propellers *8* (Figure 3 a).

The biocomposite in the hopper *1* flows through the slots *5* between the spirals of the auger *7* into the chute *3*, creating a cone of material. When the shaft *2* rotates, the fertilizer cone is taken up by the spirals of the auger under the action of gravitational force and friction forces and moved towards the discharge mouth *4*, the propeller *8* achieving the uniformity of the material flow rate. The material discharged through the discharge mouth *4* is replaced by free flow, within the limit of the natural slope angle, by the material in the hopper *1*, so that during operation the cross-section of the working enclosure in the area of the dosing device is occupied in a proportion of about 40% with material that will be distributed in full (Figure 3 b).

The amount of biocomposite distributed depends on the speed of the shaft *2*, driven by a chain transmission by the electric gear motor ECM070/030U.




*a - front view*




*b - section through a dosing device*

Figure 3. Object of the study: biocomposite hopper – chute - dosing device assembly:
1 - hopper, 2 - shaft, 3 - chute, 4 - outlet, 5 - slot, 6 -sluice, 7 - auger dosing device, 8 - propeller, 9 - support, 10 - bearing

To simulate the dosing and distribution process of biocomposite materials, Altair EDEM™

software, a simulation program based on the discrete element method (DEM), was used.
The discrete element method was also used by Sun et al. (2023) to conduct a phenomenological analysis and numerical investigation of the particle motion characteristics influenced by structural feature parameters of the groove wheel-type fertilizer discharge device. After optimization, the discharge CV was reduced from 91.54% to 31.48%, and the uniformity was improved by 60.06%.
The influence of the different fertilizer discharge parameter combinations on fertilizer discharging performances of the spiral fertilizer applicator was analyzed by Zhang et al. (2023). Furthermore, an EDEM simulation model was built and the fertilizer discharge mechanism was explored. The impact of the fertilizer discharge parameter combinations on the discharging performances was examined from both macroscopic and microscopic perspectives.
This method is particularly useful in simulating the motion and interaction of small particles, such as biocomposites. Figure 4 shows the 3D model of the biocomposite hopper made in SolidWorks, which was subsequently converted to an .stl file and imported into the Altair EDEM$^{TM}$ simulation software.

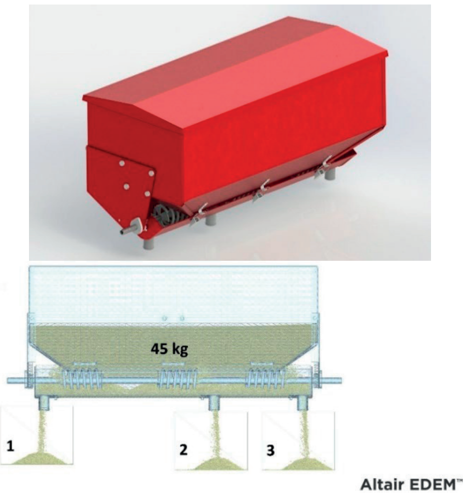



Figure 4. 3D model of the biocomposite hopper-chute-dosing devices assembly and simulation of the dosing and distribution process of the fertilizer material

Simulation in Altair EDEM$^{TM}$ allowed us to analyze with great accuracy the behavior of the material as it is transported through the chute and flows through the vertical tubes into the three collection boxes 1, 2 and 3. This approach provided us with relevant data on the uniformity of the transverse distribution of the designed equipment.
Within the simulation, the first step consisted of defining the materials from which the components of the studied assembly are made: S275JR for the biocomposite hopper and chute, 56Si17A for the auger-type dosing devices.
The next step was to create a detailed 3D CAD model of the smart mineral particle and import it into Altair EDEM$^{TM}$ (Figure 5). This approach allowed us to generate particles with similar characteristics, thus optimizing the accuracy of the simulation of their distribution.

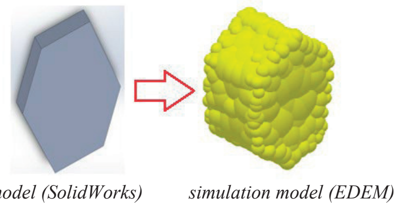



Figure 5. Mineral particle used in the simulation

Next, we realized the interaction between the biocomposite hopper-chute-dosing devices assembly and the smart mineral particles, to ensure an accurate simulation of their behavior. Subsequently, we created a polygon and a factory, in which we filled the biocomposite hopper with a quantity of 45 kg of material. After filling the hopper, we virtually modified the three sluices, allowing the material to flow into the chute and be distributed in the three tubes. Finally, we gave the dosing devices a circular motion, with preset speeds of 20, 24 and 28 rotations per minute, which will also be used in the experimental research.

## RESULTS AND DISCUSSIONS

The simulation of the fertilizer dosing process had as its main purpose the theoretical determination of the degree of non-uniformity of the transverse distribution (over the working width of the equipment). The simulation program automatically provided the quantities of fertilizer collected in the three virtual boxes, based on which the absolute mean, standard deviation and coefficient of variation were calculated using Excel. The acceptability condition is if Cv<10%.

The degree of non-uniformity of the fertilizer distribution across the working width of the equipment was highlighted by the coefficient of variation (*Cv*), calculated with the relation (1):

$$C_v = \frac{S}{\bar{x}} \times 100, \% \qquad (1)$$

where: S is the standard deviation, which was calculated with the relation (2):

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}, \text{g} \qquad (2)$$

where: n is the number of dosing devices, n=3; $x_i$ - the average amount of fertilizer collected from each dosing device;

$\bar{x}$- absolute average (average quantity collected at all dosing devices), calculated with the relation (3):

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i, \text{g} \qquad (3)$$

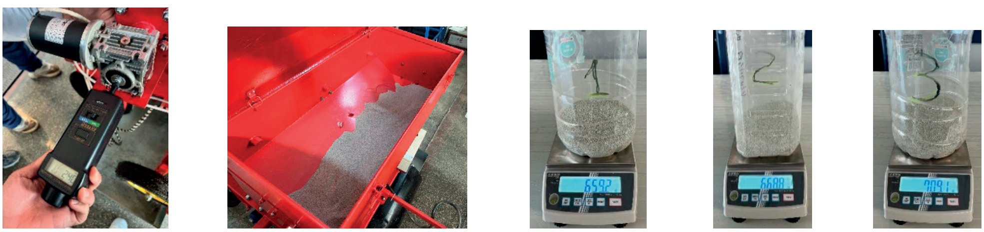
The results obtained from the simulation of the fertilizer material dosing process are presented in Table 1.

Table 1. The degree of non-uniformity of the transverse distribution (Coefficient of variation) determined theoretically (by simulation)

| Speed (rpm) | Dosing device no. | Average amount of fertilizer collected from each dosing device, $x_i$ (g) | Absolute average, $\bar{x}$ (g) | Standard deviation, *S* (g) | Coefficient of variation, $C_v$ (%) |
|---|---|---|---|---|---|
| 20 | 1 | 480 | 472 | 18.36 | 3.89 |
| | 2 | 451 | | | |
| | 3 | 485 | | | |
| | Average total quantity (g) | 1416 | | | |
| 24 | 1 | 642 | 650 | 29.82 | 4.59 |
| | 2 | 625 | | | |
| | 3 | 683 | | | |
| | Average total quantity (g) | 1950 | | | |
| 28 | 1 | 764 | 759 | 38.74 | 5.10 |
| | 2 | 718 | | | |
| | **3** | 795 | | | |
| | Average total quantity (g) | 2277 | | | |

Experimental research was carried out according to the test method regulated by the SR ISO 5690-2:1995.

The tests were carried out by driving the dosing devices at speeds of 20, 24 and 28 rpm, measured with the EXTECH Instruments tachometer, collecting and weighing the fertilizer distributed by each device with the KERN electronic balance (Figure 6).



*speed measurement* *fertilizer level in the hopper* *weighing samples*

Figure 6. Aspects during experimental research

Each test was carried out simultaneously on the three dosing devices of the equipment, in five repetitions. The time required for each test was 30 seconds. The average of the five samples from each test was calculated and an average value of the amount of fertilizer collected at each dosing device was obtained. The experimentally obtained values for the coefficient of variation ($C_v$) are presented in Table 2.

Table 2. The degree of non-uniformity of the transverse distribution (Coefficient of variation) determined experimentally

| Speed (rpm) | Dosing device no. | Average amount of fertilizer collected from each dosing device, $x_i$ (g) | Absolute average, $\overline{x}$ (g) | Standard deviation, $S$ (g) | Coefficient of variation, $C_v$ (%) |
|---|---|---|---|---|---|
| 20 | 1 | 619 | 636 | 32.97 | 5.18 |
| | 2 | 615 | | | |
| | 3 | 674 | | | |
| | Average total quantity (g) | 1908 | | | |
| 24 | 1 | 700 | 713 | 36.29 | 5.09 |
| | 2 | 685 | | | |
| | 3 | 754 | | | |
| | Average total quantity (g) | 2139 | | | |
| 28 | 1 | 792 | 791 | 66.51 | 8.41 |
| | 2 | 724 | | | |
| | 3 | 857 | | | |
| | Average total quantity (g) | 2373 | | | |

In order to verify and validate the theoretical simulation method, the results obtained from the simulation were compared with the experimental results. A first observation is that, in both cases, the coefficient of variation is below the preset upper limit of 10%. A value close (8.41%) to the upper limit of 10% was observed in the case of experiments at the speed of 28 rpm of the dosing devices, which indicates a possible inappropriate behavior of the fertilizer at high speeds. As can be seen in Table 3, the relative error between the results obtained by simulation and experimental has small values, so we can conclude that the theoretical simulation method has a good predictive capacity, and can be used to predict other qualitative indices of mobile equipment for in-situ soil bioremediation, such as the degree of non-uniformity of distribution on the soil surface.

Table 3. Comparison between the values of the coefficient of variation obtained by simulation and experimentally

| Speed (rpm) | Coefficient of variation, $C_v$ (%) | | Relative error (%) |
|---|---|---|---|
| | Values obtained from simulation | Experimentally obtained values | |
| 20 | 3.89 | 5.18 | 1.29 |
| 24 | 4.59 | 5.09 | 0.5 |
| 28 | 5.10 | 8.41 | 3.31 |

For the two working speeds (1.5 m/s and 2.5 m/s) recommended by SR ISO 5690-2:1995 and using the experimental data in Table 2 for the average total amount of biocomposite collected from the dosing devices at the three speeds of the dosing devices, the theoretical amounts of biocomposite ($Q_{tot}$) that the equipment can distribute per hectare were calculated, with the relationship (4).

$$Q_{tot}(\frac{kg}{ha}) = \frac{Q_i\,(g)}{S_i(m^2)} \times 10 \quad (4)$$

where: $Q_i$ is the total average amount of biocomposite collected from the dosing devices for each of the three speeds, in grams, calculated with the relation (5):

$$Q_i = \sum_{i=1}^{3} x_i,\ \mathrm{g} \quad (5)$$

$S_i$ is the area covered by the equipment during t=30 s, in m$^2$.

Thus, in 30 seconds, the equipment with a working width of 1.4 m, at an average speed of 1.5 m/s (5.4 km/h), would travel 45 linear meters, covering an area equal to 63 m$^2$. At an average speed of 2.5 m/s (9 km/h) the equipment would travel 75 linear meters, covering an area equal to 105 m$^2$.

The results obtained for the theoretical quantities of biocomposite that the equipment can distribute per hectare are presented graphically in Figure 7.

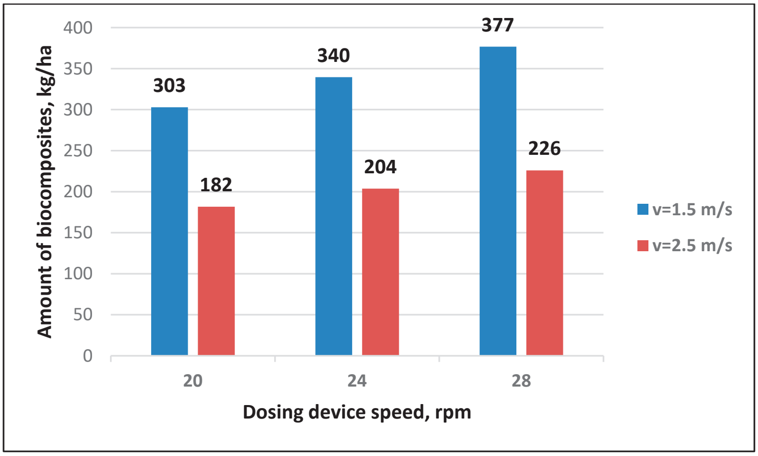



Figure 7. Evolution of the amount of biocomposites applied per hectare depending on the speed of the dosing device, for two working speeds of the equipment

Analyzing the graph in Figure 7, it is observed that the closest value of the amount of biocomposite that the equipment can distribute per hectare (377 kg/ha) to the value indicated in SR ISO 5690-2:1995 for this type of fertilizer was obtained for the dosing device speed of 28 rpm and the equipment working speed of 1.5 m/s. At the same time, it was observed that the range of amounts of biocomposite that the equipment can distribute per hectare is between 182 kg/ha and 377 kg/ha, completely covering the amounts currently used in agricultural practice and specified in the SR ISO 5690-2:1995.

## CONCLUSIONS

In this study, a complex design and simulation process was developed, starting with the realization of the biocomposite hopper - chute - dosing devices assembly of the mobile equipment for in-situ soil bioremediation, using the SolidWorks modeling software. To simulate the dosing and distribution process of biocomposite materials, the Altair EDEM$^{TM}$ software was used, a simulation program based on the discrete element method.

In order to verify and validate the theoretical simulation method, the results obtained from the simulation were compared with the results obtained experimentally, for the degree of non-uniformity of the transverse distribution highlighted by the coefficient of variation.

Since the relative error between the results obtained by simulation and experimentally had small values, it can be concluded that the theoretical simulation method has a good predictive capacity, and can be used to predict other qualitative indices of mobile equipment for in-situ soil bioremediation.

At the same time, using simulation in Altair EDEM$^{TM}$, iterative adjustments to the 3D model in SolidWorks can be made, testing improvements. This iterative design and testing process will allow the gradual optimization of the components of the mobile equipment for in-situ soil bioremediation, ensuring the efficiency and reliability necessary for use in real field application conditions.

The theoretical quantities of biocomposite that the equipment can distribute per hectare at two working speeds indicated in the current regulations were calculated and the optimal combination between the speed of the dosing devices (28 rpm) of the biocomposite materials and the working speed of the equipment (1.5 m/s) was determined.


## ACKNOWLEDGEMENTS

This research was supported by project *Establishment and operationalization of a*

*Competence Center for Soil Health and Food Safety* – CeSoH, Contract no. 760005/2022, specific project no.4 with the title: *Innovative and emerging solutions for smart valorisation of residual resources impacting health and safety of soil-food axis* (*InnES - Innovation, Emerging, Solutions-Soil*), Code 2, financed through PNRR-III-C9-2022 – I5 (PNRR-National Recovery and Resilience Plan, C9 Support for the private sector, research, development and innovation, I5 Establishment and operationalization of Competence Centers).

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