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Automated Spraying System for Post-Mining Land Reclamation – Structural Design and Functional Testing

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Abstract:

This article presents the concept and test results of a prototype automated spraying system developed as part of the REECOL project, designed for applying remediation mixtures such as water, seeded mulch, and organic biofertilizers. The system is integrated with transport platforms and consists of modular components, including a pump unit, suction manifold, mixers, IBC tanks, a power supply unit, and a compressor. The key operating element is a spray cannon equipped with two independent nozzles, enabling the application of media with varying densities and the adjustment of spray characteristics. Functional tests confirmed the correct operation of the spray cannon's rotation and deflection systems and allowed determination of control characteristics as a function of motor supply frequency and linear actuator extension. Measurements of flow, pressure, and spray range were performed for various nozzle configurations. Additional tests verified mixer performance and assessed suction and spraying capabilities for mulch and biofertilizers. The system demonstrated proper operation with cellulose-based mixtures and indicated the need for ball valves when handling mixtures containing solid fractions. The developed prototype confirmed the ability to precisely and efficiently apply remediation media, providing a basis for further technology optimization and field testing.

Keywords: automatic spray system; remediation of degraded lands; remediation mixtures; hydroseeding; organic biofertilizers; spray cannon; spray nozzles; pump-mixing systems; flow regulation; prototype testing

1. Introduction

The progressive exploitation of mineral resources leads to the formation of extensive degraded areas characterized by unfavorable physicochemical soil properties, disturbed land surface structure, and a limited capacity for natural ecosystem regeneration. A particularly significant issue concerns post-mining areas, where long-term extraction activities have resulted in substantial landform transformations and the creation of waste dumps composed of mining residues such as waste rock and processing tailings [[1], [12]]. Areas lacking stable vegetation cover constitute an important source of environmental impacts, including the emission of suspended particulate matter (PM_{10}, $PM_{2.5}$), the migration of pollutants into groundwater and surface waters, and landscape degradation [[14]].

The problem of post-mining land reclamation is widespread and affects both Central and Southern European regions, where additional challenges arise from varying climatic conditions, such as prolonged droughts, high temperatures, and limited water availability. For example, degraded areas caused by lignite mining in Greece require flexible and adaptive reclamation strategies tailored to local environmental and technical conditions [[5]].

One of the key stages of land reclamation is the stabilization of soil surfaces and the initiation of biological processes through the application of appropriate water-organic mixtures, including plant seeds, cellulose-based mulches, and organic fertilizers. The effectiveness of these measures largely depends on the proper selection of mixture composition and the application method, which determines the uniformity of distribution and nutrient availability for developing vegetation [[9]]. Under conditions typical of post-mining dumps—characterized by a high proportion of coarse fractions, water deficits, and extreme thermal conditions—this process is particularly challenging [[12], [10]].

Dump substrates exhibit properties similar to regolith, forming poor, skeletal soils with heterogeneous chemical and mechanical composition, often characterized by unfavorable pH values and low nitrogen content. These factors significantly limit plant growth and favor colonization by resilient species, primarily native plants associated with spontaneous succession [[2],[11]]. Numerous studies indicate that vegetation developing through long-term spontaneous succession on unreclaimed dumps forms the most durable and stable plant cover [[11]].

Currently applied reclamation and greening methods in post-mining areas are mainly based on contact solutions utilizing conventional agricultural machinery or construction equipment. Although widely used, these methods exhibit significant limitations in areas with difficult access, steep slopes, or unstable ground conditions. Moreover, they often require intensive maintenance measures, without which planted vegetation gradually degrades and is replaced by naturally successional species [[1], [9]].

In response to these limitations, non-contact technologies enabling remote application of reclamation media using spraying systems with adjustable operating parameters are gaining increasing importance. Such solutions reduce mechanical interference with the soil structure, extend the operational range, and allow better adaptation of application parameters to changing environmental conditions.

The aim of this paper is to present the concept, structural design, and test results of a prototype automated spraying system developed for non-contact remediation of degraded soils, particularly post-mining areas. The paper describes the key design solutions of the system, the process of prototype development and construction, and the results of functional tests confirming the flexibility and adaptive potential of the developed technology under diverse environmental conditions. The work presented herein is the result of the implementation of the European project REECOL [[4]].

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2. Concept of the technology and design assumptions

The key component of the developed non-contact soil remediation technology is an automated spraying system designed for applying reclamation mixtures, including water, water with organic fertilizers, and water with seeded mulch. The system was designed as a mobile solution, enabling transport and operation on agricultural platforms or low-bed trailers, which allows reclamation works to be carried out under diverse terrain conditions. In the initial development stage, a conceptual model of the technology was created as a 3D design. The concept assumes an automated spraying system capable of applying one of three reclamation materials, operating in conjunction with a soil monitoring system (sensors) and a vision-based decision-making system that uses data acquired from unmanned aerial vehicles (UAVs) and normalized difference vegetation index (NDVI) analysis (fig. 1).

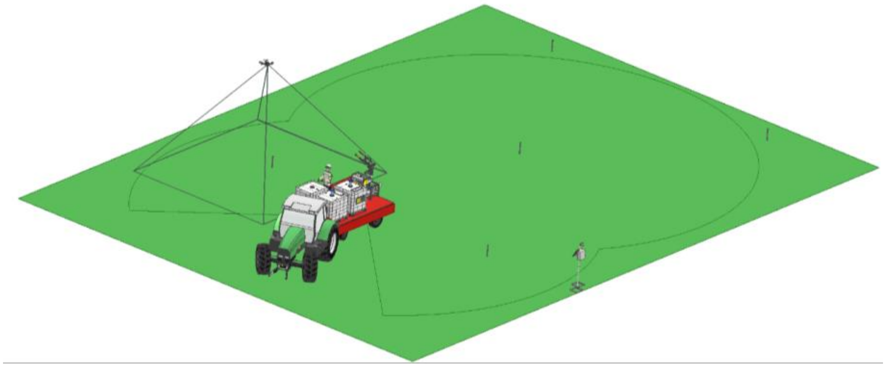

Fig. 1. Conceptual model of the non-contact soil remediation technology [[1], [13]]

The technology is based on processing data obtained from soil sensors and surface images acquired by UAVs to generate a map of required reclamation treatments. Depending on local conditions, the system can perform seeding with a seed–mulch mixture, apply organic waste in the form of compost, or provide surface irrigation. The area designated for reclamation is divided into smaller sectors corresponding to the operational range of the spray cannon. The center of each sector is positioned using a GPS system. For each sector, an individual reclamation scenario is generated as a control file and transmitted to the spraying system controller (Fig. 2). After relocating the spraying system to predefined GPS points, consecutive operating scenarios are executed automatically. Following the completion of reclamation treatments, continuous monitoring of the area is carried out. If a decline in soil parameters or NDVI values is detected, the system initiates additional reclamation actions adapted to the current conditions.

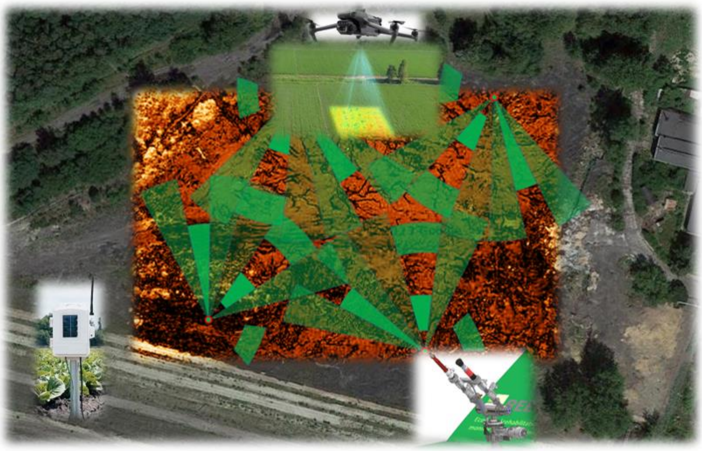

Fig. 2. Schematic concept of the operation of the post-mining land reclamation technology [[1], [13]]

3. Structure and operating principle of the automated spraying system

The primary design objective was to enable precise control of both the hydraulic parameters of the spray stream and its spatial orientation, allowing the application process to be adapted to the type of medium and the characteristics of the reclaimed area. Based on extensive experience in designing and testing prototype solutions [[7]], the entire system was developed and validated at the KOMAG Institute of Mining Technology. The system was conceived as a modular solution, enabling future expansion and adaptation to other environmental or transport-related applications.

The automated spraying system consists of the following main subsystems (fig. 3):

1. – spray cannon,
2. – pump unit with suction manifold,
3. – IBC tanks,
4. – mixers,
5. – power generator,
6. – air compressor.

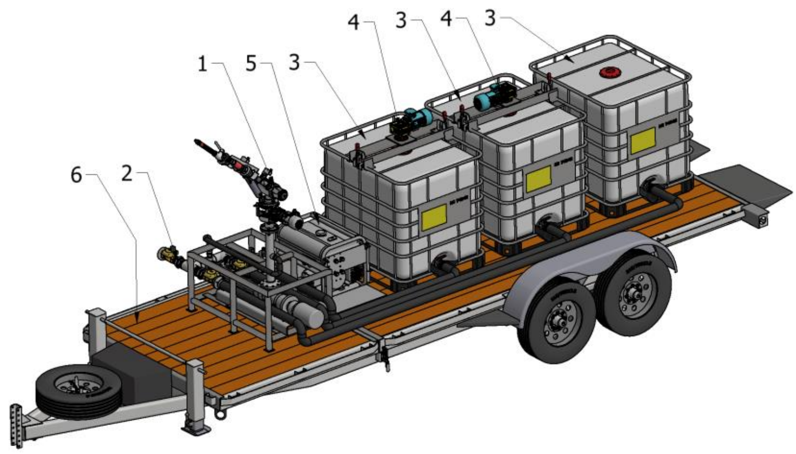

Fig. 3. Main components of the automated spraying system [[1], [13]]

The configuration of the automated spraying system ensures fully autonomous operation under field conditions, without requiring access to external power or media supply sources. The spray cannon, the key element of the system, is responsible for applying reclamation mixtures and is hydraulically coupled with the pump unit. Other subsystems handle medium preparation, homogenization, power supply, and control and auxiliary functions.

The spray cannon is designed as a mechanism with two degrees of freedom: rotation about the vertical axis of the cannon column and deflection about the horizontal axis (fig. 3). It is connected to the pump unit via a rigid pipeline equipped with pressure gauge ports and a pressure sensor for continuous monitoring of hydraulic parameters. Additionally, the pipeline includes a bypass branch that connects to the suction side of the pump through a spring-loaded check valve, acting as a relief valve to protect the system against excessive pressure. The spray cannon rotates around the vertical axis through a full 360° range using a slewing mechanism consisting of a stationary base and a rotating rotor, driven by a geared motor with a toothed gear transmission. This configuration enables smooth regulation of rotational speed as a function of motor supply frequency. The second degree of freedom—deflection about the horizontal axis—is implemented using an electric linear actuator. Both kinematic joints are equipped with encoders for precise monitoring and control of the working unit position

On the rotary sleeve, two independent outlets in the form of spray nozzles have been installed. The nozzle with a larger through diameter is intended for applying mixtures containing solid particles, such as mulch with seeds, while the nozzle with a smaller diameter is used for spraying water or homogeneous mixtures. The selection of the active nozzle is controlled via an appropriate solenoid valve.

The subsystem responsible for generating the hydraulic parameters of the working medium is the pump unit with a suction manifold. A positive-displacement screw pump driven by a three-phase electric motor is used, ensuring stable pumping of media with varying viscosity and solid particle content. On the suction side of the pump, a manifold equipped with four inlet ports fitted with control valves is installed, allowing selection of the medium supply source. This configuration enables rapid switching between different reclamation variants, including supply from water tanks, fertilizer solutions, seeded mulch mixtures, or an external water source.

4. Functional tests

Laboratory tests of the automated spraying system were conducted in several stages, including both functional verification and measurement of operating parameters. In the first stage, the system was commissioned, and the correctness of power supply to all subsystems from the power generator was verified (fig. 4). During functional testing, the system was operated using a manual operator panel with manual control mode enabled in the control software.

Fig. 4. Automated spraying system under test, with indicated spray cannon operating directions

The next stage involved testing the spray cannon positioning system, including verification of correct rotation about the vertical axis and deflection about the horizontal axis, as well as proper operation of limit switches. Subsequently, tests of the supply system were conducted, focusing on correct pump and valve operation for different tank configurations and selected spray nozzles. Additional tests included verification of mixer performance and stability of compressed air pressure in the tanks. Further stages comprised measurements of pressure and flow rate for various nozzle settings, as well as measurements of spray range at different spray cannon deflection angles. The final stage of testing involved system operation with actual reclamation media, including seeded mulch and organic biofertilizer

4.1. System start-up and power supply tests

During the test, the power generator was started, and the correctness of power supply to all system components was verified. During functional testing, the system was controlled using a manual control panel with the manual operation mode enabled in the device control software.

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The next stage involved testing the correct operation of the supply system, carried out with the pump operating continuously for the following solenoid valve configurations:

a) Supply from tank I
   - water spray nozzle,
   - mulch spray nozzle.
b) Supply from tank II
   - water spray nozzle,
   - mulch spray nozzle.
c) Supply from tank III
   - water spray nozzle,
   - mulch spray nozzle.

The purpose of these tests was to verify the correct opening and operation of individual solenoid valve configurations. In the initial phase, the tests were conducted using tanks filled with clean water. All tested configurations confirmed proper operation of the pump supply system and correct feeding of the spray cannon from each selected tank.

Subsequently, tests of mixer performance and verification of stable compressed air pressure were conducted, including the following checks:

a) activation of mixer 1,

b) activation of mixer 2.

The system tests confirmed the correct operation of the on–off cycles of the mixers installed on the tanks intended for mulch and fertilizer mixtures (fig. 5).

Fig. 5. Mixer operation test

As a result of the conducted tests, an issue of excessive current load was identified during compressor start-up when the pump was operating. The problem was resolved by connecting the compressor to a different phase of the three-phase power supply.

4.2. Tests of the spray cannon positioning system and determination of empirical correlation between control parameters and actual motion

In the first stage, the correctness of the spray cannon turret rotation was verified. The following functional tests were carried out:

a) rotation to the left,

b) rotation to the right,

c) verification of correct limit switch operation

In both rotational directions, the spray cannon turret operated correctly, stopping rotation upon entering the activation zone of the limit switch (fig. 6).

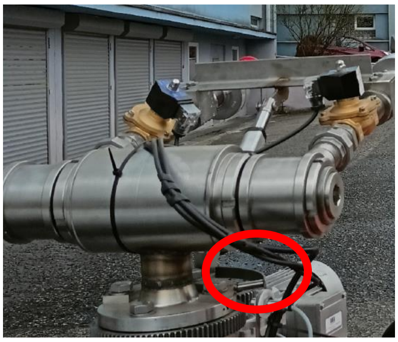

Fig. 6. Functional tests of the spray cannon slewing mechanism with the marked limit switch

The rotational speed of the spray cannon is controlled by adjusting the inverter frequency. To determine the relationship between rotational speed and inverter frequency settings, the time required for a 180° rotation was measured at different frequency values. The measurement results are summarized in table 1.

Table 1. Rotation time of the spray gun as a function of inverter frequency

Inverter frequency, Hz	15	20	25	30	35	40	45	50
Rotation 180° – Time, s	34,7	25,3	20	16,7	14	12,7	11,3	10

Subsequently, the data were plotted as connected points on a graph illustrating the relationship between the rotation time and the inverter supply frequency (Fig. 7).

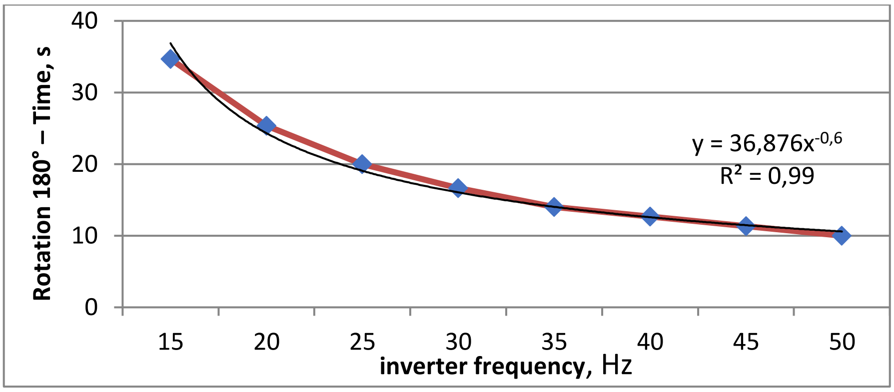

Fig. 7. Rotation time of the spray cannon as a function of inverter frequency

Based on the measured rotation times, an empirical approximation function was determined, enabling calculation of the time required for a 180° rotation at a given inverter frequency. The coefficient of determination for the obtained function was $R^2 = 0.99$.

$$t = 36,876 \cdot f^{-0,6} \tag{1}$$

Where:

t – rotation time for 180°, s,

f – inverter frequency, Hz.

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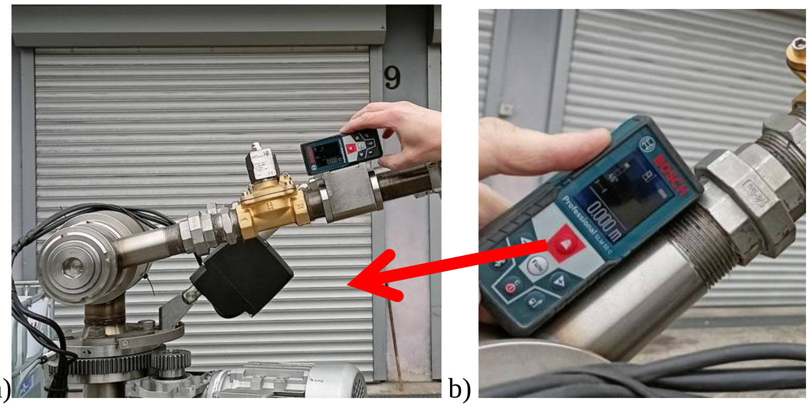
The next stage of the spray cannon functional tests involved verification of correct vertical deflection. The following tests were performed:

a) upward deflection,

b) downward deflection.

Vertical deflection of the working assembly is achieved using an electric linear actuator with an extension range of 0–99 mm. The kinematic system allows preliminary adjustment of the deflection angle for the initial actuator extension. The system was configured so that at maximum actuator extension, the spray cannon was deflected by 45° relative to the horizontal plane. The procedure for measuring the spray cannon deflection angle as a function of actuator extension is shown in fig. 8. The measured deflection angles corresponding to different actuator extensions, with a step of 5 mm, are presented in table 2.



a) b)

Fig. 8. Measurement of the spray cannon deflection angle as a function of actuator extension

Table 2. Spray cannon deflection angle relative to the horizontal plane as a function of actuator extension

actuator extension L, mm	0	10	20	30	40	50	60	70	80	90	99
deflection angle α, °	5	9	13	17	21	25	29	32	37	41	45

Subsequently, the data were plotted as connected points on a graph illustrating the relationship between actuator extension and the resulting spray cannon deflection angle relative to the horizontal plan (fig. 9).

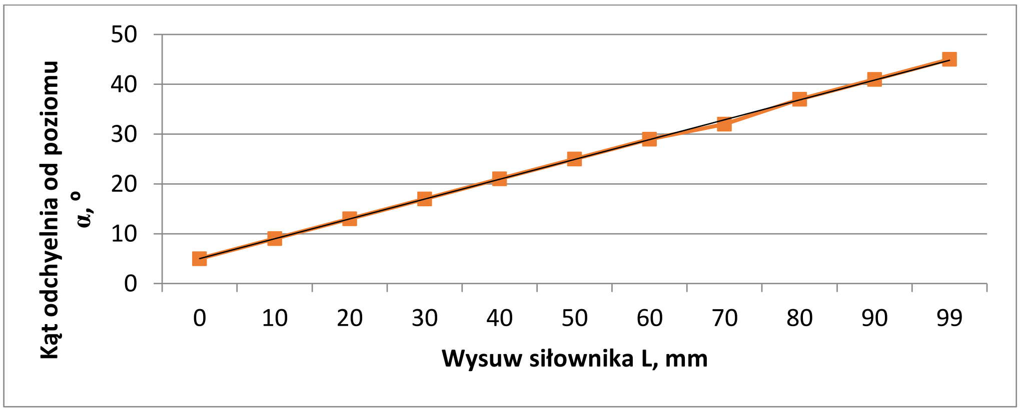


Fig. 9. Relationship between actuator extension and spray cannon deflection angle relative to the horizontal plane

Based on the measured values of the deflection angle relative to the horizontal plane, an empirical approximation function was determined, enabling calculation of the spray cannon deflection angle as a function of actuator extension. The coefficient of determination for the obtained function was $R^2 = 0.99$.

$$\alpha = 3{,}9818\, l + 1{,}0182 \tag{2}$$

Where:

α – spray cannon deflection angle relative to the horizontal plane, °,

l – actuator extension, mm

The conducted functional tests of the spray cannon positioning system enabled not only verification of correct operation of the actuating components but also determination of empirical relationships between control parameters and the actual motion of the spray cannon. The obtained characteristics are of key importance for the implementation of control algorithms and programming of the system operating logic.

5. Performance tests of the system

Measurements of water flow rate through the spray nozzles, the shape of the generated spray stream, and its impact range were carried out to quantitatively evaluate the operating parameters of the spray cannon and assess the possibility of adjusting them as a function of hydraulic system settings. The obtained results form the basis for analyzing the relationships between nozzle geometry, operating pressure, spray cannon inclination angle, and the efficiency and range of medium application.

5.1. Measurement of pressure and flow rate

Measurements of water pressure and flow rate were performed using a HYDAC data recorder. Two types of spray nozzles were used in the system. Both nozzle types allowed modification of the generated spray stream through appropriate adjustment of the nozzle valve or outlet configuration, as shown in fig. 10 and summarized in table 3:

- **water spray nozzle (DW)** with four operating positions corresponding to outlet adjustment of 0.5, 1.0, 1.5, and 2.0 turns,
- **mulch spray nozzle (DM)** with two operating positions, denoted as position II and position III.

a)  b) 

Fig. 10. Measurement of pressure and flow rate at the tested outlet nozzle: a) water spray nozzle, b) mulch spray nozzle

Table 3. Flow rate and operating pressure

	Flow Q, dm^3	Pressure p, MPa
FLow without nozzle	115,2	0,24
DM – position II	72,3	0,40
DM – position III	72,2	0,40
DW - 0,5 turn	103,7	0,36
DW - 1,0 turn	107,9	0,35
DW - 1,5 turns	109,4	0,34
DW - 2,0 turns	113,5	0,29

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Fig. **10** presents the recorded plots of water flow rate variations for different nozzle settings.

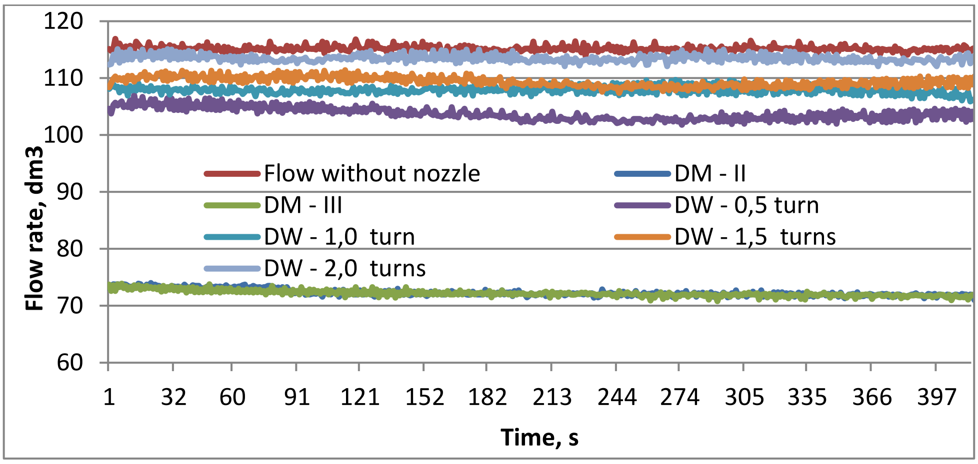

Fig. 11. Water flow rate measurements for different nozzle settings

For each test, photographs of the generated spray stream shape were taken. Fig. 12 and Fig. 13 present a general view of the spray stream from two perspectives (side and rear views).

Fig. 12. Photographic documentation of the spray stream shape generated by the water spray nozzle (DW) at different outlet adjustment settings (from top: 2.0, 1.5, 1.0, and 0.5 turns of the nozzle outlet)

Fig. 13. Photographic documentation of the spray stream shape generated by the mulch spray nozzle (DM) at different operating positions (top: position III, bottom: position II)

5.2. Measurements of Nozzle Operating Range

The theoretical range of the liquid jet discharged from the spray cannon nozzle can be described using classical ballistic motion equations, assuming a constant outlet velocity of the jet and neglecting aerodynamic drag. Under these assumptions, the trajectory of the spray stream takes the shape of a parabola, and its horizontal range depends primarily on the outlet velocity and the inclination angle of the spray axis relative to the horizontal plane. According to classical mechanics theory, the maximum spray range is achieved at an inclination angle of approximately 45°, which directly results from the analysis of motion equations in a gravitational field [[8], [6], [3]]. For inclination angles smaller or greater than the optimal value, the spray range decreases, as illustrated by the characteristic trajectories corresponding to different outlet angles (e.g., 15°, 35°, 45°, 60°, and 70°), as shown in fig. 14.

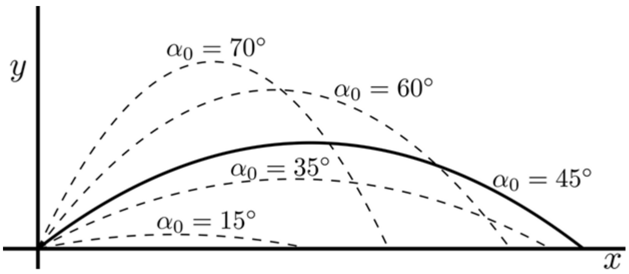

Fig. 14. Theoretical influence of the deflection angle relative to the horizontal plane on the operating range of the spray cannon

However, due to the influence of external factors, the spray range of the nozzles was evaluated experimentally. The tests were conducted for various spray cannon deflection angles. The spray range measurements were performed for actuator extensions in the range of 0–99 mm, with a step of 5 mm.

During the tests, for each deflection angle the following spray ranges were measured:

- maximum range (Z max),
- average range (Z av.)
- minimum rang (Z min).

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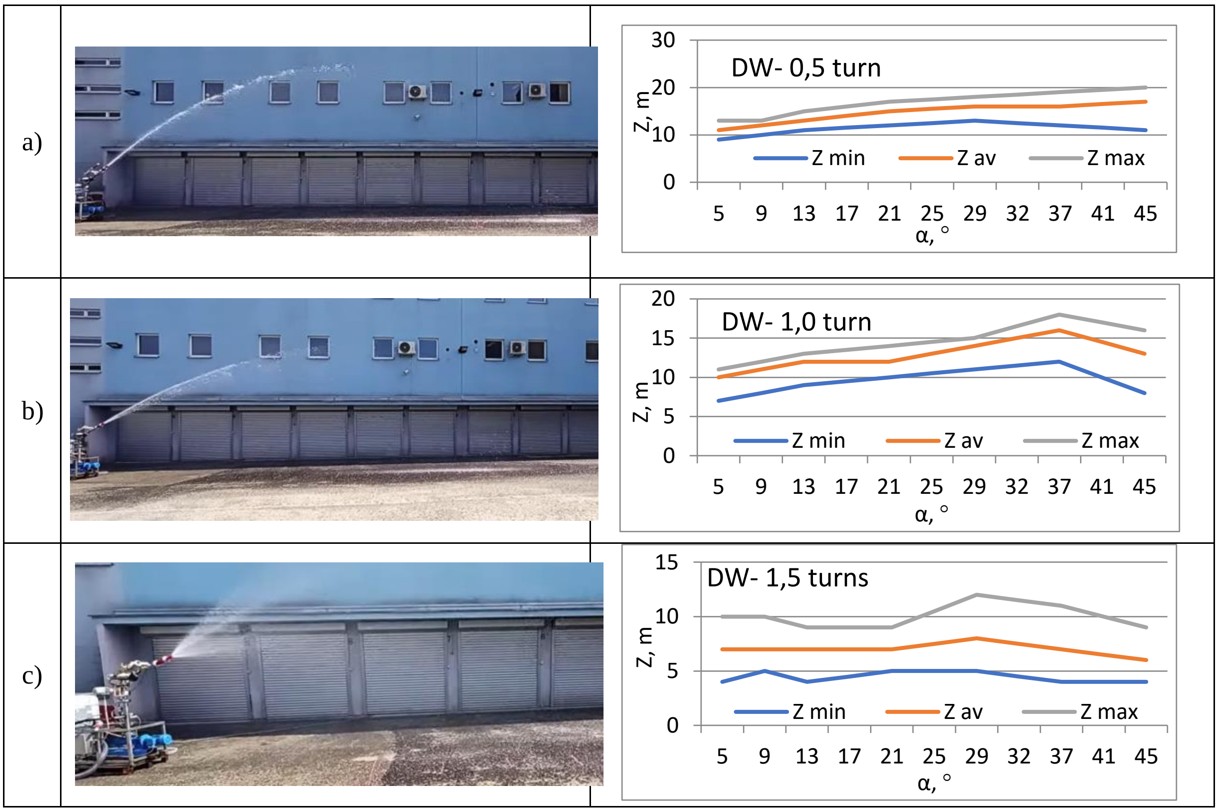
In order to properly assess the spray range, a measurement scale with meter markings in the range of 0–25 m was placed at the test site. The spray ranges were evaluated based on direct observations and analysis of photographs taken during the tests. The results of the spray range measurements for all combinations of the water spray nozzle (DW) and the mulch spray nozzle (DM) operating settings are summarized in table 4.

Table 4. Spray range during nozzle operation

Typ dyszy		DM - II			DM - III			DW - 0,5 turn			DW - 1,0 turn			DW - 1,5 turns			DW - 2,0 turns		
		spray range Z, m																	
Wysuw	Kąt	min	av	max	min	av	max	min	av	max	min	av	max	min	av	max	min	av	max
0	5	9	11	13	9	11,5	14	7	10	12	7	10	11	4	7	10	3	4	7
10	9	10	12	13	10	13	16	7	9	13	8	11	12	5	7	10	3	5	7
20	13	11	13	15	11	14	16	7	10	12	9	12	13	4	7	9	3	5	7
30	17	11,5	14	16	12	15	17,5	7,5	10,5	13	9,5	12	13,5	4,5	7	9	3	4,5	6,5
40	21	12	15	17	13	16	19	8	11	14	10	12	14	5	7	9	3	4	6
50	25	12,5	15,5	17,5	14	16,5	19,5	6,5	10	12,5	10,5	13	14,5	5	7,5	10,5	2,5	4	6
60	29	13	16	18	15	17	20	5	9	11	11	14	15	5	8	12	2	4	6
70	32	12,5	16	18,5	13,5	17,5	21	6	9,5	11,5	11,5	15	16,5	4,5	7,5	11,5	1,5	4	6
80	37	12	16	19	12	18	22	7	10	12	12	16	18	4	7	11	1	4	6
90	41	11,5	16,5	19,5	11	16,5	21	7	10	12,5	10	14,5	17	4	6,5	10	0,5	4	5,5
100	45	11	17	20	10	15	20	7	10	13	8	13	16	4	6	9	0	4	5

Fig. **15** presents the graph of spray range variation as a function of the deflection angle, along with a photograph illustrating the maximum operating range of the nozzle.



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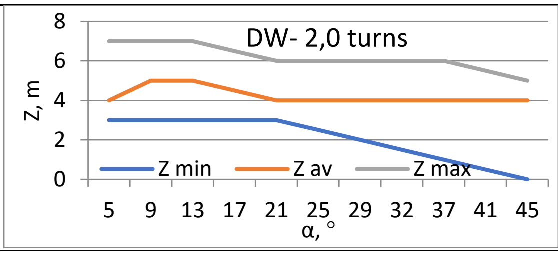
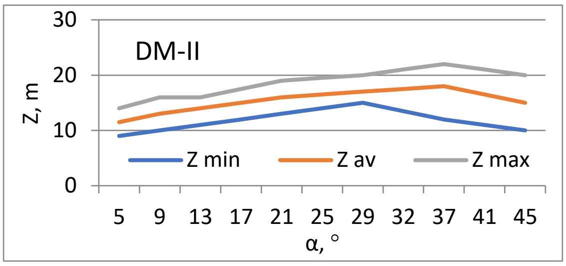


e)



f)

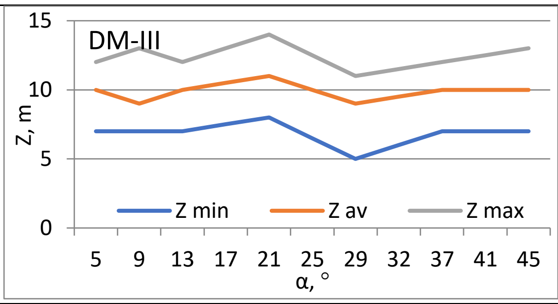


Fig. 15. Results of spray range measurements for the nozzles in different configurations; a) DW- 0,5 turn, b) DW- 1,0 turn, c) DW- 1,5 turn, d) DW- 2,0 turn, e) DM-II, f) DM-III

6. Discussion

The laboratory tests conducted on the prototype automated spraying system enabled a comprehensive assessment of its suitability for implementing non-contact remediation technology for degraded soils. The obtained results clearly confirmed the correctness of the adopted design solutions and the appropriateness of the selected drive and hydraulic systems in relation to the assumed operating functions of the system.

Particularly important are the results of the spray cannon positioning system tests, which established empirical relationships between control parameters and the actual motion of the working unit. The relationship between the time required for a 180° rotation of the spray cannon and the inverter supply frequency, described by a power function with a coefficient of determination $R^2 = 0.99$, indicates very high repeatability of rotational motion. Similarly, the linear relationship between actuator extension and the spray cannon deflection angle ($R^2 = 0.99$) confirms the stability and predictability of motion in the vertical plane. These results are crucial for further automation of system operation, as they enable unambiguous mapping of control settings to the actual position of the spray stream.

An important component of the study involved measurements of hydraulic parameters, including flow rate and operating pressure for different nozzle configurations. The obtained flow rate values, summarized in Table 3, demonstrated the possibility of smooth adjustment of spray discharge depending on the nozzle type and its opening setting. Simultaneous analysis of the spray stream shape, documented photographically, confirmed the influence of nozzle geometry on jet concentration and its susceptibility to breakup. These results indicate that the system enables adaptation of spray characteristics to the type of applied medium, which is particularly important for mixtures with varying viscosity and solid particle content.

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Analysis of spray range measurements showed that the achieved maximum values—reaching approximately 22 m for the mulch spray nozzle under specific configurations—allow effective reclamation treatments to be carried out over large areas without frequent repositioning of the system. Comparison of experimental results with the theoretical spray trajectory model based on classical ballistic motion equations confirmed the consistency of general trends, particularly the occurrence of maximum range at an inclination angle close to 45°. At the same time, differences between theoretical and measured values indicate the significant influence of real-world factors such as air resistance, spray breakup, and the physical properties of the applied medium.

A particularly important outcome of the study is the possibility of quantitative analysis of the reclamation medium application process. Combining flow rate measurements with the determined spray cannon motion velocities enables calculation of the amount of medium applied per unit area. Knowledge of spray discharge and the duration of spray impact on a given surface sector allows conversion of the applied medium volume into units such as dm^3/m^2 for a given angular range and spray cannon rotational speed. This means that the system enables not only geometric control of the spray stream but also quantitative control, which is crucial for the effectiveness of reclamation treatments.

In this context, the conducted measurements were essential for the correct development of control algorithms and system execution codes. The obtained characteristics allow programmatic linking of hydraulic and kinematic parameters with the target intensity of medium application for selected working areas. This provides a foundation for further development of the technology, including integration of the spraying system with sector-based reclamation maps and automatic adjustment of operating parameters to local soil conditions.

Tests conducted with real reclamation media also provided valuable operational insights. Correct system operation during application of cellulose-based mulch confirmed the validity of the selected screw pump and mixing system. In contrast, difficulties encountered during application of biofertilizers containing solid fractions revealed limitations associated with the applied solenoid valves, leading to a technically justified design modification involving the use of pneumatically actuated ball valves.

In summary, the obtained research results confirm that the developed system constitutes a functional and flexible platform for implementing non-contact soil reclamation technology. At the same time, the results clearly indicate that the conducted measurements were crucial not only for prototype validation but also for ensuring precise, repeatable, and controlled execution of reclamation treatments in designated areas.

The next stage of work will involve field tests to verify the developed control algorithms under real operating conditions and further optimize the technology. These tests are also essential for preparing application scenarios for degraded areas belonging to the PPC partner in Greece, including various variants of reclamation material application.

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