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Efficient maize cultivation: pre-sowing seed inoculation system - optimal nozzle pressure and diameter

M.S. Shelest[1], M.L. Shuliak[1], A.O. Butenko[2,*], O.M. Bakumenko[3], V.M. Zubko[1], O.M. Datsko[2], I.M. Masyk[2], V.M. Yatsenko[2], K.H. Sirovitskiy[1] and S.V. Rieznik[4]

[1]Sumy National Agrarian University, Faculty of Engineering and Technology, Department of Agroengineering, 160 H. Kondratieva Str., UA40021 Sumy, Ukraine
[2]Sumy National Agrarian University, Faculty of Agrotechnologies and Natural Resource Management, Department of Agrotechnologies and Soil Science, 160 H. Kondratieva Str., UA40021 Sumy, Ukraine
[3]Sumy National Agrarian University, Faculty of Agrotechnologies and Natural Resource Management, Department of Crop Protection, 160 H. Kondratieva Str., UA40021 Sumy, UA40021 Sumy, Ukraine
[4]State Biotechnological University, Faculty of Agronomy and Crop Protection, Department of Soil Science, 44 Alchevsky Str., UA61002 Kharkiv, Ukraine
[*]Correspondence: andb201727@ukr.net

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Abstract. Inoculation, as a technological operation, is currently underestimated, yet it has repeatedly proven its effectiveness. Its application in production or scientific research typically leads to improvements in yield, grain quality, or plant biometric parameters under study. However, the inoculation process itself is not standardized by any legislative act, so farmers rely solely on recommendations from manufacturers of inoculants and carry out this operation using, so to say, makeshift means. Therefore, a system of at-planting inoculation has been developed, which involves conducting this operation directly in the field. Hence, the aim of this study was to investigate the parameters of pressure and nozzle diameter that would provide the optimal amount of inoculant on the seeds and would be as close as possible to the manufacturer's recommendations. To conduct the study, a system model was created in which nozzles with diameters of 0.2, 0.3, 0.4 and 0.5 mm were investigated under pressures of 3, 4, 5 and 6 atm. The optimal amount of working solution per 1 ton of seeds was calculated for conducting the operation in the usual way, and the amount of liquid reaching 1,000 maize seeds was determined. Thus, the optimal pressure and nozzle diameter were identified. With a pressure of 3 atm in the system, none of the nozzles provide the required amount of working fluid. A similar situation occurs with a nozzle diameter of 0.2 mm. However, at higher pressure in the system and with other nozzle diameters, it is still possible to provide the necessary amount of liquid. Therefore, for the at-planting inoculation system, it is advisable to use a pressure of 4 atm and a nozzle diameter of 0.4 mm.

Key words: 1,000-seed weight, *Zea mays*, planter, seeder, tilled crops, density, inoculation system, optimal operating parameters.

INTRODUCTION

Maize (*Zea mays L.*) is one of the most important crops worldwide and maximizing its productivity is imperative (Hegazy et al., 2014; Abo-Habaga et al., 2018). Currently, inoculation is an extremely relevant issue. The very term inoculation means settlement of beneficial microorganisms on the seed material in order to improve the germination properties of the seeds. More and more agricultural producers are considering growing organic products. Firstly, they are motivated by the price of organic products, which is usually significantly higher than that of products grown using conventional technologies (Balaji, 2016). Secondly, some, particularly farmers, are concerned about the state of the environment. Therefore, they use all possible means to increase crop productivity without using inorganic substances.

The effectiveness of inoculation has been proven for many crops and in different parts of the planet. For example, inoculation is considered most effective for leguminous crops, as nodular bacteria primarily inhabit the roots of these crops (Koliada et al., 2022; Michta et al., 2023). However, inoculation is carried out not only by bacterial organisms but also by arbuscular mycorrhiza (Kharchenko, 2019; Tanchyk, et al., 2021; Boymatova, 2022). However, inoculation is not only available for legumes but also for other crops. In particular, the positive effect of seed treatment with effective microorganisms has been proven for maize (Radchenko et al., 2022; Beltran-Medina et al., 2023), wheat (Gaspareto et al., 2023), rapeseed (Valetti et al., 2018), and others.

However, current inoculation methods are not perfect. For example, in the production scale of Ukrainian agricultural companies, inoculation is usually performed using seed treatment machines, such as auger, rotary, or chamber types, when it comes to wet inoculation (Bakhmat & Chinchyk, 2010; Moskalets & Moskalets, 2015). Another technical means used in production for seed treatment is concrete mixers. Alternatively, another way to inoculate seeds is to apply a working solution containing effective microorganisms directly into the furrow. A broader overview of possible methods and techniques is provided by Shelest., (2023). In general, it can be said that devices for inoculation are usually not specialized and cannot provide complete and quality treatment of planting material.

Therefore, the issue worth addressing in this article is the quality of seed treatment with inoculant. When applying it to the seed surface using such dubious methods, one should not expect to maintain the recommended dose of the preparation on the planting material, as specified by the manufacturers in their recommendations. For example, for the 'Bio-gel' preparation, it is stated that for pre-sowing seed treatment of grain and technical crops, it is advisable to apply 2 L t^{-1} of the preparation dissolved in 10 L of water (Application methods, 2015). Thus, it is assumed that this dose will provide the optimal amount of effective microorganisms on the seed surface and sufficient coverage with the preparation. However, when overloading the planting material, during transportation and unloading at-plantinging complex, there is a high probability that the layer of inoculant applied to the seeds will be lost.

There is also a question regarding the norm of inoculant application. A review of legislative or other regulatory documents did not reveal any examples of regulating the dosage of such substances. Therefore, one has to rely solely on the recommendations of inoculant manufacturers. In particular, the well-known Ukrainian company 'BTU-Center' usually provides recommendations to use 2–3 liters of the preparation per ton (Inoculants BTU-CENTER, 2023). Typically, such a dosage is also proposed by other manufacturers.

Therefore, the aim of the study was to improve the adjustment of the at-planting inoculation system, which would allow for seed treatment in the optimal quantity up to the recommended dose of inoculants by manufacturers.

MATERIALS AND METHODS

To conduct research on seed inoculation in accordance with regulatory documentation, the recommended amount of inoculant was added to water at 20% of the water quantity. It is worth noting that the inoculant solution did not significantly affect the physico-mechanical properties of the working solution compared to water. It can be said that with such an amount of inoculant, its properties are almost identical to the physical properties of water. In particular, the density of water samples was 997 kg cm^{-3}, and the density of the working solution was 1,003 kg cm^{-3} (Fig. 1). Thus, the deviation in density is 0.6%, which can be attributed to the measurement error. Therefore, further experiments were conducted with water to save inoculant and eliminate its influence on the operation of the research equipment.

Figure 1. Density of water and working solution.

Experimental Stand

To conduct experiments at Sumy National Agrarian University, a model layout was created. Using the SolidWorks 2024 program, a sowing device was designed and printed on a 3D printer Flying Bear Ghost 5 for the main components. The model includes a tank (1) for the working solution, connected to the main pipeline (2) with a safety valve (3) and a filter (4). The working solution is delivered by a water pump (5) (Good PUMPs, 12V, 6A, 72W), through an analog pressure gauge (6) for the pressure control by a relief valve (7) (Ebowan DC 5 V G1/4, 12 MPA, China) and a two-way directional control valve (8). The solution is delivered to the nozzle (9) under a defined pressure (Fig. 2). The nozzle is mounted in the sowing tube at an angle of 17° relative to the plane on which the stand is located, and it is used for inoculation, i.e., spraying the working solution onto the planting material. The detailed structure of the system is presented in the work of Shelest et al. (2023). Therefore, this is how the device operates: when the stand is started, negative pressure is created in the seeding apparatus, which attaches the seed to the hole of the seeding disc. The seed is transported to the seed tube, where the pressure is turned off, and the seed begins to move along the tube in which the nozzle is located. The nozzle creates a conical spray on the seed path. Passing through this cut, the seed is covered with a working solution and falls out.

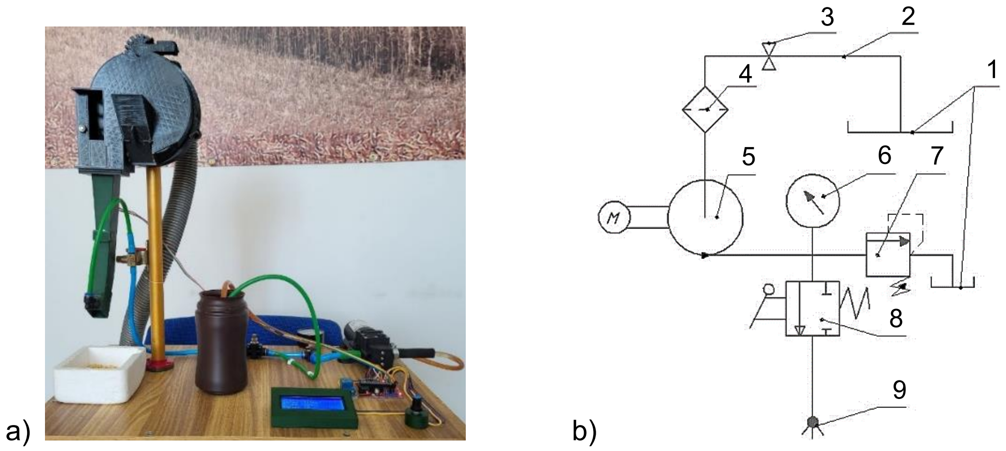

Figure 2. Model of the pre-sowing inoculation system, where a – prototype; b – hydraulic circuit of the inoculation system.

To spray the working solution and create the necessary droplet dispersion, TW6020, TW6030, TW6040 and TW6050 nozzles were used. The structure of the nozzle is shown in Fig. 3. The nozzle body (1) is made of stainless steel and contains an anti-drip valve (2), a spring (3), and a piston for mist formation (4). The nozzle head with a nozzle (5) works in tandem with the piston, ensuring uniform spraying. Nozzles with different nozzle diameters were used to vary the spray dispersion at different pressures.

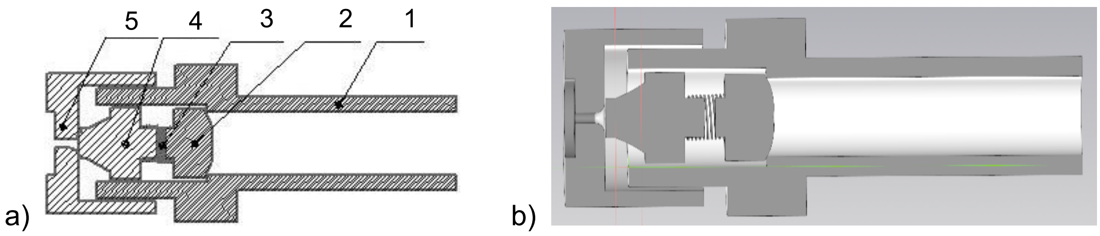

Figure 3. Structure of the nozzle, where a – schematic representation, b – 3D model.

Inoculation on the Stand

During the experiments, a two-factorial study was conducted. Table 1 presents the factors investigated during the experiment.

The tank was filled with water, the pressure was set using an electric regulator, then the at-planting inoculation system was activated, and the pressure was monitored using an analog pressure gauge. After reaching the required pressure and its stabilization, the nozzle was activated. During the study, a batch of 1,000 seeds was used, which were previously weighed on scales (Radwag, WLC 0.2/C/1, Poland) and placed in the sowing device. Then, sowing simulation together with seed treatment on the stand was performed. Thus, the seeds passed through the sowing tube

Table 1. Study Scheme

Factor	Indicator
Pressure (Factor A), atm	3, 4, 5, 6
Nozzle diameter (Factor B), mm	0.2 (2 in figures), 0.3 (3), 0.4 (4), 0.5 (5)

into the container for seed collection. To control the amount of liquid that reached the seeds, separately collected seed covered with liquid and liquid that did not adhere to the seeds were collected in a weighed container. Thus, results were obtained for each study variant, and the methodology was repeated for other pressures and nozzle sizes, with the main parameters of operation being recorded. Each experiment was repeated 10 times. The hybrid used for the study was Hemingway ES from Lidea company, with a declared seed weight of 1,000 seeds being 350 g. The actual seed weight slightly differed, so it was determined separately for each experimental variant.

Analysis of the Obtained Results

After obtaining the initial data, calculations were performed for their interpretation. The calculation of the optimal amount of inoculant that should reach the seeds in case of operation by the usual method is performed using the formula 1:

$$x_1 = \frac{a}{b} \times 1{,}000 \qquad (1)$$

where x_1 is optimal dose of working solution according to the manufacturer's recommendations per 1,000 seeds, g; a is the dose of working solution per 1 ton of planting material, g; b is the number of seeds in 1 ton, pcs.

To determine the number of seeds in 1 ton of planting material, formula 2 was used.

$$b = \frac{10^9}{m_{1,000}} \times 1{,}000 \qquad (2)$$

where $m_{1,000}$ is the mass of 1,000 seeds, g.

The obtained indicator serves as an estimate point for the study and indicates whether the given pressure and nozzle can be used in the at-planting inoculation system to ensure the optimal quality indicator of inoculant treatment.

Statistical data processing was performed using Statistica 10.0 and MS Excel. For determination of NDVI was used OneSoil program.

RESULTS AND DISCUSSION

The conducted research provided data indicating that the consumption of working fluid increases with increasing nozzle diameter at the specified pressure (Table 2).

Table 2. Average fluid consumption for treating 1,000 seeds at 3 atm pressure, g

Nozzle diameter, mm	Mean value, g	Minimum value, g	Maximum value, g	Dispersion, g^2	Standard deviation/SD
0.2	0.9	0.9	0.9	0.0	0.0
0.3	2.0	2.0	2.0	0.0	0.0
0.4	2.38	2.3	2.5	0.007	0.08
0.5	2.78	2.7	2.9	0.007	0.08

It is worth to mention that for the series of experiments, nozzles with diameters of 0.2 and 0.3 mm showed the most stable indicators which did not show any variations from the amount of liquid during each repetition all along of the experiment. For larger nozzle diameters, the indicator varied within 0.007 with a standard deviation of 0.08.

According to Eq. (1), the standard amount of working solution that should adhere to the seeds for each batch of 1,000 seeds was calculated based on the manufacturer's specifications. Fig. 4 clearly shows that at 3 atm pressure, the amount of working solution per 1,000 seeds cannot be provided by any of the nozzles compared to the standard value. At the same time, it is important to understand that introducing the next nozzle with a diameter of 0.6 mm could satisfy the requirement, but this would lead to an increase in the total fluid consumption, which is economically impractical. Incidentally, the total fluid consumption also increases with increasing nozzle diameter. For example, when using the optimal nozzle and pressure for a seeding density of 65 thousand seeds per ha, almost 5 tons of working solution will be used, while if a higher pressure will be used and a larger diameter of the nozzle, the required amount of working fluid will increase and will be 6.2 tons per ha. Accordingly, this will significantly affect the cost of growing products per hectare.

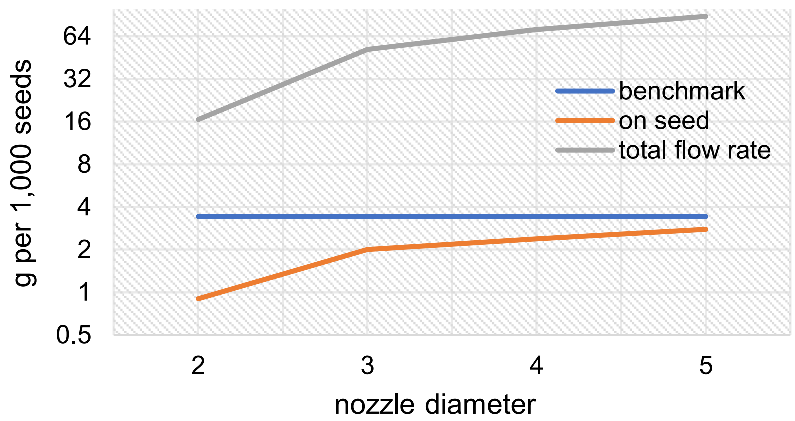

Figure 4. Working fluid consumption when using a pressure of 3 atm in the system.

When changing factor 'A' (Table 1), the research results presented in Table 3 were obtained. At a system pressure of 4 atm, the indicators have greater dispersion deviations and standard deviations compared to a pressure of 3 atm. This is due to the fact that the speed of the liquid spray has changed when it breaks up into droplets.

Table 3. Average fluid consumption for treating 1,000 seeds at 4 atm pressure, g

Nozzle diameter, mm	Mean value, g	Minimum value, g	Maximum value, g	Dispersion, g^2	Standard deviation/SD
0.2	1.1	1.1	1.2	0.003	0.05
0.3	2.6	2.3	2.9	0.08	0.28
0.4	3.2	2.9	3.9	0.14	0.38
0.5	3.7	3.1	4.3	0.32	0.56

Analysis of the research results allows stating that the consumption of working fluid at a pressure of 4 atm can meet the requirement for the standard liquid norm using nozzles with diameters of 0.4 and 0.5 mm. As seen from Fig. 5, the nozzle with a nozzle diameter of 0.2 mm, like the previous series of experiments, cannot achieve the standard liquid norm. The nozzle (with a diameter of 0.3 mm) is almost at the standard level, but considering the conditions of real operation, it will not ensure the quality of the technological process execution. Its use will not meet the requirements for the uniformity of seed coverage with the working solution. Nozzles with diameters of 0.4 and 0.5 mm are capable of providing the required amount of working solution. However, with the increase in the amount of liquid covering the seeds, the total fluid consumption also increases. So, nozzles with diameters of 0.4 mm and 0.5 mm provide the required amount of working solution more reliably and with lower variability. The 0.4 mm nozzle, in particular, is identified as the most rational choice because it meets the standard treatment value with significantly lower total fluid consumption compared to the 0.5 mm nozzle. Therefore, the rational choice for use at-planting inoculation system is to choose a nozzle with a diameter of 0.4 mm. Using a nozzle that consumes more fluid than necessary is not economically practical. The 0.4 mm nozzle provides a balance between meeting the required liquid norm and minimizing fluid consumption, making it the most efficient choice.

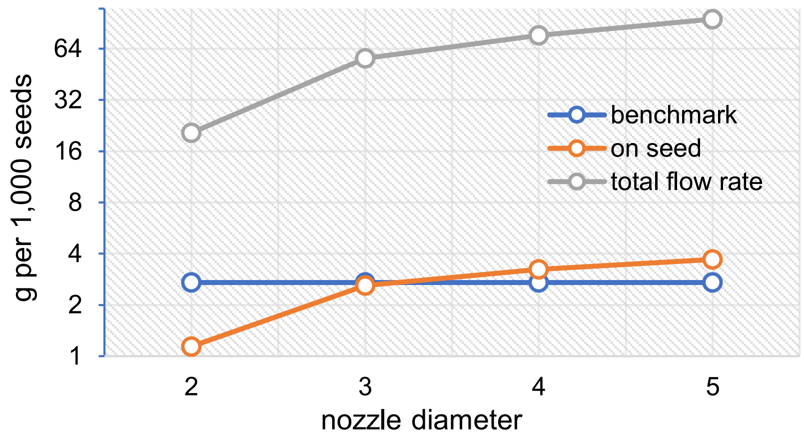

Figure 5. Working fluid consumption when using a pressure of 4 atm in the system.

With a pressure of 5 atm in the system, the dispersion and standard deviation indicators continue to increase. For the 0.2 mm nozzle, there is an increase in the spray rate compared to previous data (Table 4). At the same time, the consumption of working fluid for nozzles with diameters of 0.3 and 0.4 mm is significantly higher compared to the nozzle with a nozzle diameter of 0.2 mm. However, for the nozzle with a diameter of 0.5 mm, the amount of liquid on the seeds has decreased, which may be due to the increase in droplet size during spraying.

Table 4. Average fluid consumption for treating 1,000 seeds at 5 atm pressure, g

Nozzle diameter, mm	Mean value, g	Minimum value, g	Maximum value, g	Dispersion, g^2	Standard deviation/SD
0.2	1.64	1.1	2.0	0.11	0.33
0.3	4.18	3.2	5.7	0.85	0.92
0.4	4.5	3.2	5.6	1.23	1.11
0.5	3.14	2.6	3.8	0.21	0.46

From Fig. 6, it can be seen that the total consumption of the working fluid used for inoculation at a pressure of 5 atm has increased for all nozzles. Thus, the least amount spent was noted for the use of a 0.2 mm nozzle, and the highest, accordingly, for the 0.5 mm diameter nozzle.

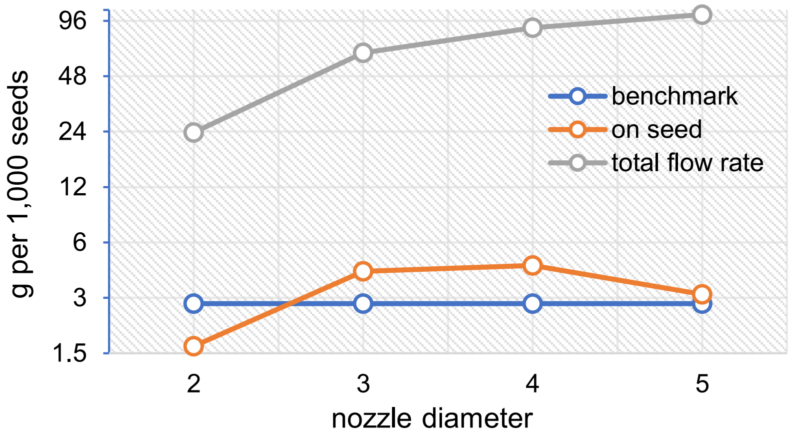

Figure 6. Working fluid consumption when using a pressure of 5 atm in the system.

At a pressure of 6 atm (Table 5), the fluid consumption for a 0.2 mm diameter nozzle doubles compared to the same diameter nozzle at 3 atm pressure (Table 2). However, the dispersion and standard deviation values indicate that the spray characteristics of the working fluid in it are the most stable compared to other nozzles. The 0.3 mm diameter nozzle has the highest dispersion and standard deviation values. The amount of working fluid for the 0.4 mm nozzle is lower compared to the previous one and has less variation in the indicators. For the 0.5 mm diameter nozzle, the fluid consumption significantly decreased and is almost at the same level as for a pressure of 5 atm, meaning that further increasing the pressure does not affect increasing the amount of liquid on the seeds, but only increases the total consumption of the working solution.

Table 5. Average fluid consumption for treating 1,000 seeds at 6 atm pressure, g

Nozzle diameter, mm	Mean value, g	Minimum value, g	Maximum value, g	Dispersion, g^2	Standard deviation/SD
0.2	1.86	1.8	1.9	0.003	0.05
0.3	5.18	3.6	6.8	1.56	1.24
0.4	4.92	3.9	6.1	0.84	0.91
0.5	3.24	3.0	3.5	0.03	0.19

From Fig. 7, it is clear that the total fluid consumption at a pressure of 6 atm in the system is highest compared to other series of experiments, and the trend of distribution of the amount of working solution from the smallest nozzle to the largest is maintained.

From the above data, it is clear that the nozzle diameter and system pressure at which it should operate can be determined. Thus, for a system pressure of 3 atm, none of the nozzles meets the requirement and does not provide the necessary amount of liquid discharge onto the seeds, meaning that such pressure is insufficient for the system to work properly. At the same time, increasing the nozzle diameter to 0.6 mm makes no sense, as likely, the total amount of liquid during the nozzle operation will also increase, which is not economically feasible.

For a pressure of 4 atm, only 2 nozzles are capable of providing the standard treatment value for planting material, their diameter being 0.4 and 0.5 mm. The most rational option to use at-planting inoculation system is precisely the nozzle with a 0.4 mm diameter nozzle. Since the amount of liquid it can discharge exceeds the standard value, and the total consumption of working fluid is significantly lower than in nozzles with a diameter of 0.5 mm.

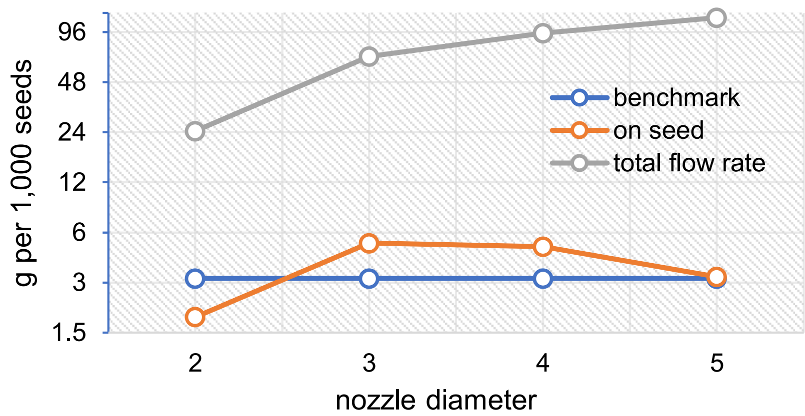

Figure 7. Working fluid consumption when using a pressure of 6 atm in the system.

Almost all nozzles, except for the one with a 0.2 mm diameter nozzle, can be used for incorporation at-planting inoculation system at a pressure of 5 atm. However, the consumption of working fluid for them significantly exceeds the option with a 0.4 mm diameter nozzle at a pressure of 4 atm. Moreover, the total fluid consumption of these nozzles at 5 atm pressure is also higher.

Similar results were obtained using a pressure of 6 atm in the system. Thus, nozzles with a nozzle diameter of 0.3–0.5 mm provide the standard value, but the indicators of working fluid consumption are significantly higher compared to the 0.4 mm nozzle and pressure in the system at 4 atm.

Therefore, it is rational to use a nozzle with a nozzle diameter of 0.4 mm at a pressure in the system of 4 atm, as it provides the standard value for the amount of liquid covering the seeds with the minimum total consumption of working fluid.

The study is limited by its focus on only four nozzle diameters and specific pressure conditions, which may not be representative of all possible scenarios. Additionally, the experiments were conducted under controlled laboratory settings and will only in spring of 2024 were tested in the field. That is why the investigated system was installed on the Elvorti Vega 8 Profi seeder (Fig. 8) with the and was used with nozzle diameter and pressures that were found to be most acceptable. As the field season is not over yet, the results of the experiment could not be highlighted yet. However, first impact of the developed system could be seen at the Fig. 9. The area of the field where the studied pre-sowing inoculation system was used is marked in green.

a) b)

Figure 8. The view of the seeder, where a – reequipment of it with the pre-sowing inoculation system, b – work of the system in field conditions.

A similar system was invented by Chinese scientists. Although the system has some similarity in components and their arrangement, the use and location of the nozzle in the prototype (Wang et al., 2019) provides treatment of the row where the planting material is sown, not just the seeds. Therefore, the nozzle type (conical or sectorial) and the amount of liquid discharge by the nozzle per minute were investigated. A similar invention was made by scientists from India, whose aim was to measure the amount of working fluid that would be poured through nozzles with a nozzle diameter of 8, 10, and 12 mm (Lande & Mani, 2020). A similar system was developed by Manea et al. (2009) however, it does not involve getting the inoculant directly on the seeds. The task of this system is to introduce the inoculant directly into the soil. During the experiment, a lower pressure and only one nozzle diameter was used.

Figure 9. NDVI index of the research field.

However, scientists from Kharkiv have developed a slightly different system that can meet the need for inoculation, although they did not set such a task. Thus, a hydropneumatic seeder was created, which allows the planting material to be constantly in the liquid (Pastukhov et al., 2020). Nevertheless, this is not the first such planting complex that operates on this principle (Pill, 1991).

CONCLUSIONS

The developed system and technology of at-planting seed inoculation are capable of providing the necessary amount of inoculant on the seeds directly during sowing, thus eliminating the drawbacks of previous treatment.

The research results indicate that it is not advisable to use a nozzle with a nozzle diameter of 0.2 mm or less for the at-planting seed inoculation system, as they are unable to provide the standard working solution norm for 1,000 seeds.

Research has shown that it is rational to use a nozzle with a nozzle diameter of 0.4 mm at a pressure in the system of 4 atm. This nozzle is capable of providing the standard usage norm of the inoculant and preventing excessive use of the working fluid.

Future research should be conducted with the installation of a pre-sowing inoculation system on a planter and field testing of the system.

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