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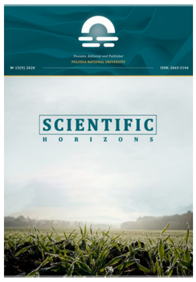

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System of pre-sowing seed inoculation

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Abstract. Pre-sowing inoculation of agricultural crops increases the parameters that affect the yield and quality of the crop, which has been proven by many Ukrainian and foreign researchers. The purpose of the study was to set the operating parameters of the injectors at different pressures, which allowed calculating the rate of discharge of the working solution during sowing to create a system of pre-sowing inoculation, which will simplify the process of seed treatment and increase the energy efficiency of farms. Methods of system and structural analysis, mathematical statistics, abstraction, and mathematical modelling based on the Euler-Lagrange equation, and using the foundations of theoretical mechanics, physics and machine theory were used for

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experimental research. The planning of the experiment met the current standards, and computer graphics systems and Microsoft Excel software suite were used for statistical data processing. Based on the conducted studies, the amount of liquid that one nozzle can pass in 1 min at pressures of 300, 400, and 500 kPA was determined. It was found that the lowest result was shown by a nozzle with a diameter of 0.1 mm with a pressure of 300 kPA – 10.493 ml/min, and the highest – a nozzle with a diameter of 0.8 mm and a pressure of 500 kPA – 146.379 ml/min. At the same time, injectors with a diameter of 0.4-0.6 mm used almost the same amount of liquid at pressures of 300 and 500 kPA. The amount of liquid that can be poured per 1 ha using a six-row seeding machine with a working width of 4.2 m per sowing unit of corn was calculated. The obtained data can be used to improve any systems that use similar nozzles, such as calculating the rate of discharge of agricultural sprayers or systems that allow cooling pig farms during the summer period

Keywords: operation of the sowing complex; nozzle; yield; pressure; spout rate; seed coating; biologics; fertilisers; microorganisms; sowing quality

INTRODUCTION

The issue of seed inoculation is quite relevant today. Humanity is trying to improve the global environment, and therefore, reduce the use of chemicals in agriculture. Inoculants, as a means to increase yields and improve the quality of plant products, have proven themselves quite well. For example, in studies on the effect of an inoculant (strain *Rhizobium*) on chickpea plants under salinity conditions, not only an increase in yield was recorded, but also an increase in the protein and oil content in seeds (Khaitov *et al.,* 2020). An increase in protein content was recorded with the use of Microgumin, Diazophyte, and mineral fertilisers in studies of oat cultivation (*Avena nuda L.* and *Avena sativa L.*) (Ilchenko *et al.,* 2019). And during the investigation of the effects of four strains of *Bacillus spp*. on corn plants under water stress, an increase in the mass of raw and dry matter, the length of plants, and the amount of photosynthetic pigments in them was observed (Azeem *et al.,* 2022). Therefore, against the background of complicated opportunities for the supply of fertilisers from abroad and the need to provide crops with the necessary substances, inoculants or other biologics that are recommended to be used during sowing are a very promising due to their relatively low price, environmental friendliness, positive effect on crop yields, and most importantly – the ability of domestic producers to provide farmers with this product (Polischuk *et al.,* 2023).

The advantages of settling microorganisms on the seed surface (inoculation) before sowing have been proven by many researchers (Stassinos *et al.,* 2021; Datsko, 2021). The history of their use began in 1896, when the first patent for an inoculant was registered in the United States (Santos *et al.,* 2019). Inoculation of seed material allows populating the necessary microorganisms in the rhizosphere of agricultural crops for better interaction and increase plant productivity (Sandini *et al.,* 2019). Mostly, when it comes to inoculation procedure, most suggest that it applies only to legumes, however, this is not a fair expression. Studies using inoculants have also been conducted for crops such as corn (Stoffel *et al.,* 2020), wheat (Erdemci, 2021), rice (Guimarães *et al.,* 2020; Singh *et al.,* 2020), rapeseed (Premachandra *et al.*, 2020) etc.

Inoculation in production is mainly carried out with the help of seed treatment machines and in addition to or simultaneously with seed treatment. However, the method of liquid inoculation has significant disadvantages, which can lead to an increase in the cost of production or to the death of microorganisms contained in the inoculant. The first and most important of them is that the operation with a liquid inoculant is quite a time-consuming process, since it is usually recommended to apply microorganisms immediately before sowing, which requires the additional use of the necessary equipment and people in a short time. Second, direct exposure to sunlight on already treated seed material can lead to the death of beneficial microorganisms (Ushkarenko *et al.,* 2016). The reason for this harmful effect of solar radiation on bacterial cells is ultraviolet light, which has a bactericidal effect (Bilokonska, 2018).

Therefore, researchers of Sumy National Agrarian University decided to develop and implement a system that will simplify the inoculation process and conduct it during corn sowing. Since the methods used by agricultural producers for inoculation are outdated and energy-consuming, the purpose of this study was to obtain data that will allow assessing which nozzles should be used to create a seed inoculation system that can be installed in any sowing complex.

MATERIALS AND METHODS

Structure of the test system for determining required nozzle diameter and operating pressure. Since the system is designed and manufactured from scratch, it became necessary to investigate the properties of components and select the necessary parameters. To begin with, the pressure needed to be created in the system and the diameter of the nozzles to be used were considered. To do this, the volume of liquid that the nozzle can pass through with a certain pressure was measured for one minute for each of the options in triple repetition.

Laboratory balances (Radwag, WLC 0.2/C/1, Poland) were used to accurately determine the weight of liquid. The pressure was created using a high-pressure diaphragm pump (Good PUMPs, 12V, 6A, 72W, China). The low-pressure mist-forming TW6010 ....TW6080 with a diameter of 0.1; 0.2.....0.8 mm were chosen as nozzles (Fig. 1).

Figure 1. *Low-pressure mist forming nozzles TW60*

A pressure gauge, quick-release connections, hoses, clamps, and a digital pressure sensor (Ebowan DC 5 V G1/4, 12 MPA, China) were also used to create the test sample, the connection diagram is shown in Figure 2.

Figure 2. *Connection diagram of devices for determining the required nozzle diameter and operating pressure for creating a stand, where 1 – tank; 2 – pressure gauge; 3 – water pump; 4 – pressure sensor; 5 – actuator; 6 – nozzle*

Based on the requirements of inoculant manufacturers, a darkened tank was used to minimise the contact of microorganisms with ultraviolet rays. The liquid filled into the tank is sucked in by a pump that pumps pressure into the main line, which contains a pressure gauge for visual monitoring and a digital pressure gauge for maintaining pressure. An actuator valve regulates the period of use of the nozzle (Shelest *et al.,* 2022).

After conducting the study, the appropriate equation was used to determine the actual amount of liquid that can be poured per 1 ha by a six-row row seeding machine with a working width of 4.2 m. (Bosoy *et al.,* 1980):

$$Q = \frac{600q \times n}{L \times V}, \quad (1)$$

where Q – actual working fluid discharge, l/ha; 600 – coefficient; n – number of sprayers; q – liquid flow rate through one sprayer, l/min.; L – working width of the unit, m; V – actual velocity, km/h.

For statistical processing of the spray fluid flow rate, the root-mean-square deviation (2) and the coefficient of variation (3) were determined:

$$\sigma = \sqrt{\frac{(q_{1e}-\overline{q})^2+(q_{2e}-\overline{q})^2+.....+(q_{ne}-\overline{q})^2}{n}}; \quad (2)$$

where $q_{1e}, q_{2e}....q_{ne}$ – amount of liquid consumed by the sprayer in 1 minute, g; q – arithmetic mean; n – number of experiments.

$$\overline{q} = \frac{q_{1e}+q_{2e}+....q_{ne}}{n}$$

The coefficient of variation was determined by the equation:

$$V = \frac{\sigma}{\overline{q}} \cdot 100. \quad (3)$$

To evaluate the results of the study of nozzles of different sizes when using a pressure of 300-500 kPA, a two-fold variance analysis with repetitions was conducted in MS Excel.

As a liquid, water-based injectors were first tested, and then Leanum biologic preparation was used, which contains effective microorganisms and organic matter, and is approved for use by "Organic Standard". It is evident that the density of different liquid fertilisers/biologics may differ, different volumes of working solution can be used in different dosages (200-300 l/ha), depending on the manufacturer's recommendations.

RESULTS AND DISCUSSION

Investigation of the amount of liquid that the nozzles can pass in 1 min. Studies were conducted on nozzles of different diameters and at different pressures of liquid supply to them for the same period of time. Analysing the data in Table 1, the dependence of the volume of liquid through the nozzles on the diameter of the hole is observed: with an increase in the nozzle diameter from 0.1 mm to 0.2 mm at a constant pressure of 300 kPA, the weight of liquid that was sprayed in 1 min increased from 10.373 g to 13.445 g, which is 22.2%.

Table 1. *Result of the study of nozzles of different sizes at a pressure of 300 kPA*

Nozzle size, mm	Experiment number						$\bar{q}$, g	σ, g	V_σ, %
	1	2	3	4	5	6			
0.1	10.373	10.609	10.511	10.456	10.305	10.702	10.493	0.13	1.3
0.2	13.445	13.56	13.472	13.601	13.27	13.602	13.492	0.12	0.9
0.3	35.69	35.822	35.973	35.599	35.984	35.902	35.828	0.14	0.4
0.4	52.7	52.329	52.629	52.485	52.502	52.688	52.556	0.13	0.2
0.5	65.426	65.429	65.408	65.281	65.29	65.692	65.421	0.14	0.2
0.6	81.03	81.243	81.207	81.401	81.011	81.102	81.166	0.14	0.2
0.7	92.385	92.729	92.921	92.393	92.829	92.809	92.678	0.21	0.2
0.8	114.926	115.06	115.203	115.182	114.903	115.102	115.063	0.12	0.1

Source: *obtained by the authors*

Starting from the nozzle diameter of 0.3 mm, the weight of the liquid relative to the original diameter increased by almost 3.5 times. As the injector nozzle diameter increased from 0.3 mm to 0.8 mm, the increase in the volume of liquid pouring through the nozzles significantly increased from the minimum water mass of 35.69 g to 114.926 g, which is an average increase of 69%. During statistical data processing, the root-mean-square deviation was in the range of 0.12-0.14 g, with the maximum value for the nozzle diameter of 0.7 mm – 0.21 g. The coefficient of variation decreased and corresponded to an increase in the nozzle diameter and was a minimum value of 0.1% for 0.8 mm and a maximum value of 1.3% for 0.1 mm.

When analysing the weight values of the spray liquid at a constant pressure of 400 kPA in 1 minute (Table 2), the lowest value of the weight of liquid through the nozzles of low-pressure mist-forming nozzles was 0.1 mm – 12.146 g and 0.2 mm – 15.101 g. When the diameter of the mist-forming nozzles increases from 0.3 mm to 0.7 mm, respectively, the liquid flow rate increases from 40.907 g/min up to 97.443 g/min. The highest consumption of sprayed liquid is 142.209 g/min with a nozzle diameter of 0.8 mm, because the increase relative to 0.7 mm is the largest – 45 g/min. When evaluating the data in Table 2, a root-mean-square deviation was determined with a minimum value of 0.05 g for a nozzle diameter of 0.8 mm and a maximum value of 0.32 g for 0.5 mm. The coefficient of variation was reduced from 1% for nozzle diameters of 0.1 mm and 0.2 mm to 0% for nozzle diameters of 0.8 mm.

Table 2. *Result of the study of nozzles of different sizes at a pressure of 400 kPA*

Nozzle size, mm	Experiment number						$\bar{q}$, g	σ, g	V_σ, %
	1	2	3	4	5	6			
0.1	12.509	12.183	12.146	12.231	12.403	12.307	12.297	0.13	1.0
0.2	15.576	15.32	15.101	15.297	15.477	15.218	15.332	0.16	1.0
0.3	40.428	40.869	40.695	40.641	40.445	40.907	40.664	0.19	0.5
0.4	57.871	58.225	58.184	57.698	58.308	58.274	58.093	0.23	0.4
0.5	72.606	73.005	72.504	72.695	73.105	72.315	72.705	0.27	0.4
0.6	92.746	91.993	92.328	92.629	91.899	92.537	92.355	0.32	0.3
0.7	97.41	97.417	97.503	97.269	97.381	97.68	97.443	0.13	0.1
0.8	142.202	142.073	142.192	142.152	142.102	142.209	142.155	0.05	0

Source: *obtained by the authors*

At a constant pressure of 500 kPA, the volume of sprayed liquid increases accordingly with an increase in the diameter of fine nozzles from 0.1 mm to 0.8 mm: from a minimum value of 13.696 g/min at 0.1 mm to a maximum of 146.827 g/min at 0.8 mm (Table 3). From the nozzle diameter of 0.3 mm, there is an increase in the flow rate of the sprayed liquid relative to the diameter of 0.1 mm by almost 3.5 times. From the statistical analysis of the table data, the minimum root-mean-square deviation is 0.19 g from the arithmetic mean of 17.094 g for a nozzle diameter of 0.2 mm, and the maximum is 1.1 g from the arithmetic mean of 64.388 g for a diameter of 0.4 mm. The coefficient of variation increased from 0.2% for 0.7 mm and 0.8 mm nozzle diameters to 1.7% for a nozzle diameter of 0.4 mm.

Table 3. *Result of the study of nozzles of different sizes at a pressure of 500 kPA*

Nozzle size, mm	Experiment number						$\bar{q}$, g	σ, g	V_σ, %
	1	2	3	4	5	6			
0.1	13.947	13.836	13.811	13.748	13.696	13.947	13.831	0.09	0.7
0.2	17.181	16.758	17.399	17.123	16.992	17.109	17.094	0.19	1.1.
0.3	44.764	45.088	44.68	45.141	44.592	44.799	44.844	0.20	0.5
0.4	62.576	65.427	65.765	63.599	64.966	63.997	64.388	1.11	1.7
0.5	81.557	80.993	81.648	81.312	80.898	81.203	81.269	0.27	0.3
0.6	98.416	98.336	98.432	97.892	98.598	98.692	98.394	0.25	0.3
0.7	113.408	113.499	113.509	113.101	113.791	113.521	113.472	0.20	0.2
0.8	146.375	146.372	146.394	146.102	146.827	146.201	146.379	0.23	0.2

Source: *obtained by the authors*

By increasing the fluid supply pressure to the 0.1 mm diameter nozzle from 300 kPa to 500 kPa, the fluid output increased by 32%. On average, at a pressure of 500 kPA, all injectors delivered almost 580 g/min, which is 9.16% more than at a pressure of 400 kPA, and 24.21% more than at a pressure of 300 kPA.

Calculation of the amount of liquid per 1 ha. The flow rate of the working fluid of the nozzle with a diameter of 0.1 mm at different pressures ensures the discharge of liquid in the range of 1.12-1.48 l/ha (Fig. 3), and the nozzle with a diameter of 0.2 mm – 1.44-1.83 l/ha, while the difference between the values of the 0.1 mm nozzle with a pressure of 500 kPA and the 0.2 mm nozzle at a pressure of 300 kPA is only 2.7%, which is not a critical deviation, but when working in the field to save energy resources, it is undoubtedly better to use a nozzle with a diameter of 0.2 mm and a pressure of 300 kPA. A similar pattern can be observed in 0.4 and 0.5 mm nozzles, where the difference between the values at a pressure of 500 and 300 kPA is 1.7%. A similar pattern is observed between the 0.5 and 0.6 mm injectors, the difference between the indicators is also not significant and amounts to 0.2%. At the same time, there is no similar trend between 0.6 and 0.7 mm injectors and the same pressure, but this phenomenon again becomes true for 0.7 and 0.8 mm injectors, while the difference between the liquid output at a pressure of 500 and 300 kPA is 1.3%.

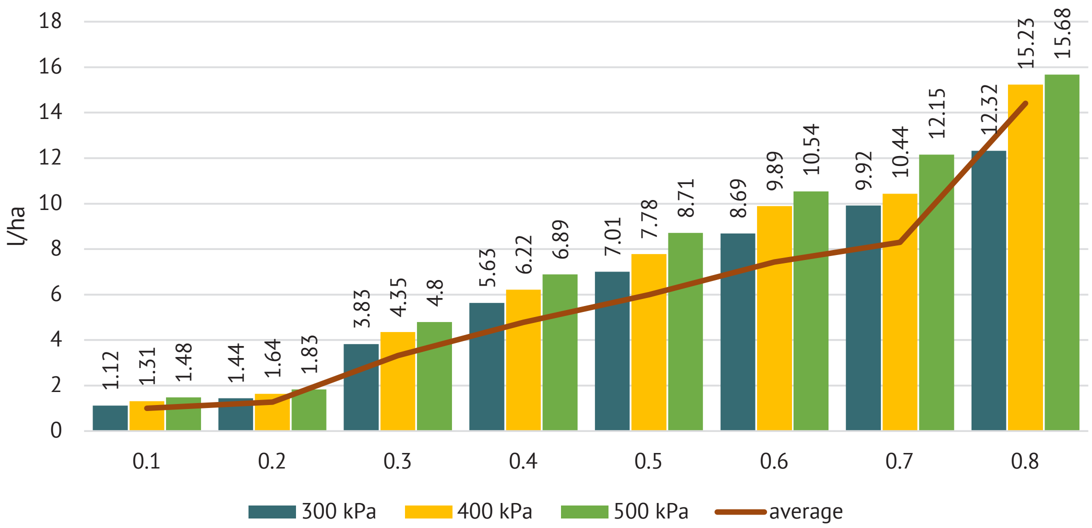

Figure 3. *Flow rates through the TW6010....TW6080 nozzles at different pressure values*

Therefore, the diagram shows that injectors with a diameter of 0.1 and 0.2 mm provide extremely low use of the working solution per hectare, which casts doubt on the effectiveness of their use. At the same time, nozzles with a diameter of 0.3 to 0.8 mm have the potential for use in the designed pre-sowing inoculation system.

Other researchers have also created a sowing complex that can carry out seed inoculation during corn sowing (Dražić, 2017). However, their research is somewhat inconsistent with the subject matter and the need for creating a seed inoculation system. For example, the paper by Klaedtke *et al.* (2022) contains information about the amount of liquid passed by nozzles per minute under different pressures, but they do not contain specifics about the diameter of the injectors. Pathan *et al.* (2019) provide information about working under different pressures for three nozzles (diameter 13.1; 16.2; 19.3 mm), however, these nozzles have a fairly high output of liquid, while this study is based on saving water and creating a mist for more uniform treatment of seeds with a working solution. A similar experiment was conducted by Han *et al.* (2020), however, using a different type of nozzle. Wang *et al.* (2020) investigated the efficiency of using larger nozzles and higher pressures (from 1 to 8 mPA). However, according to the estimates, a pressure greater than 500 kPA is not appropriate for a mobile inoculation system, as it requires high energy consumption.

In the literature, attention is drawn to the fact that seed treatment with biologics is more effective than their foliar application (Barbosa *et al.,* 2022), and the effect is noticeable in the growth of the root system, the concentration of nutrients in the leaf-stem mass, and grain, which ultimately affected the yield. But biologics can have one or more strains of microorganisms, and depending on weather and soil conditions, their effectiveness may decrease or not appear at all in temperate climates (Reis *et al.,*2022). However, the application of biologics and fertilisers in liquid form is more effective than in the form of powder and granules, and the most important thing at the beginning is uniform application to the seed and good adhesion, since the seeds of different agricultural plants have different shapes, structures, sizes, and germination rates (Paravar *et al.,* 2022; Veremeenko *et al.,* 2023). That is, considering seed treatment with biologics only in organic farming, then the purpose of this event is to directly affect the seed and the plant will better resist abiotic and biotic stresses through rhizobiome (Kharchenko *et al.,* 2022; Orozco-Mosqueda, 2022). By using xerotolerant microorganisms in the seed coating, it is possible to promote better plant development in conditions of prolonged moisture limit (Romao *et al.,* 2022).

Thus, data on the amount of solution pouring through different nozzles were obtained in other papers, but the effectiveness of using different pressures and diameters of nozzles, and the density of fertiliser liquids and pesticides was not fully investigated. The development of complexes for inoculation with minimal moisture and energy consumption is relevant and requires further study.

CONCLUSIONS

Based on the data obtained, it can be concluded that the smallest liquid output per minute in a nozzle with a diameter of 0.1 mm with a pressure of 300 kPA is 1.247 l/ha, while the largest output in nozzles of 0.8 mm with a pressure of 500 kPA is 15.683 l/ha. The range of fluctuations in these values is quite high, so further, more in-depth studies of injectors with a diameter of 0.3-0.6 mm are needed. Nozzles with a diameter of 0.1 and 0.2 are not suitable for further research, as they pass too little liquid from 1.127 to 1.831 l/min at different pressures, while nozzles with a diameter of 0.7-0.8 are rejected because they have too unstable indicators. Moreover, an interesting pattern was noticed in the 0.4, 0.5, and 0.6 nozzles at a pressure of 500 and 300 kPA: the amount of liquid that they can pour per 1 ha is almost similar and the difference between these values does not exceed 2.7% (and some even less), which is insignificant. These circumstances suggest the feasibility of using a nozzle with a smaller diameter and higher pressure in the inoculation system, or with a larger nozzle diameter and lower pressure, which would directly affect the amount of energy consumed by the tractor during the use of this system.

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CONFLICT OF INTEREST

The authors declare no conflict of interests.

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Анотація. Передпосівна інокуляція сільськогосподарських культур дозволяє підвищити параметри, що впливають на урожайність та якість врожаю, це було доведено багатьма українськими та закордонними дослідниками. Метою роботи було встановити робочі параметри форсунок за різного тиску, що дало змогу розрахувати норму виливу робочого розчину під час сівби для створення системи припосівної інокуляції, що дозволить спростити процес обробки насіння та підвищити енергоефективність господарств. Для проведення експериментальних досліджень використовувалися методи системного та структурного аналізу, математичної статистики, абстрагування та математичного моделювання на основі рівняння Ейлера-Лагранжа, а також з використанням основ теоретичної механіки, фізики та теорії машин. Планування експерименту відповідало діючим стандартам, а для статистичної обробки даних використовувалися системи комп'ютерної графіки та програми Microsoft Excel. Завдяки проведеним дослідженням було встановлено кількість рідини, що може пропустити одна форсунка за 1 хв під тиском 300, 400 і 500 кПа. Було виявлено, що найменший результат показала форсунка діаметром 0,1 мм з тиском 300 кПа – 10,493 мл/хв, а найбільший – форсунка діаметром 0,8 мм і тиском 500 кПа – 146,379 мл/хв. Водночас, форсунки діаметром 0,4 – 0,6 мм використовують майже однакову кількість рідини під тиском 300 та 500 кПа. Було розраховано кількість рідини, що може бути вилито на 1 га за використання шестирядної просапної сівалки із шириною захвату 4,2 м на одну посівну одиницю кукурудзи. Отримані дані можуть бути використані при вдосконаленні будь-яких систем, де використовуються схожі форсунки, як то для розрахунку норми виливу сільськогосподарських оприскувачів чи систем, що дозволяють охолоджувати свинокомплекси під час літнього періоду

Ключові слова: експлуатація посівного комплексу; форсунка; урожайність; тиск; норма виливу; покриття насіння; біопрепарати; добрива; мікроорганізми; якість сівби