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Predicting the seeding quality of radish seeds with the use of a family of Nakagami distribution functions

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A b s t r a c t. The study evaluated the seeding quality of radish seeds *cv*. Saxa Polana (percentage of single seeds, double seeds and missed seeds (skips) sown with a Max Pneumatic S 156 seed drill fitted with a pneumatic seed dosing unit set at different forward speeds of a metering unit and different sowing disc speeds. The seeding quality was analysed using Nakagami distribution functions, a chi-squared goodness of fit test, linear regression functions, and the ISO 7256/1, 1984 (E) Standard. The diagrams predicting the effect of the different speeds on the percentage of singles, doubles and skips were highly consistent with the results of the seeding quality analysis based on the ISO 7256/1, 1984 (E) Standard. The authors relied on Nakagami distribution functions to develop a new method for predicting the in-row distance between seeds within the analysed range of speeds, including those which were not empirically tested speeds. The proposed method can be used to predict seeding quality at different speeds when only the selected settings of the dosing unit are taken into account in the analysis. This approach significantly shortens the research time and also decreases the relevant costs.

K e y w o r d s: precision seeding, mathematical modelling, seeding quality

1. INTRODUCTION

The radish is a plant of the family *Brassicaceae* which has a short growing cycle and is well suited to temperate climates. Radishes thrive in fertile soils with a high humus content and are usually grown in the early spring and fall (Born *et al.,*1982). Similarly to other agricultural crops, radishes require the appropriate cultivation methods, chemical protection, fertilization and precise seeding to produce high yields. Radish seeds should be accurately placed in the soil at the desired depth and uniformly distributed in rows (Dobrowska-Kopecka *et al.*, 1999). Uniform seed spacing in the field creates favourable conditions for plant growth by improving the use of solar energy by the plants, promoting root development, enhancing water and nutrient uptake efficiency, and, above all, minimizing intraspecific competition. The resulting plants are not only taller, but they are also characterized by higher and more uniform yields (Fritzsch, 1983; Estler, 1985; Frederick and Marshall, 1985; Joseph *et al*., 1985; Ozturk *et al*., 2006; Valério *et al*., 2013; Ignaciuk and Zarajczyk, 2020).

Seeding uniformity (seeding quality) is one of the most important considerations in the process of the mechanized sowing of agricultural crops. In precision seeding, spacing accuracy is determined by calculating the percentage of single seeds, double seeds and missed seeds (skips). For many years, numerous research efforts have been made:

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– to improve the accuracy of seed distribution within rows (Solie *et al.,* 1991; Błaszczak and Przybył, 2000; Firsov and Cherepakhin, 2002; Lipiński *et al.,* 2004; Banasiak and Michalak, 2000);

– to improve the working units and subassemblies in seed drills, these play a key role in seeding quality (Bozdogan, 2006);

– and finally, to develop new methods for evaluating seeding quality with the application of contact and contactless sensors which are used to measure the distances between seeds (Kachman and Smith, 1995; Kęska and Kośmicki, 1986; Łazarczyk *et al*., 1996; Feder *et al.*, 2012; Bracy and Parish, 1998; Lan *et al.,*1999; Özmerzi *et al.,* 2002; Karayel *et al.,* 2006; Çakir *et al.,* 2016; Markowski, 2017).

Regardless of the applied method for measuring in-row seed spacing (after seeding in the field, using contact and contactless methods in a laboratory), seeding quality was evaluated based on the applicable standards. In precision seeding, the applicable standard is ISO 7256/1, 1984 (E) (ISO 7256/2, 1984; John, 2021). To date, seeding quality (the percentage of singles, doubles and skips) has been analysed within a given range of forward speeds (at selected intervals) and for the operating parameters of various seed drill subassemblies (also at selected intervals). As a result, the accuracy of seed distribution was only determined within a given range of parameters. At present there are no methods for predicting the in-row distance between seeds based on parameters that have not been tested empirically.

Given the above, this study aimed to evaluate the seeding quality of radish seeds *cv*. Saxa Polana sown with a precision seed drill with a pneumatic seed dosing unit (namely Max Pneumatic S 156) using a particular family of distribution functions. In the first stage of the study, seed distribution was tested empirically in a laboratory test stand with the help of adhesive tape (Fig. 1). In the second stage, seeding quality was evaluated with the use of a family of Nakagami distribution functions, a chi-squared goodness of fit test, a linear regression function, and the ISO 7256/1, 1984 (E) Standard (ISO 7256/2, 1984) was applied.

2. MATERIALS AND METHODS

2.1. Obtaining laboratory data

In order to meet the research objectives, the seeding quality of the radish seeds was tested in a laboratory by registering the positions of the seeds deposited in a row. A test stand composed of two core functional components was designed for the analysis: a seeding (dosing) unit and a metering unit for registering the position of the distributed seeds, which consisted of continuous adhesive tape with a measuring section with a length of 5 m and a width of 0.15 m (Fig. 1). The tape was stretched between two belt drives powered by an alternating current motor, and it simulated the movement of a seed drill. The parameters describing the position of a seed deposited on the tape were determined to the nearest ±1 mm. A linear scale was placed on the measuring segment of the adhesive tape in order to determine the seed's position accurately. The tape's linear speed was modified by changing the motor's rotational speed with a TAIAN series E 2, 440 V (0.75-2.2 kW) frequency converter. The electrical frequency was determined based on a previously tested frequency range.

The dosing unit of the examined seed drill was mounted directly above the adhesive tape at a height of 0.05 m (the distance between the point where the seed was detached from the metering disc and the adhesive tape). The rotational speed of the drill's metering disc was controlled using a frequency converter by changing the electrical frequency and the rotational speed of the alternating current motor. The test stand, which was composed of two core functional components (the seed dosing unit and metering unit) and frequency converters, supported the independent and scale-free control of the tape's linear speed as well as the rotational speed of the metering disc. The control system of the dosing unit was identical to that of a standard precision seeder. The operating parameters of the test stand are presented in Table 1.

The designed test stand was used to analyse the effect of the drill's forward speed and the rotational speed of the metering disc in the Max Pneumatic S 156 seed drill on the seeding quality of radish seeds *cv*. Saxa Polana.

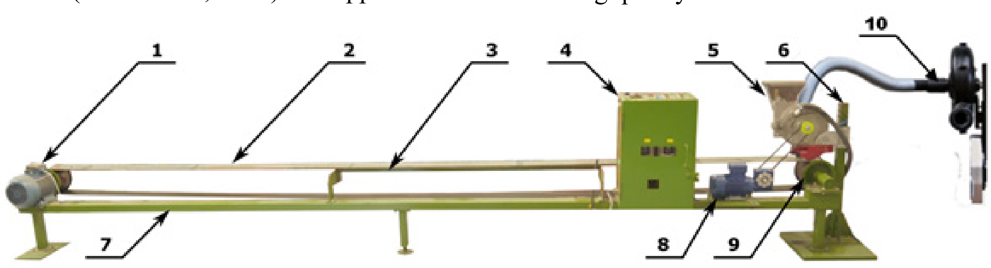

Fig. 1. Diagram of the test stand: 1 – electric motor for powering the adhesive tape, 2 – adhesive tape, 3 – tape guide, 4 – frequency converter unit, 5 – dosing unit, 6 – dosing unit support, 7 – support frame, 8 – the electric motor for powering the dosing unit, 9 – belt drive stretching the adhesive tape, 10 – fan.

Table 1. Operating parameters of the test stand

Parameter	Value
Linear speed of the adhesive tape (km h^{-1})	1.44÷10.00
Tape speed intervals (km h^{-1})	0.23
Rotational speed of the metering disc (rpm)	0.07÷59.00
Speed intervals of the metering disc (rpm)	0.059
Positive pressure (MPa)	up to 0.5
Negative pressure (MPa)	up to 0.3
Length of the measuring segment (tape) (m)	5.00
Width of the measuring segment (tape) (m)	0.15
Distance between the metering disc and adhesive tape (m)	0.05÷0.75

One hundred radish seeds were randomly selected for the study based on their geometric dimensions (Table 2). The metering disc featured 60 holes with a diameter of 2 mm. The operating parameters of the dosing unit were within the range of values recommended by the drill manufacturer (Table 3).

The laboratory experiment was performed on seeds from the same batches that were previously sampled for the analysis of their geometric dimensions and the moisture content of the seeds as well as determining the 1000-seed weight. Impurities and damaged seeds were removed in order to obtain seed batches with 100% purity. The seeds were not subjected to additional treatments such as calibration or coating.

The basic geometric dimensions of the seeds, including their length (largest dimension) and width (medium dimension), were determined using an MWM 2325 laboratory microscope, whereas seed thickness (smallest dimension) was determined using a thickness gauge. All of the measurements were conducted to the nearest 0.01 mm. The seed mass was determined to the nearest 0.1 mg using a WAS 100/C/2 laboratory weighing scale. The measurements were conducted based on a method described by Kaliniewicz *et al.* (2018).

The average 1000-seed weight of the radish seeds with a moisture content of 10.3 and a 98% germination capacity was determined to be 1.26 g. The average geometric dimensions of the radish seeds were calculated to be 3.22 mm (length), 2.59 mm (width) and 1.99 mm (thickness) (Table 2).

Table 3. Operating parameters of the dosing unit in the Max Pneumatic S 156 seed drill

Forward speed v_j (km h^{-1})	Rotational speed of metering disc V_j (rpm)	Number f seeds at the preset speed l_j (seed)	Average distance between seeds determined in the test r_j (mm)
1.14	2.0	238	47.31
1.68	3.0	245	47.38
2.22	4.0	228	45.64
2.79	5.5	252	46.15
3.35	6.3	237	47.28
3.91	7.4	262	52.23
4.44	8.4	238	51.32
5.04	9.5	207	55.61
5.46	10.6	211	57.93

A substantially constant ratio between the dosing unit's forward speed and the metering disc's rotational speed (Table 3) was fixed. The relationships between the preset values of the abovementioned parameters were simulated by adjusting the rotational speed of the metering disc to suit the forward speed of the dosing unit for specific plant density. The seed position was determined by stopping the adhesive tape and reading the seed's position on the scale. Then the average in-row distance between seeds r_j was determined based on the distance measured between the consecutive seeds in a row. In the next step, the distance between the consecutive seeds measured at nine speeds v_j was normalized by dividing the results by the average distance from each measurement. The distance between the seeds was normalized in line with the provisions of the ISO 7256/1, 1984 (E) Standard for precision seeding. Moreover, this procedure may be used to compare the results (distances between seeds, now normalized distances between seeds) obtained at different speeds.

Table 2. Statistical characteristics of the physical parameters of radish seeds *cv*. Saxa Polana

Physical parameter	Value of trait			Standard deviation of trait	Variability coefficient of trait (%)
	minimum	maximum	average		
Length (mm)	2.29	3.96	3.22	0.361	11.60
Width (mm)	1.95	3.46	2.59	0.331	12.75
Thickness (mm)	1.39	2.71	1.99	0.281	13.42

2.2. Statistical analysis

The authors searched for a probability distribution function that best fits the measured data for each of the nine speeds. A list of over twenty such functions was checked (including Weibull, normal, gamma, Nakagami distribution *etc*.). For the tested function, a set of the best parameters was selected for each speed using the fitdist function in the Matlab program (Matlab documentation of the fitdist function, 2023). Then a chi-squared goodness of fit test was performed separately for each of the nine distribution functions chi2gof in Matlab (Matlab documentation of the fitdist function, 2023). By applying the null hypothesis it was postulated that the tested data should have the chosen distribution F for the preset values of the parameters. It was assumed that the probability distribution function F that fits the data for the tested nine speeds v_j adequately describes the normalized distances between seeds for a whole range of speeds in the range from 1.14 to 5.46 km h^{-1}.

2.3. Mathematical model of sowing seeds

Creating a model of uniformity for sowing seeds requires a relationship to be found between the parameters of the previously obtained probability function F and the speed of movement of the sowing section v (bearing in mind that the ratio between the forward speed of the dosing unit and the rotational speed of the metering disc was fixed). Such a relationship was determined using linear regression functions. The verification of the model consisted of re-checking the fit of the probability function against nine new sets of parameters obtained from the linear regression function. Again, the functions of the Matlab program listed in paragraph 2.2 were used for this purpose.

2.4. Quality assessment system analysis through the application of the iso standard

The ISO 7256/1, 1984 (E) Standard describes the quality parameters of precision seeding by calculating the percentage of single seeds, double seeds and missed seeds (skips) in relation to the theoretical seed spacing given by the manufacturer. In this paper, the authors decided to count these parameters in relation to the average distance r_j obtained separately for each of the nine speeds v_j. A distance of less than half of the average distance r_j was counted as a double sowing (double), between half and one and a half times the average distance was counted as a single sowing (single) and a distance greater than that was counted as a skip seeding (skip). Seed sowing simulations were then carried out using a model based on a selected family of probability distributions. A comparison between these parameters was obtained from empirical data with the prediction obtained from the model being included at the end of the Results chapter.

3. RESULTS

The Nakagami distribution was tested as one of the possible seeding models. It is a probability distribution which is related to the gamma distribution. Each distribution of the Nakagami family has two parameters m (shape parameter-positive scalar value) and ω (scale parameter positive scalar value). Such distributions are used, among others, to describe the radio signals. It may be asserted that in a sense this corresponds to the situation of the seeds which appear with a certain frequency on the adhesive tape. The probability density function for each of the nine speeds v_j (with the corresponding parameters m and ω) was fit to the data using the fitdist function in the Matlab program. Then the chi-squared goodness of fit test was performed.

For each of the nine cases the null hypothesis postulating that the studied data have a Nakagami distribution for the given values of m and ω was not rejected (p-value > 0.05, Table 4), therefore it was assumed that the Nakagami distribution functions describe the normalized seed distances to an acceptable degree (Fig. 2).

In the next step, the relationships between parameters m and ω, and forward speed v of the dosing unit were determined with linear regression functions (Fig. 3).

Table 4. Nakagami distribution parameters for the real distance between seeds at nine speeds of the Max Pneumatic S 156 seed drill and the p-values for the chi-square test for each of the nine distributions

Average distance between seeds determined in the test (mm)	Forward speed v_j (km h^{-1})	Value of parameter m	Value of parameter ω	p-value
47.31	1.14	0.8420	1.2929	0.0887
47.38	1.68	0.7890	1.3344	0.2602
45.64	2.22	0.7713	1.3377	0.7838
46.15	2.79	0.7188	1.3673	0.0551
47.28	3.35	0.5964	1.4398	0.0634
52.23	3.91	0.6790	1.4213	0.2441
51.32	4.44	0.5913	1.5000	0.2287
55.61	5.04	0.5120	1.6274	0.5998
57.93	5.46	0.4808	1.5914	0.4767

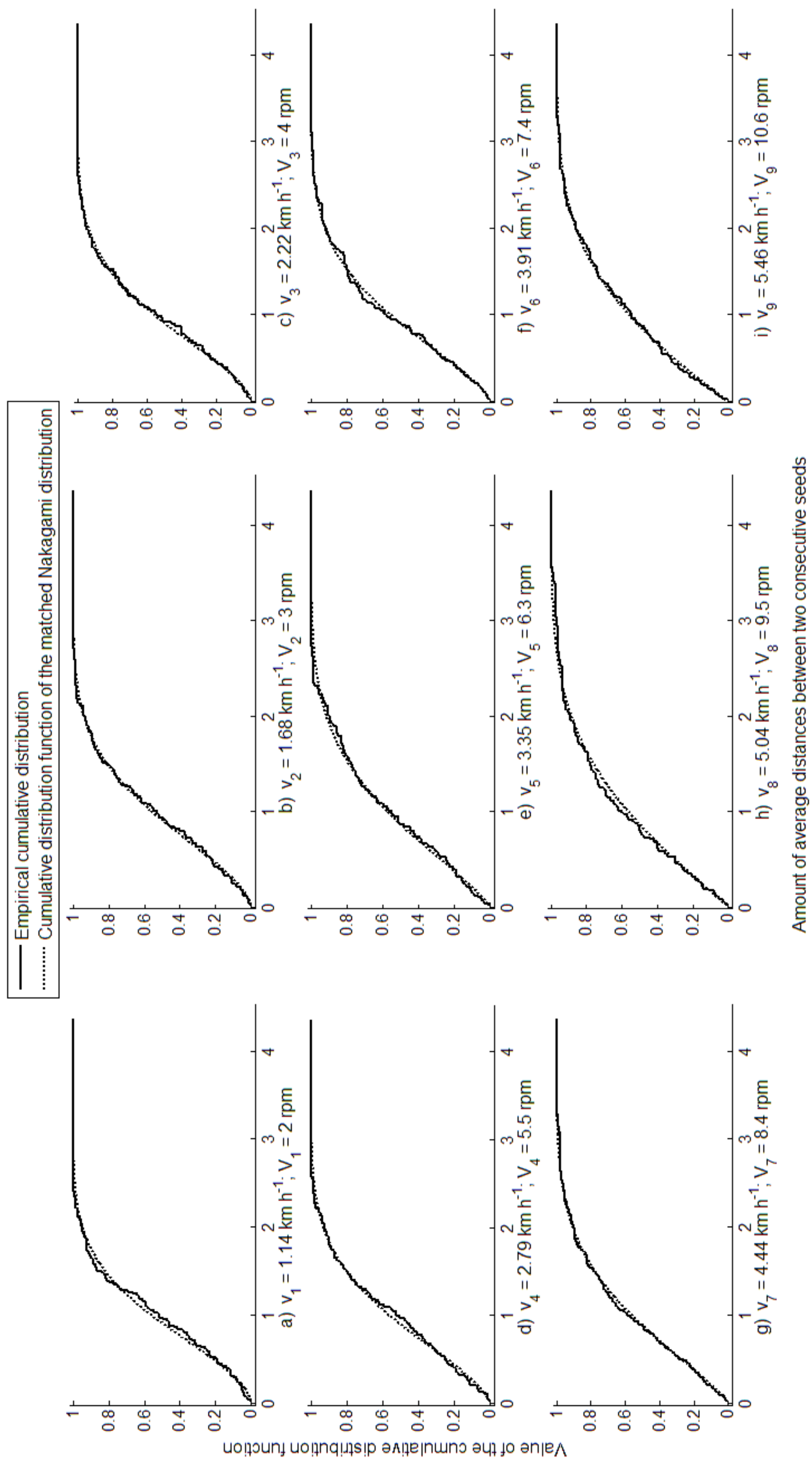

Fig.2. Empirical cumulative distribution function *vs.* cumulative distribution function of the matched Nakagami distribution at nine speeds of the Max Pneumatic S 156 seed drill.

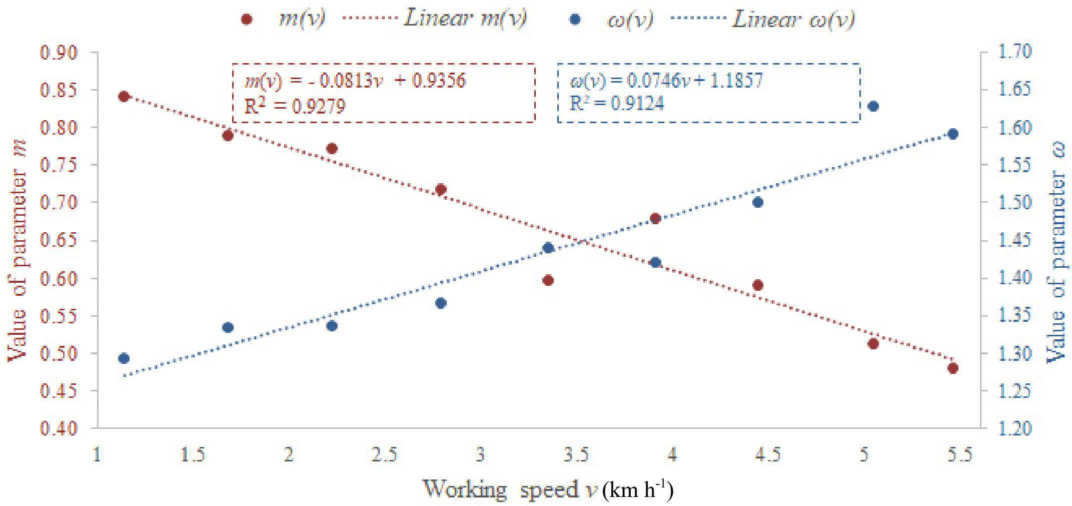

Fig. 3. Relationships between parameters m and ω, and the forward speed of the Max Pneumatic S 156 seed drill.

Hence the following Nakagami distribution functions were obtained using the parameters below:

$$m(v) = -0.0813v + 0.9356, \tag{1}$$

and

$$\omega(v) = 0.0746v + 1.1857. \tag{2}$$

Based on Eqs (1) and (2) nine new parameter pairs ($m(v_j)$, $\omega(v_j)$), $j = 1, \ldots, 9$, were obtained for the experimental speeds v_j and the Nakagami distributions were set up again. Their good fit to the experimental data is shown in Table 5 (p-value).

The good fit of the Nakagami distribution functions developed based on the linear regression models (1) and (2) means that they can be successfully applied in the process of predicting doubles, singles and skips depending on the speed v in the range from 1.14 to 5.46 km h^{-1}. The predicted effect of the drill's forward speed on the percentage of single seeds, double seeds and missed seeds (skips) is illustrated graphically in Fig. 4.

Table 5. p-values for the Chi-squared test for Nakagami distribution functions with parameters $m(v_j)$ and $\omega(v_j)$ at the nine tested forward speeds v_j of the Max Pneumatic S 156 seed drill

Forward speed v_j (km h^{-1})	Value of parameter m (v_j)	Value of parameter ω (v_j)	p-value
1.14	0.84	1.27	0.6655
1.68	0.8	1.31	0.2027
2.22	0.76	1.35	0.4633
2.79	0.71	1.39	0.8891
3.35	0.66	1.44	0.1409
3.91	0.62	1.48	0.1321
4.44	0.57	1.52	0.4174
5.04	0.53	1.56	0.4003
5.46	0.49	1.59	0.8281

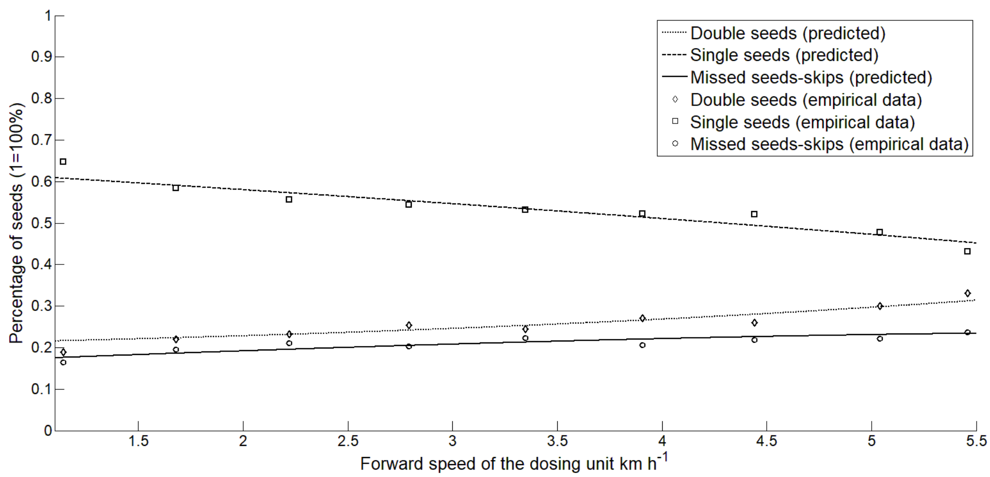

Fig. 4. Predicted effect of the forward speed of the Max Pneumatic S 135 seed drill on the percentage of single seeds, double seeds and missed seeds.

4. DISCUSSION

Recent decades have witnessed a considerable improvement in control systems for agricultural machines. Significant advancements have also been made in the area of seed drill improvements, these devices are often equipped with electronic systems for monitoring seeding parameters such as the seeding rate and depth. Seeding parameters are controlled by comparing the input (preset) data with the real data. Control and metering devices are the key elements of automatic control systems in modern row and precision seeders. The continuity of seed flow is monitored in row seeders, whereas the cyclicity of seeding is controlled in precision seeders. The relevant control and metering systems alert the user concerning any irregularities in seed flow. They are the indispensable elements of agricultural machines designed for precision farming, and they support the evaluation of the seeding process (Markowski, 2017; Kęska, 2002; Gierz, 2015; Jia-lei Zhang *et al*., 2020; Bai *et al*., 2022). In addition, the sowing quality is affected not only by the speed of the seeder, but also by the relevant soil parameters and its structure, which may be changed by applying the appropriate biostimulators (Findura *et al.,* 2022; Bredykhin *et al*., 2023; Krawczuk *et al*., 2023; Szparaga, 2023a,b). The physical properties of the seeds used during sowing are also of great importance in forecasting the quality of the crop, and they significantly affect the quality of the work of the sowing mechanism of the precision seeder (Findura *et al.,* 2023; Krzaczek *et al.,* 2006). The seeds should be cleaned and selected before sowing (Krzysiak *et al*., 2017; Marczuk *et al*., 2019; Krzysiak *et al*., 2020a,b). Numerous research attempts have been made to design electronic systems that not only control the number of dispensed seeds but also monitor the cyclicity of seed flow, *i.e.* the distance between seeds. Such systems are equipped with cameras with a fast shutter speed as well as photoelectric and piezoelectric sensors. Various seed counting sensors have been patented (United States Patent 4.555.624, 1983; United States Patent 8.441.247, 1995) and described in the literature, and yet to date seed counting accuracy has only been discussed by two authors (Markowski, 2017; Gierz, 2015).

A review of the existing literature also indicates that mathematical modelling has never been used to predict sowing quality parameters. Therefore, this paper proposes an innovative, mathematical approach to assessing the results of sowing radish seeds with a Max Pneumatic S 156 seeder, taking into account the adjustment of the Nakagami distribution for normalized distances between successive seeds. The details of the method used in the article to determine the qualitative parameters of point sowing based on the ISO 7256/1, 1984 (E) standard are described in chapter 2.4. The effect of seeder speed on the parameters of the Nakagami distribution, which is used to determine the percentage of single, double and omitted (skipped) seeds, was described using a regression function.

It is worth emphasizing that the range of forward speeds of the metering unit examined in the article was quite significant, both in terms of absolute numbers [1.14 (km h^{-1}); 5.46 (km h^{-1})] and, above all, in relative terms (the maximum speed was almost five times higher than the minimum). Therefore, the results of the study (percentage of singles, doubles and skips was determined based on the ISO 7256/1, 1984 (E) Standard) quite predictably revealed that the seeding quality decreases slightly as the seed drill's forward speed increases. At the same time, the average in-row distance between seeds increased from 47.31 to 57.93 mm. In the case of vacuum seeders, the increase in the average in-row distance between seeds is due to the fact that at higher sowing speeds, the seeds fall off the metering disc. This increase is notable but within the limits of acceptability. Moreover, the percentage of singles remains high, well above doubles and skips (Ding *et al.,* 2021; Zhang *et al*., 2021).

The sowing quality assessment method proposed in the article was characterized by a high degree of compliance with the seeding quality parameters determined based on the provisions of the ISO 7256/1, 1984 (E) Standard (Fig. 4). Furthermore, the proposed method supports the relevant predictions of the actual in-row distance between seeds at different forward speeds when only certain selected settings of the dosing unit are taken into account. This approach considerably shortens the research time and decreases the relevant costs. The presented method is promising and this should encourage others to undertake further research to check its reliability. The applicability of the Nakagami distribution function for predicting the distance between seeds can be verified at different seed drill parameter settings. The results of the relevant laboratory analyses should also be confirmed in a field study before the proposed method can be implemented in practice.

5. CONCLUSIONS

1. The use of the Nakagami distribution is appropriate to describe the normalized distances between successive radish seeds sown with precision seed drills.
2. The developed linear regression models match the empirical data very well, hence they are capable of determining the speed-dependent parameters of the Nakagami distribution with a high degree of accuracy.
3. The research conducted shows that the working speed of the seeder influences the sowing quality.
4. A novel method for the evaluation of sowing quality allows for the prediction of the distance between seeds in rows at different driving speeds. This achievement is a new approach to the research problem and significantly reduces both the research time and related costs.

5. The proposed new method of sowing quality assessment is characterized by a high degree of compliance with the quality parameters calculated on the basis of the ISO 7256/1, 1984 (E) standard.

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