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Optimisation of the fertilisation process for selected field spreaders

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Fertiliser application is one of the most important operations in agricultural production. It helps to increase the quality and quantity of the crop. However, the addition of too many ingredients or an unbalanced nutrient profile has a negative effect on crops. It is therefore important to apply fertiliser rationally and to achieve the correct level and uniformity of fertiliser distribution. The aim of this study was to develop a new model for lateral distribution uniformity during fertilisation. The tests were carried out under field conditions in a winter wheat crop. The quality of operation of three two-disc fertiliser spreaders at a travel speed of 1.22 m s-1 was investigated. A Lagrange interpolation model was used to analyse the data. The accuracy of models was very high (R2 > 0.985). The models developed can be used in practice to facilitate control of the spreader operation, which will help to ensure uniform fertiliser distribution..

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1. Introduction

Fertiliser spreading is a crucial aspect of modern agriculture, playing a significant role in achieving high-quality and high-yield crops [1-4]. However, it is important to keep in mind several factors when it comes to rational fertilisation. Firstly, incomplete utilisation of nutrients or an imbalanced nutrient profile can have a negative impact on crop growth. However, the use of fertilisers can lead to nutrient losses and environmental pollution if not applied correctly. Factors such as soil type, weather conditions, and application methods can all contribute to this issue. In their study, Beard et al. [5] found that soil crusting is affected by both silicon content and the use of nitrogenous fertilisers. Wan et al. [6] highlighted soil deterioration in citrus orchards due to excessive mineral fertiliser application. Wiggenhauser et al. [7] observed that over-application of phosphorus-containing fertilisers can lead to cadmium accumulation in the soil and subsequently in the edible plant parts. Hence, improper fertiliser application can have negative effects on the environment, as well as on humans and animals [8-10]. Therefore, it is important to achieve balanced fertilisation to ensure that the optimum amount of nutrients is provided, resulting in maximised yields [11-12].

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The most commonly utilised fertiliser spreaders are disc spreaders. Disc spreaders are distinguished by their high output and working width, low weight and straightforward construction, which results in a relatively low market price [13-14]. For this reason, they are being systematically improved, for example, by increasing the lateral and longitudinal uniformity of fertiliser spreading or by utilising elements of precision farming, such as the use of on-board computers or the use of images captured by unmanned aerial vehicles to create fertiliser maps. As with any agricultural machine, fertiliser spreaders are evaluated in terms of their suitability. This encompasses three key areas:

– structural,
– technological-functional (NPK basic fertilisation, late top dressing, granulated and dusty fertilisers),
– technological and bio-technological (soil and climatic conditions and agrotechnical period).

Among the design suitability indicators for spreaders are the fertiliser application rate, the working width and the lateral distribution uniformity.

In the era of precision farming, agricultural machinery used for sowing mineral fertiliser is subject to high technical demands. The main objective is to optimise the design of the machines to increase their reliability and efficiency. For fertiliser spreaders, the primary focus is to achieve high lateral and longitudinal uniformity of fertiliser distribution [15-17]. Tests to assess the uniformity of fertiliser distribution are conducted i.a. in accordance with the ISO standard, which is available in two forms: ISO 5690/1 and ISO 5690/2 [18-19], as well as ASAE/ASABE S573 [20]. The lateral distribution permits the performance of different spreader models operating at a constant working speed to be evaluated. The width and shape of this distribution are of significance for spreader design, with the latter being employed to determine the maximum working width of the machine.

The uniformity of the lateral distribution depends on a number of factors, including the length and shape of the spreading vanes, the physical properties of the fertiliser to be spread, and the atmospheric conditions during the fertilising process [21-23].

The application of a rational dose of fertiliser over the entire field is made possible by precision farming and high spreading uniformity. The nutrient-richness and fertility of the soil can be taken into account in the application of fertiliser, for example based on crop yields in individual parts of the field, through the use of satellite navigation. Precise fertilisation enables the reduction of not only fertiliser application, but also fertilisation costs and energy consumption. This is achieved by adjusting the quantity of fertiliser to the abundance of soil and the needs of the plants.

According to Papadopoulos et al. [24] savings in fertiliser application due to precision farming can amount to 25–30% while at the same time equalising the crop yield. The precise application of minerals ensures that the plants only receive the dose they are able to take up from the soil, thus limiting the harmful effects of excess fertiliser on the environment. This is achieved by limiting the amount of fertiliser that reaches groundwater and surface water, which can otherwise be contaminated by excess run-off.

Mathematical models are frequently utilised to enhance the effectiveness of agronomic treatments [25-27]. Martinez-Rodriguez et al. [28] developed a model and software to compute parameters in the centrifugal disc of fertiliser spreaders. Yuan et al. [29] introduced a discrete element model for compound fertiliser particles in a variable-rate application. Du et al. [30] designed a circular fertiliser applicator with an outer groove wheel and helical teeth and analysed this design using discrete element modelling. Liu et al. [31] developed a discrete element model to optimise the parameters of the fertiliser shunt plate. Marcal and Cunha [32] presented the automatic calibration system (ACFert) based on image processing techniques, to develop an algorithm and to evaluate the accuracy of fertiliser spreading. Sharipov et al. [33] developed a mathematical model using kinematic analysis of fertiliser granules to accurately determine the position and mass of a single fertiliser granule. Abbou-ou-cherif et al. [34-36] developed a model for fertiliser spreading on hilly areas and hills with variable slopes. Therefore, the aim of this study is to develop a new model for lateral distribution uniformity during fertilisation. The researchers suggest the need for further research in mathematical modelling to extend the fit of the models to real values.

2. Materials and methods

2.1 Experimental set-up

This research concerns an assessment of the uniformity of the lateral distribution of spreaders based on the ASAE/ASABE S341 standard [20].

The study tested the quality of operation of three double-disc fertiliser spreaders in a winter wheat crop under field conditions. The area of the field in which the experiments were carried out was 10 ha. Three experimental plots were established in this area. Each plot was 100 m wide and 50 m long. The Amazone and Unia Group MX spreaders had spreading discs that allowed for a 15-metre working width, while the Kuhn spreader had spreading discs that allowed for a 30-

metre working width. Table 1 shows the characteristics of the spreaders used in the study. The ammonium nitrate fertiliser was sown at a rate of 250 kg·ha-1. The granulometric composition of the fertiliser was determined using the sieve method, as shown in Table 2.

The tests were conducted with the fertiliser spreaders travelling at a speed of 1.22 m·s-1. The distance from the top edge of the containers to the spreading discs was 650 mm, and the disc speed was 540 rev min-1. Throughout the experiments, the blade height and angle remained constant at 50 mm and 40°, respectively. The hopper opening was adjusted to achieve a fertiliser flow rate of 40 kg min-1. The working width was adjusted and the fertiliser application rate was determined based on the manufacturer's operating instructions.

Fertiliser was applied to 0.5 × 0.5 metre containers, which were equipped with safety devices to prevent the fertiliser granules from falling out due to bouncing. The tests involved placing 10 containers in a row, taking up half of the working width. The experiments were conducted in triplicate. Along the route of the spreaders, containers were placed in three rows, with each row separated by a distance of 10 metres. After each pass of the spreader, the fertiliser was collected from the container and weighed using an analytical balance. The data was entered into Microsoft Excel 2013 and analysed to determine the average weight of fertiliser in each container. The coefficient of variation (CV) was calculated in accordance with the following formula:

$$CV = \frac{\sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (m_i - \bar{m})^2}}{\bar{m}} \qquad (1)$$

where mi is the mass of fertiliser in the i-th container (g), m¯ is the average mass of fertiliser in all containers (g), and n is the number of containers.

The coefficient of variation, which was employed in the study, is a commonly utilised metric for assessing lateral distribution. A lower value of the CV indicates a more uniform distribution of the fertiliser. Based on international test methods, it is assumed that the CV for nitrogen-containing fertilisers should not exceed 15%, while for nitrogen-free products it should not exceed 25%.

A linear function was then used to describe the relationship between the average weight of fertiliser and the distance from the centre of the spreader. The zero point of the function was calculated to determine the limit of the fertiliser spread. The equations obtained were used to calculate the values of fertiliser spread over the entire spreading width on both sides, which allowed the total fertiliser distribution to be determined.

2.2 Development of a new model for uniform transverse distribution

The data were analysed using a new approach that employed the Lagrange interpolation model to determine the relationship between path distance and fertiliser mass. A polynomial of degree n is formed based on n+1 observations x_0,x_1,…,x_n. The Lagrange interpolating polynomial has the following form:

$$L(x) = \sum_{i=0}^{n} y_i \prod_{j=0 \,\wedge\, j \neq i}^{n} \frac{x - x_j}{x_i - x_j} \qquad (2)$$

Table 1. Characteristics of the spreaders

	Unia – A	Amazone – B	Kuhn – C
Volume of hopper (l)	850	1200	1200
Width (mm)	2000	2150	1890
Length (mm)	1100	1420	1400
Height (mm)	1060	1070	1440
Vane number of each disc (piece)	2	2	2
Weight (kg)	273	319	289
PTO rev (min^{-1})	540	540	540
Power requirement (kW)	44–51	66	48

Table 2. Granulometric composition of ammonium nitrate 34% N

Fertiliser granule size [mm]	Fertiliser weight [kg]	Individual fractions proportion [%]
>4	0.114	45.6
3–4	0.126	50.4
2–3	0.007	2.8
1.5–2	0.001	0.4
<1.5	0.002	0.8
Sum	**0.25**	**100**

Ten observations were collected for each type of spreader, and three polynomials were generated for each type based on the formula 2. Based on (2) we obtain three formulas for each type of spreader. The Lagrange interpolation produced spline functions for various types of spreaders, which are as follows:

- Kuhn:

$$K(x) = \begin{cases} 5.47 - 1.1285x + 0.317945x^2 - 0.0388656x^3 + 0.00152263x^4, & x \in [0; 13.85] \\ -229743 + 60088x - 5888.76x^2 + 256.299x^3 - 4.18x^4, & x \in (13.85; 16.35] \end{cases} \quad (3)$$

- Amazone:

$$A(x) = \begin{cases} 4.13 - 2.58162x + 2.13842x^2 - 0.662458x^3 + 0.0642526x^4, & x \in [0; 5.05] \\ 977.122 - 539.897x + 111.869x^2 - 10.28x^3 + 0.353333x^4, & x \in (5.05;\ 8.25] \end{cases} \quad (4)$$

- Unia:

$$U(x) = \begin{cases} 5.37 - 1.12258x + 0.718609x^2 - 0.20416x^3 + 0.0179834x^4, & x \in [0; 5.05] \\ 2685.61 - 1487.27x + 308.362x^2 - 28.3333x^3 + 0.97333x^4, & x \in (5.05;\ 8.25] \end{cases} \quad (5)$$

3. Results

The results of the tests of lateral unevenness are presented in Table 3. For all types of fertiliser spreaders, the coefficient of variation of the transverse distribution parameter was below 15%. However, the Unia spreader obtained the lowest coefficient of variation and, at the same time, the highest uniformity of fertiliser distribution.

Figure 1 shows the distribution of fertiliser in the individual container and the average values from the three repetitions for the Amazone, Unia and Kuhn spreaders, respectively. The average values of the fertiliser mass in the individual containers are described by a linear function, assuming a linear distribution of fertiliser over the path width. Based on the function's equation, its zero points were calculated. This provides the limit for the spread of fertiliser, which is 12.7465 m for the Amazone spreader, 17.0562 m for the Unia spreader, and 31.6534 m for the Kuhn spreader.

Equations 3–5 were used to calculate values for individual points between adjacent spreader tracks, on the left and right sides, and to determine the total distribution of fertiliser for the analysed spreaders (see Fig. 2–4). As the limit to which the fertiliser was spread was greater than the working width, the application of fertiliser from adjacent passes was also considered. Figure 5 displays graphs comparing the average fertiliser masses in the containers with those generated by the model.

Table 3. Results for the coefficient of variation for the spreaders under study

	Kuhn	**Amazone**	**Unia**
CV (%)	12.03	13.33	6.80

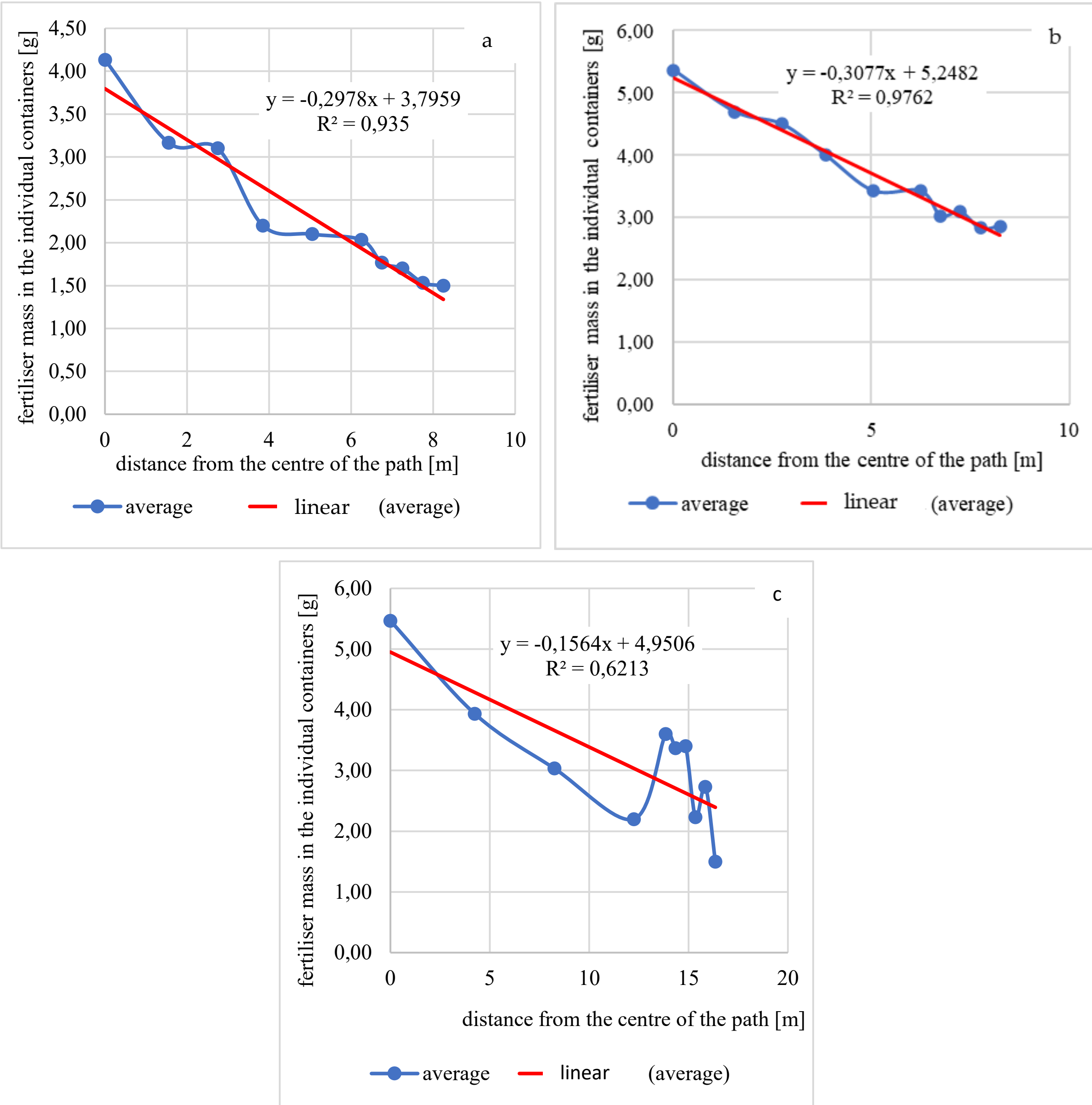

Fig. 1. Fertiliser weight as a function of distance from the spreader axis perpendicular to the direction of movement: a. Amazone, b. Unia, c. Kuhn spreader

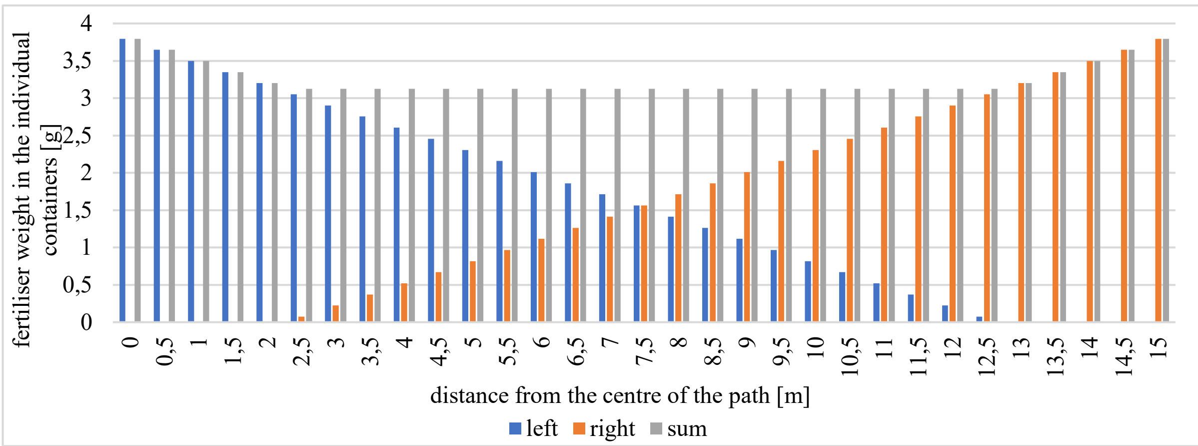

Fig. 2. Total fertiliser weight as a function of the distance between two passes of the Amazone ZA-M spreader

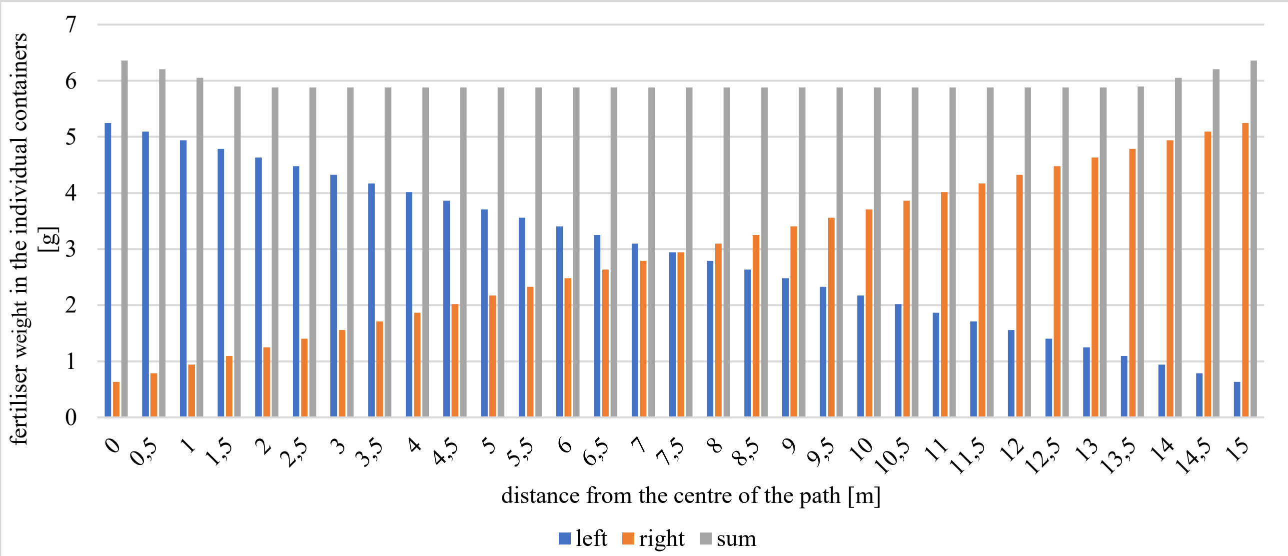

Fig. 3. Total fertiliser weight as a function of the distance between two passes of the Unia Brzeg 850MX spreader

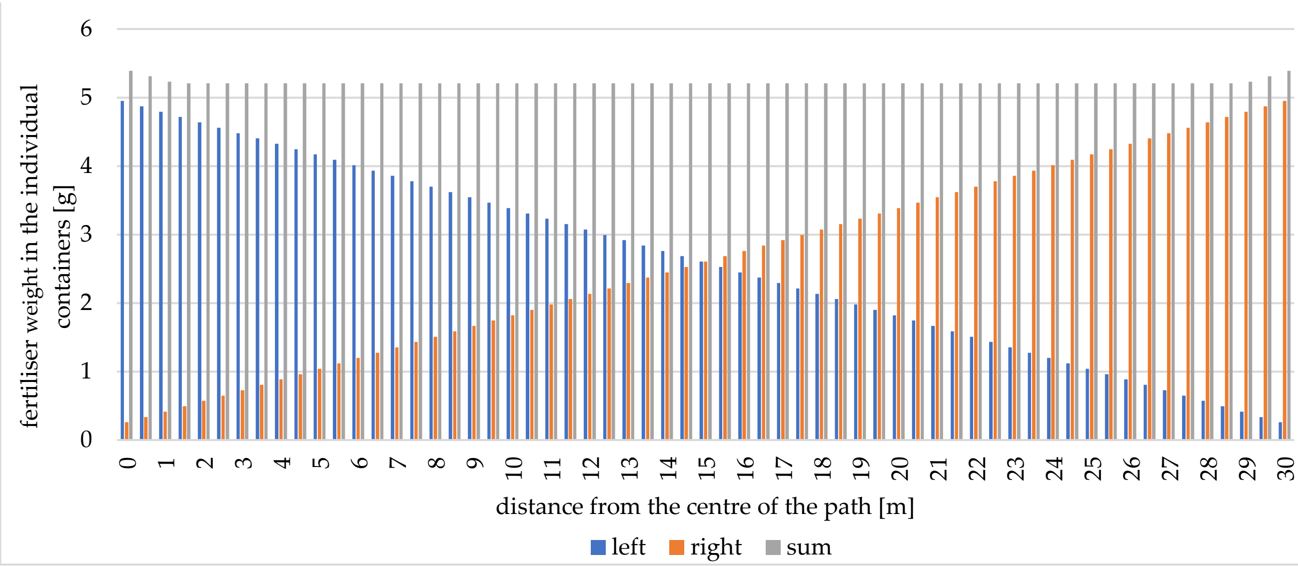

Fig. 4. Total fertiliser weight as a function of the distance between two passes of the Kuhn Rauch Axis 30.1EMC.W spreader

Table 4. Values of measures of model fit to experimental data for the three spreaders tested

	Kuhn	Amazone	Unia
Correlation coefficient	0.9927	0.9999	0.9999
Determination coefficient (R^2)	0.9855	0.9999	0.9999

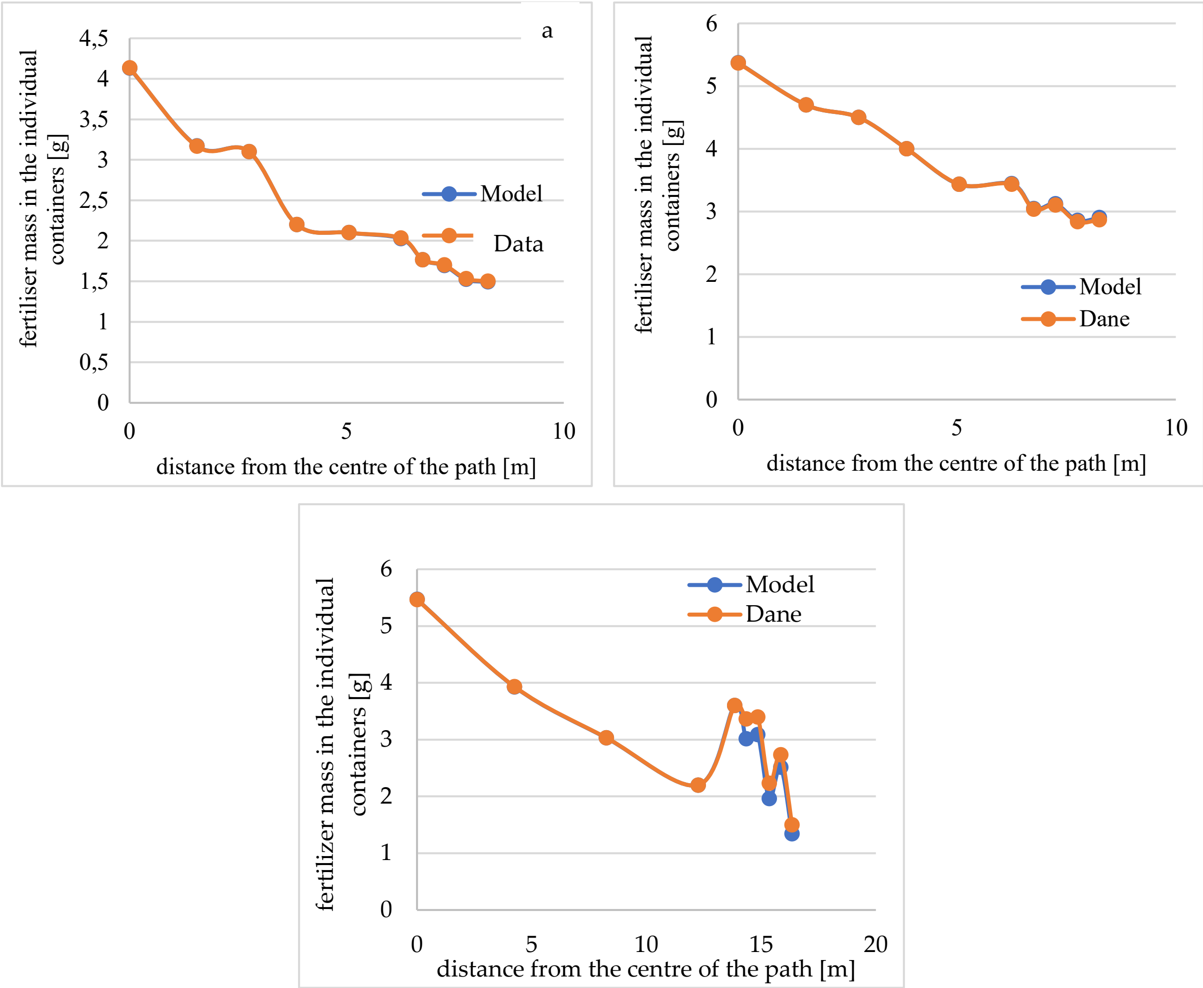

Fig. 5. Graph showing the goodness of fit of the constructed model to the experimental data for a. Amazone spreader, b. Unia Brzeg 850MX spreader, c. Kuhn Rauch Axis 30.1EMC.W spreader

Specifically, for the Amazone and Unia types, the coefficient of determination is above 0.999, while for the Kuhn spreader it is 0.985. Thus, it can be inferred that the model is a suitable fit for the experimental data, enabling effective simulation of the weight of fertiliser spread depending on the distance from the centre of the spreader.

4. Discussion

This work presents mathematical models for prediction of the uniformity of fertiliser application using different spreaders. Many researchers have emphasised the need for research into the uniformity of lateral and longitudinal distribution of fertiliser [37-39]. Many papers have been devoted to the optimisation of the fertiliser application process. Shi et al. [40] carried out a numerical simulation of the fertiliser spreading process using the discrete element method. They developed a regression model of the fertiliser particle distribution and the structural parameters of the formulation used, and employed a surface analysis method for optimisation. They then carried out a validation test under real conditions to compare the performance of the optimised system with that of the numerical model. The results of this test showed that the most influential factors on the lateral distribution of fertiliser granules were the angle of the blade, the angle of the disc cone and the height of the spreader.

The researchers presented the optimal combination of parameters analysed.

Liu et al. [41] designed a deflector plate according to the fertilisation characteristics of alfalfa, and optimised its structural parameters using discrete element simulation. They determined the inclination angle and horizontal distance, and verified the accuracy of the simulation results under field conditions [42]. In turn, Sun et al. [42] designed and developed a fertiliser apparatus with helical grooved wheels using 3D printing technology. They then used the EDEM simulation test to analyse the effects of various factors on fertilisation efficiency and determined the optimum parameters of groove radius, helix angle, rotational speed, and tilt angle.

Rußwurm et al. [43] developed a predictive control scheme for optimal control of a centrifugal spreader based on the kinematic model of the tractor, the model of the field, and the spread pattern. In their study they presented three algorithms: a one-step optimisation based on the current time step only, and two algorithms using model predictive control – one with a simplified distribution model in the prediction horizon and the other with a complex model. The best results were obtained with model predictive control using the comprehensive model. Koko and Virin [44] developed a mathematical model that took into account the prescribed fertiliser dose by adjusting the centrifugal spreader at each fertiliser application period in the field. They determined the parameterisation of the spreader based on minimising the error between the actual and the prescribed fertiliser dose.

5. Summary

One of the important objectives of modern agriculture is to achieve an appropriate level and uniformity of fertilisation. Based on the results of the optimisation, models are presented as a practical basis for representing the characteristics of fertiliser distribution.

The use of this model will make it easier to control the operation of spreaders and to assess the appropriate uniformity of fertiliser application.

References

1. Wang, Z.; Hassan, M.U.; Nadeem, F.; Wu, L.; Zhang, F.; Li, X. Magnesium Fertilization Improves Crop Yield in Most Production Systems: A Meta-Analysis. Front. Plant Sci. 2020, 10, 1727.
2. Liu, Q.; Xu, H.; Yi, H. Impact of Fertilizer on Crop Yield and C:N:P Stoichiometry in Arid and Semi-Arid Soil. Int. J. Environ. Res. Public Health 2021, 18, 4341.
3. Kakar, K.; Xuan, T.D.; Noori, Z.; Aryan, S.; Gulab, G. Effects of Organic and Inorganic Fertilizer Application on Growth, Yield, and Grain Quality of Rice. Agriculture 2020, 10, 544. https://doi.org/10.3390/agriculture10110544
4. Krasilnikov, P.; Taboada, M.A.; Amanullah. Fertilizer Use, Soil Health and Agricultural Sustainability. Agriculture 2022, 12, 462. https://doi.org/10.3390/agriculture12040462.
5. Beard, T.; Maaz, T.; Borrelli, K.; Harsh, J.; Pan, W. Nitrogen Affects Wheat and Canola Silica Accumulation, Soil Silica Forms, and Crusting. J. Environ. Qual. 2018, 47 (6). https://doi.org/10.2134/jeq2018.01.0052.
6. Wan, L.-J.; Tian, Y.; He, M.; Zheng, Y.-Q.; Lyu, Q.; Xie, R.-J.; Ma, Y.-Y.; Deng, L.; Yi, S.-L. Effects of Chemical Fertilizer Combined with Organic Fertilizer Application on Soil Properties, Citrus Growth Physiology, and Yield. Agriculture 2021, 11, 1207.
7. Wiggenhauser, M.; Bigalke, M.; Imseng, M.; Keller, A.; Rehkämper, M.; Wilcke, W.; Frossard, E. Using Isotopes to Trace Freshly Applied Cadmium through Mineral Phosphorus Fertilization in Soil-Fertilizer-Plant Systems. Sci. Total Environ. 2019, 648. https://doi.org/10.1016/j.scitotenv.2018.08.127.
8. Pahalvi, H.N.; Rafiya, L.; Rashid, S.; Nisar, B.; Kamili, A.N. Chemical Fertilizers and Their Impact on Soil Health. In Microbiota and Biofertilizers; Dar, G.H., Bhat, R.A., Mehmood, M.A., Hakeem, K.R., Eds.; Springer: Cham, Switzerland, 2021; Volume 2, pp. 1–20.
9. Food and Agriculture Organization of the United Nations. The international Code of Conduct for the sustainable use and management of fertilizers. 2019. Rome. ISBN 978-92-5-131705-1[10] European Commission, *EU biodiversity strategy : bringing nature back into our lives*. Publications Office, 2020. doi: doi/10.2779/9896.
10. Yousaf, M.; Li, J.; Lu, J.; Ren, T.; Cong, R.; Fahad, S.; Li, X. Effects of fertilization on crop production and nutrient-supplying capacity under rice-oilseed rape rotation system. Sci. Rep. 2017, 7, 1270.
11. Antonangelo, J. A.; Firmano, R. F.; Alleoni, L. R. F.; Oliveira, A.; Zhang, H. Soybean Production under Continuous Potassium Fertilization in a Long-Term No-Till Oxisol. Agron. J. 2019, 111 (5). https://doi.org/10.2134/agronj2019.02.0084.
12. Colaço, A. F.; Molin, J. P. Variable Rate Fertilization in Citrus: A Long Term Study. Precis. Agric. 2017, 18 (2). https://doi.org/10.1007/s11119-016-9454-9.
13. Thaper, R. K.; Fulton, J. P.; McDonald, T. P.; Fasina, O. O. Potential of Fertilizer Segregation during Application Using Spinner Disc Spreader. Precis. Agric. 2022, 23 (1). https://doi.org/10.1007/s11119-021-09828-5.
14. Przywara, A.; Santoro, F.; Kraszkiewicz, A.; Pecyna, A.; Pascuzzi, S. Experimental Study of Disc Fertilizer Spreader Performance. Agriculture 2020, 10, 467. https://doi.org/10.3390/agriculture10100467.
15. Gao, J.; Zhang, J.; Zhang, F.; Hou, Z.; Zhai, Y.; Ge, L. Analysis of Movement Law and Influencing Factors of Hill-Drop Fertilizer Based on SPH Algorithm. Appl. Sci. 2020, 10 (5). https://doi.org/10.3390/app10051643.
16. Przywara, A. The impact of structural and operational parameters of the centrifugal disc spreader on the spatial distribution of fertilizer. Agric. Agric. Sci. Procedia 2015, 7, 215–222.
17. Andrade, A.D.; Araújo e Silva Ferraz, G.; Machado de Barros, M.; De Oliveira Faria, R.; Moreira da Silva, F.; Sarri, D.; Vieri, M. Characterization of the Transverse Distribution of Fertilizer in Coffee Plantations. Agronomy 2020, 10, 601. https://doi.org/10.3390/agronomy10040601.

ISO 1985. ISO 5690/1: Equipment for distributing fertilizers – Test methods – Part 1: Full width fertilizer distributors.

ISO 1984. ISO 5690/2: Equipment for distributing fertilizers – Test methods – Part 2: Fertilizer distributors in lines.

ASABE: S341:2018. Procedure for measuring distribution uniformity and calibrating broadcast spreaders. American Society of Agricultural Engineers

18. Fulton, J. P.; Thaper, R. K.; Virk, S. S.; McDonald, T. P.; Fasina, O. O. Effect of Vane Shape on Fertilizer Distribution for a Dual-Disc Spinner Spreader. Appl. Eng. Agric. 2020, 36 (5). https://doi.org/10.13031/AEA.13634.
19. Roodi, S. M.; Abbaspour-Fard, M. H.; Aghkhani, M. H. Improvement of Centrifugal Spreader Performance in Order to Spread the Pellet Fertilizer. Agric. Mech. Syst. Res. 2020, 20 (73).
20. Cool, S. R.; Pieters, J. G.; Van Acker, J.; Van Den Bulcke, J.; Mertens, K. C.; Nuyttens, D. R. E.; Van De Gucht, T. C.; Vangeyte, J. Determining the Effect of Wind on the Ballistic Flight of Fertiliser Particles. Biosyst. Eng. 2016, 151. https://doi.org/10.1016/j.biosystemseng.2016.10.011.
21. Papadopoulos, G.; Arduini, S.; Uyar, H.; Psiroukis, V.; Kasimati, A.; Fountas, S. Economic and Environmental Benefits of Digital Agricultural Technologies in Crop Production: A Review. Smart Agric. Technol. 2024. https://doi.org/10.1016/j.atech.2024.100441.
22. Li, J.; Nie, Z.; Chen, Y.; Ge, D.; Li, M. Development of Boom Posture Adjustment and Control System for Wide Spray Boom. Agriculture 2023, 13, 2162. https://doi.org/10.3390/agriculture13112162
23. Cieniawska, B.; Parafiniuk, S.; Kluza, P. A.; Otachel, Z. Matching the Liquid Atomization Model to Experimental Data Obtained from Selected Nozzles. Appl. Sci. 2023, 13 (7). https://doi.org/10.3390/app13074433.
24. Ding, Y.; Li, H.; Gao, J.; Yu, H.; Wang, Y.; Feng, D. Parameter Optimization of Finger Clip Plate Garlic Seed-Metering Device. Agriculture 2023, 13, 2071. https://doi.org/10.3390/agriculture13112071
25. Martínez-Rodríguez, A. D. I.; Gómez-Águila, V. M. I.; Soto Escobar, M. M. I. Model and Software for the Parameters Calculation in Centrifugal Disk of Fertilizer Spreaders. Revista Ciencias Técnicas Agropecuarias 2021, 30.
26. Yuan, F.; Yu, H.; Wang, L.; Shi, Y.; Wang, X.; Liu, H. Parameter Calibration and Systematic Test of a Discrete Element Model (DEM) for Compound Fertilizer Particles in a Mechanized Variable-Rate Application. Agronomy 2023, 13, 706. https://doi.org/10.3390/agronomy13030706
27. Du, J.; Yang, Q.; Xia, J.; Li, G. Discrete Element Modeling and Verification of an Outer Groove Wheel Fertilizer Applicator with Helical Teeth. Trans. ASABE 2020, 63 (3). https://doi.org/10.13031/TRANS.13289.
28. Liu, J. S.; Gao, C. Q.; Nie, Y. J.; Yang, B.; Ge, R. Y.; Xu, Z. H. Numerical Simulation of Fertilizer Shunt-Plate with Uniformity Based on EDEM Software. Comput. Electron. Agric. 2020, 178. https://doi.org/10.1016/j.compag.2020.105737.
29. Marcal, A. R. S.; Cunha, M. Development of an Image-Based System to Assess Agricultural Fertilizer Spreader Pattern. Comput. Electron. Agric. 2019, 162. https://doi.org/10.1016/j.compag.2019.04.031.
30. Sharipov, G. M.; Heiß, A.; Eshkabilov, S. L.; Griepentrog, H. W.; Paraforos, D. S. Variable Rate Application Accuracy of a Centrifugal Disc Spreader Using ISO 11783 Communication Data and Granule Motion Modeling. Comput. Electron. Agric. 2021, 182. https://doi.org/10.1016/j.compag.2021.106006.
31. Abbou-ou-cherif, E. M.; Piron, E.; Chateauneuf, A.; Miclet, D.; Lenain, R.; Koko, J. On-the-Field Simulation of Fertilizer Spreading: Part 1 – Modeling. Comput. Electron. Agric. 2017, 142. https://doi.org/10.1016/j.compag.2017.09.006.
32. Abbou-ou-cherif, E. M.; Piron, E.; Chateauneuf, A.; Miclet, D.; Lenain, R.; Koko, J. On-the-Field Simulation of Fertilizer Spreading: Part 2 – Uniformity Investigation. Comput. Electron. Agric. 2017, 141. https://doi.org/10.1016/j.compag.2017.07.004.
33. Abbou-Ou-Cherif, E. M.; Piron, E.; Chateauneuf, A.; Miclet, D.; Villette, S. On-the-Field Simulation of Fertilizer Spreading: Part 3 – Control of Disk Inclination for Uniform Application on Undulating Fields. Comput. Electron. Agric. 2019, 158. https://doi.org/10.1016/j.compag.2019.01.050.
34. Bulgakov, V.; Adamchuk, O.; Pascuzzi, S.; Santoro, F.; Olt, J. Experimental Research into Uniformity in Spreading Mineral Fertilizers with Fertilizer Spreader Disc with Tilted Axis. Agron. Res. 2021, 19 (1). https://doi.org/10.15159/AR.21.025.
35. Cunha, J. P. A. R.; Filho, R. S. Broadcast Distribution Uniformity of Fertilizer with Centrifugal Spreaders Used in Variable Rate Application. Eng. Agric. 2016, 36 (5). https://doi.org/10.1590/1809-4430-eng.agric.v36n5p928-937/2016.
36. Kim, J. M.; Woo, D.; Kim, T. Analysis on Fertilizer Application Uniformity of Centrifugal Fertilizer Distributor. Biosyst. Eng. 2018, 43 (4).
37. Shi, Y.; Chen, M.; Wang, X.; Zhang, Z.; Odhiambo, M. O.; Ding, W. Numerical Simulation and Optimization of Scattering Performance of a Conical Centrifugal Variable-Rate Fertilizer Spreader. Int. Agric. Eng. J. 2018, 27 (1).
38. Liu, X.; Ding, Y.; Shu, C.; Liu, W.; Wang, K.; Du, C.; Wang, X. Design and Experiment of Spiral Disturbance Cone Centrifugal Fertilizer Apparatus. Nongye Gongcheng Xuebao/Transactions Chinese Soc. Agric. Eng. 2020, 36 (2). https://doi.org/10.11975/j.issn.1002-6819.2020.02.006.
39. Sun, J.; Chen, H.; Duan, J.; Liu, Z.; Zhu, Q. Mechanical Properties of the Grooved-Wheel Drilling Particles under Multivariate Interaction Influenced Based on 3D Printing and EDEM Simulation. Comput. Electron. Agric. 2020, 172. https://doi.org/10.1016/j.compag.2020.105329.
40. Rußwurm, F.; Osinenko, P.; Streif, S. Optimal Control of Centrifugal Spreader. In IFAC-PapersOnLine; 2020; Vol. 53. https://doi.org/10.1016/j.ifacol.2020.12.239.
41. Koko, J.; Virin, T. Optimization of a Fertilizer Spreading Process. Math. Comput. Simul. 2009, 79 (10). https://doi.org/10.1016/j.matcom.2009.03.001.