Research Article

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Strip spraying technology for precise herbicide application in carrot fields

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Abstract: The aim of this empirical field research was to show potential differences due to the precise application of herbicides in the quality and size of the carrot root yield and the amount of working liquid used compared to those for control samples. Empirical verification of the effectiveness of the developed technology, confirmed by statistical analyses of the obtained results, allows for a comparative assessment of this method with the conventional method of herbicide application used in this study. Due to the methodology used, it can be assumed that for carrots, the years were a random factor, and the experiments carried out were a series. It can be assumed that in the analysis of a series of experiments, for each of the examined features there are no differences between the groups and there is no interaction of the groups with the years. The yields of the groups weeded manually, sprayed in a conventional way, and weeded with precise spraying did not differ in a statistically significant way. In the precise application, a 20–30% lower herbicide consumption was observed, which has an impact on the protection of the environment and improves the economic effect of carrot production.

Keywords: herbicide, glyphosate, strip spraying, chemical protection, phytotoxicity

1 Introduction

The newly introduced European Union regulations emphasize the need to reduce harmful compounds in agricultural crops which are residues from the chemicals used and to reduce the amount of pesticides used in field cultivation. The solution to this problem, presented in this study, may be strip spraying technology and the precise application of working liquid, which, as many researchers say, allows us to reduce the size of the sprayed surface and reduces the amount of chemical compounds used [1–4].

According to Main et al. [5], in carrot cultivation, by strip spraying of rows 30 cm wide, with the addition of weeding by other methods, 66% less herbicide was used. Oliver et al. [6], in research carried out on the cultivation of sugar cane, showed that strip application of herbicide allowed for a 60% saving of the working liquid used to destroy weeds in the case of cultivation on elevated ridges and a reduction of active substances in the water in the drainage system. Similar results were obtained by Ivany [7] in an experiment in potato cultivation, where the herbicide was applied in rows 30 cm wide and weeds were destroyed in an interrow manner using mechanical hoes. Despite the presence of individual weeds in this method of controlling them, the yield amount did not differ when compared to that from conventional methods.

In the case of chemical methods of reducing weed infestation, the row zone of crops is often sprayed with selective herbicides, while the inter-row zone is sprayed with cheaper nonselective ones. However, the use of non-selective herbicides requires a different approach in terms of application and the use of crop protection shields, which are the objectives of the presented research results. Such research was carried out by Collins and Roche [8] in lupin cultivation, confirming the effectiveness of spraying with herbicide shields. An experiment carried out by Misra and Enge [9] in the cultivation of sugar beet with the use of a high-precision positioning system (RTK-GPS) showed that strip spraying with selective herbicide shields in rows and nonselective ones in the interrows allowed a...
53% reduction in the average manual weeding time and a 76% reduction in the use of selective herbicides. The use of this experimental technology, according to Carballido et al. [10], allowed savings of 54 €/ha and optimized sugar beet production in terms of weed control technology. Savings in the application of pesticides of about 50% when using the above weed control method with the use of an automatic steering system with high accuracy were also confirmed in research by Perez-Ruiz et al. [11]. Similarly favorable results were obtained by Serim et al. [12] in an experiment in sunflower cultivation, where strip spraying with nonselective herbicide with shields in inter-rows was also used and selective herbicides were used in rows. Hunt [13], in his experiments on strip spraying of sugar cane in Australia, proved that this solution allows spray liquid drift to be limited. Research by Foster et al. [14] also showed the beneficial effect of the use of shields to reduce the working liquid drift. Under the set conditions of comparative tests, at a wind speed of 11−14 km/h, the relative drift at a distance of up to 7 ft was definitely different for the two spraying methods. Shielded spraying reduced the fine drop drift to 20%, where virtually 100% of fine drops were carried away in the conventional method without shields. In the case of medium drops, it was below 20% for spraying with shields and more than 60% for conventional spraying. For very coarse drops, less than 10% of the liquid was carried away in shielded spraying, and less than 20% of the liquid was carried away in conventional spraying. On the other hand, when spraying with ultrathick drops, less than 5% of the liquid was carried away in shielded spraying and less than 15% in conventional spraying. Clayton’s [15] research showed that the use of shields in a wind tunnel reduces drift at the wind speed of 2 m/s and at a distance of up to 7 m against the wind by between 95 and 100% for all tested sprayers. Many other researchers confirmed that for various crops, strip application allows us to reduce the amount of spray liquid used to 60% due to the smaller actual spraying area, which is not without significance for the environment and crops [16−37]. Appropriate construction of the sprayer enables additional application of other pesticides or fertilizers during one treatment, which, in connection with precise automatic steering with an accuracy of 2−3 cm, improves the economic and environmental aspects of this technology.

The use of mechanical methods is limited in crops such as carrots grown in ridges; therefore, various solutions are sought that have an impact not only on reducing weeds, but also on reducing the possibility of weed resistance to herbicides and accumulation in the crop. The species composition of segetal flora depends on many factors. One of them is the crop. Some weed species are more common and more frequent in cereal crops, e.g., Apera spica-venti L.; others, in vegetables, e.g., Galinsoga parviflora L.

2 Aim and scope of this work

The aim of this study was to develop a technology for the precise application of herbicides in ridge carrot cultivation, the main pillars of which are an automatic steering system for a farm tractor and a designed sprayer with innovative multifaced adjustment of the spraying unit equipped with a herbicide shield. The research hypothesis assumes that the proposed solution ensures the precise application of plant protection products in various field vegetable cultivation systems, which will reduce the likelihood of active substance accumulation in the crop and the penetration of chemical compounds into groundwater. In addition, precise application enables us to limit the dose of active substances per 1 ha of sprayed area, as well as to perform effective treatments at wind speeds exceeding 4 m/s. Adjusting the level of weed infestation in the developed technology enables carrot yield at a level comparable to that achieved when using conventional technology. Over the whole vegetation period the weather conditions were controlled. A meteorological station was used to measure rainfall and temperature.

In carrot cultivation during the 2016 growing season, the rainfall value was recorded at 291 and 155 mm of irrigation was applied. During the vegetation season a number of ground frosts has been recorded: 1 April: −1°C, 2 April: −4°C, 3 April: −1°C, 23 April: −2.5°C, 25 April: −3.5°C, 26 April: −3°C, and 29 April: −1°C. The 2017 carrot vegetation season was characterized by the rainfall at 371 mm and irrigation of 121 mm. During this vegetation period ground frosts have been also occurred, i.e. 19 April: −1.5°C and 9−10 May: −4°C, respectively. In the 2018 carrot cultivation season, 210 mm of rainfall was recorded and 258 mm of irrigation was applied. No ground frosts were noticed.

3 Experimental materials and research methods

The research site was a carrot plantation during three growing seasons in 2015/2016, 2016/2017, and 2017/2018. Carrots were grown on trapezoidal ridges, and the distance between ridges was 75 cm. Four ridges were formed during
one pass. The aggregate operating speed was 3.2–3.6 km/h, and the depth was 20–25 cm. The forming aggregate was aggregated by the rear three-point linkage of a tractor with maximum power of 162 kW. The tractor was equipped with tires with the width of 600/60R28 at the front and 710/60R38 at the back and an automatic steering system with an accuracy of 2 cm with RTK NET signal correction. Immediately after the ridges were formed, carrots were sown in the crests of the ridges using appropriate seeding discs. Two rows were sown on one crest at a distance of 7 cm. Depending on the conditions, the sowing depth was in the range of 2.0–2.3 cm. The working speed during sowing was 4.0 km/h.

In this experiment, the hybrid variety Bangor F1 was cultivated, which according to the breeder’s data, is very fertile but requires deep cultivation, and the crop can be used for fresh consumption, industrial processing (juices, frozen food, cubes, slices), or storage. Roots are mainly cylindrical, and the foliage is strong with good tolerance to fungal diseases.

The experimental unit in the study was a plot with an area of 9 m² for carrot cultivation on ridges. The guidelines on how to conduct research in root crops determined the minimum size of the experimental plot at 5 m². The experimental factor was the method of weed control on the plots.

The following methods of weed control were adopted in the research: without weeding (control), A; manual weed control (manual weeding), B; conventional herbicide application, C; precise herbicide application (strip type with herbicide shield using an automatic steering system), D. Four observations were made for each method (Figure 1).

The most common weeds on the experimental plots were *Chenopodium album* L., *Fallopia convolvulus* L., *Stellaria media* L., *Gallium aparine* L., *Sinapis arvensis* L., *Viola arvensis* L., *Senecio vulgaris* L., *Galinsoga parviflora* L., *Amaranthus retroflexus* L., and *Echinochloa crus-galli* L.

The number of individual species was not calculated, and only the degree of the experimental plot area coverage was analyzed. It was found that they were dominated in the lower part of the furrow, due to the favorable humidity conditions.

Conventional spraying (depending on the level of weed growth; 2016 – 5 times, 2017 – 4 times, 2018 – 5 times) of carrots was carried out using a trailed sprayer with a working beam width of 18 m aggregated with the tractor. The sprayer was equipped with wheels with narrow tires for inter-row cultivation 270/95 R48, and the tractor also had wheels 270/95 R32 at the front and 270/95 R46 at the rear. The working speed during spraying was 7.0 km/h, and the pressure was 3.5 bar. AirMix 110-03 Blue Agrotop universal injector flat jet nozzles were used, producing coarse droplets. Technical characteristics of this nozzle: spray angle 110°, size 3 mm, and pressure range 3–8 bar.

Precise (similar number of times) strip spraying was carried out using a designed and made prototype sprayer aggregated with a tractor, which was used to perform sowing. During spraying, an automatic steering system with a declared accuracy of 2 cm was also used. The frame was fitted with a 400 L tank made of polyethylene with a liquid level indicator and a pump with a capacity of 120 L/min and a tank for clean water with a capacity of 15 L. In addition, the tank had a hydraulic injector mixer to maintain the same concentration of working liquid. The working pressure was controlled by a constant pressure distributor along with the possibility of excluding individual sections, and its value was indicated by the glycerin manometer. The working liquid was distributed to the spraying units using flexible round pipe. Depending on the type of weeds, the following herbicides were used: Aflex Super 450SC (Linuron), Sencor Liquid 600SC (Metrybuzyna), and Szogun 10EC (Chizalofop P-ethyl).

The actual width of the sprayed surface and the arrangement of the spraying sections during precise spraying of carrot cultivation on ridges is shown in Figure 2. Due to the trapezoidal shape of the sprayed ridge and the need to set the spraying sections parallel to its sides, the actual sprayed surface is larger than that in the case of conventional spraying. During spraying of carrots in phases from BBCH 42 (scale by Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie, where the root has 20% typical diameter) to the last herbicide treatment, when the leaves were closing in the interrows, the applied shields pushed the leaves aside and the spraying of ridge sides was possible (Figure 3).
The width of the sprayed strip during precise spraying in carrot cultivation was adjusted by nozzle rotation on its vertical axis and by changing the distance from the sprayed surface in accordance with the sprayer manufacturer’s recommendations for strip spraying.

Carrot harvesting from all plots was done manually in a single step to reduce any mechanical damage. The leaves were removed at the root head itself. The division into fractions was made at the initial stage, after digging the roots out. In order to avoid the loss of root mass, the weighing was performed within a few hours after harvesting. Yield results were statistically analyzed by two-way analysis of variance and the Fisher–Snedecor F test.

4 Research results

After each application of herbicides in carrot cultivation, visual observations were made for possible chemical damage to the crop. The plants from herbicide-sprayed plots were compared with those from manually weeded plots and control plots. There were no significant changes that could indicate phytotoxicity of the active substances used during the conducted study.

Figure 4 shows the relations between the average carrot yields in 2016–2018. They include total yield, commercial yield, i.e., roots with a maximum diameter not less than 30 mm, and noncommercial yield, with a maximum diameter of less than 30 mm. The analysis did not show any differences in yields between years.

The average carrot yield in 2016 from the group where weeding was carried out at a similar level; in the case of total yield it was in the range from 97 t/ha to nearly 100 t/ha, and in the case of commercial yield it was 2 t/ha lower. The control yielded on average about 63 t/ha (total yield). The commercial yield was almost 4 t/ha lower than the total yield.

In 2017, the average total carrot yield and the average commercial yield were the highest compared to those in 2016 and 2018 for all methods of weed control, and it amounted to slightly over 100 t/ha, with a noncommercial yield of about 21 t/ha. In the case of the control group, the average total yield was relatively high and it amounted to slightly more than 93 t/ha, and the noncommercial yield was less than 3 t/ha.

In 2018, the average total yield for each weeding method was in the range from 100.7 to 101.9 t/ha, whereas the average commercial yield was in the range from 97 to 98.3 t/ha. The noncommercial yield was the highest compared to the
previous years and it amounted to almost 4 t/ha. In the control group, the average total yield was less than 23 t/ha, of which the average commercial yield was slightly over 12 t/ha and the non-commercial one was over 10 t/ha.

The average weight of a carrot root varied between individual years of research and was the lowest in 2016, remaining in the range from 202 to 216 g for the different weeding methods and 153 g for the control group (Figure 5).

The highest average weight of carrot root in 2017 was in the range from 280 to 296 g for methods B, C, and D and 268 g for the control group. The lowest average root weight for the control group was in 2018 and it amounted to 112 g, while for various weeding methods it was in the range from 241 to 248 g.

Due to the large variance in observations for the group without weeding (A) compared to other groups

Figure 4: Average carrot yield (source: own work).

Figure 5: Qualitative assessment of carrot commercial yield (Ø ≥ 30 mm) in terms of the average weight of one root in 2016–2018 (source: own work).
for all years of research, no joint analysis of variance was performed. The average of group A in most cases differed significantly from those of other groups. Analysis of variance of the observations was done for the groups weeded manually (B), with conventional spraying (C), and with precise spraying (D).

In 2016, the total root weight in the case of precise spraying was significantly lower than that in manual weeding, but it did not differ statistically when compared to weed control by conventional spraying (Figure 6). The commercial yield and the average weight of one root did not differ statistically in 2016, regardless of the method of carrot weeding (Figures 7 and 8).

Also, in 2017, no significant differences were observed in the total carrot yield for individual weeding methods, as shown in Figure 9.

In the case of carrot commercial yield in 2017, there was a statistically significant difference between the group weeded manually (higher yield) and the group where weeds were destroyed by conventional spraying (lower yield). However, there were no statistically significant differences in yield between the herbicide application methods (Figures 10 and 11).

For the remaining analyzed features of the methods described as B, C, and D did not differ significantly, as shown in Figures 12–14.

Due to the methodology used, it can be assumed that for carrots, the years were a random factor, and the experiments carried out were a series. When carrying out analysis of variance for this series of experiments in carrot cultivation, due to the large variance of group A, it was carried out only for the other groups (B, C, and D). It can be assumed that in the analysis of a series of experiments, for each of the examined features there are no differences between the groups and there is no

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**Figure 6:** The expected marginal averages for 0.95 confidence intervals for total yield according to the various methods of weeding carrots in 2016 (source: own work).

**Figure 7:** The expected marginal averages for 0.95 confidence intervals for commercial yield according to the various methods of weeding carrots in 2016 (source: own work).

**Figure 8:** The expected marginal averages for 0.95 confidence intervals for the average weight of carrot root in various weeding methods in 2016 (source: own work).

**Figure 9:** The expected marginal averages for 0.95 confidence intervals for total yield according to the various methods of weeding carrots in 2017 (source: own work).
interaction of the groups with the years. The yields of the
groups weeded manually (B), sprayed in a conventional
way (C), and weeded with precise spraying (D) did
not differ in a statistically significant way. The yield
response to individual weed control methods is similar
when the weather conditions change in different years
of the experiment.

5 Discussion of results

Precise application of herbicides was possible due to the
working unit with high accuracy and to separating the
working liquid area from the crop and the areas that were
not the intended site of application. In the case of crops
at an advanced stage of development, i.e., when their

Figure 10: The expected marginal averages for 0.95 confidence
intervals for commercial yield according to the various methods of
weeding carrots in 2017 (source: own work).

Figure 11: The expected marginal averages for 0.95 confidence
intervals for the average weight of carrot root in various weeding
methods in 2017 (source: own work).

Figure 12: The expected marginal averages for 0.95 confidence
intervals for total yield according to the various methods of weeding
carrots in 2018 (source: own work).

Figure 13: The expected marginal averages for 0.95 confidence
intervals for commercial yield according to the various methods of
weeding carrots in 2018 (source: own work).

Figure 14: The expected marginal averages for 0.95 confidence
intervals for the average weight of carrot root in various weeding
methods in 2018 (source: own work).
aboveground part largely covers the ground surface, the leaves that cover the weeds at an early stage of development are a problem. Another factor affecting the precision of application is drift of the working liquid. A low wind with a speed of 1–2 m/s is beneficial from the point of view of crop penetration; however, it causes the risk of the spray liquid drifting to neighboring plants and reduces the retention of spray liquid on the weed surface.

The presented research results show statistically significant differences in the yield between the groups where weeding was done via various methods and the control group where weeding was discontinued. Studies conducted by many researchers confirm these results and similarly note the need to search for different methods and their combinations [14,23]. Due to the diversity of habitats and species compositions of weeds and the varietal differences in the case of carrots, methods that give satisfactory results are still being sought. A number of studies in various areas allow for the formulation of general conclusions as a basis for the development of herbicide strategies [16–37].

As it is in the case of many crops, in carrot cultivation, failure to control weeds leads to significant crop loss. The research conducted herein confirms the need to fight weeds by showing significant differences between control plots and the plots where the weeding was carried out by various methods, particularly taking into account the commercial yield, which is the most important from an economic point of view.

Achieving yield at a satisfactory level with proper weed control and a reduction of herbicide consumption has been the subject of many studies. Main et al. [5] conducted studies in a split-block system in 2008–2009. In 8 blocks there were 12 combinations of weed control, 6 control objects with 4 repetitions, and 2 sowing dates. The carrots for fresh market were grown on ridges with a top width of 24 cm and a height of 26 cm. The experimental plots included 4 ridges with a length of 6 m. The commercial yield was defined as the carrot roots with a maximum diameter of >19 mm in accordance with Canadian standards. In the experiment, the weeds were destroyed by conventional (full-area) spraying with linuron, strip spraying of row tops with linuron, strip spraying with substances of natural origin, and burning weeds in a strip manner. The weeds in interrows were systematically controlled mechanically with the use of knives and working elements spreading the soil to the sides of the ridges. The best results in terms of the total yield were obtained for both sowing dates when spraying the entire surface with linuron (71.5 and 68.1 t/ha), while the highest commercial yield for both sowing dates was obtained by spraying with linuron (57.1 and 59.9 t/ha). The lowest yields, both total and commercial, were obtained for the earlier sowing dates with strip burning of weeds (58.6 and 47.5 t/ha) and for the later sowing date when spraying with acetic acid. The technology of strip spraying with linuron, indicated in this study, allowed yields at the same level as the method of full-area application to be obtained and resulted in a significant reduction in the cost of using herbicide. The conclusions drawn by Main et al. [5] are consistent with the results presented in this study.

Another method of reducing herbicide consumption and, as in the presented work, ensuring its precise application is through variable dosing of the working liquid based on real-time image analysis. Research in this respect carried out by Dammer [19] allowed yield at a level similar to that from conventional herbicide application to be obtained. The method consisted of minimal application of herbicides when weeds were not detected, and the application was increased to the required level if they were detected. In research years 2007 and 2010, this method allowed herbicide savings of 30–43%. Neither the quality of the crop nor the total and commercial yields showed statistical differences when compared to conventional herbicide application.

An experiment conducted in 2009 and 2010 by Pacanoski et al. [29] assessed the effect of herbicides and their mixtures on carrot yield in Macedonia. The experiment was conducted using random complete blocks in four repetitions. The plot area in the experiment was 20 m². In the course of the experiment, the results were compared from plots treated with herbicides and their mixtures, the control plots which were not weeded, and the plots which were weeded manually. The percentage of yield loss recorded in the experiment was estimated on the basis of a comparison of yield from the control group (without weeding) and plots weeded manually; in the first year of the experiment it amounted to 58%, and in the second year it was 66%.

In the experiment by Pacanoski et al. [29], similarly to this work, no damage to the carrot plants resulting from the application of herbicides was observed. None of the herbicides used significantly reduced carrot yield.

Similar results in the effectiveness of weed control in maize cultivation, using belt spraying technology and precision tractor guidance, were obtained by Loddo et al. [37]. The authors used RTK-GPS positioning systems and automatic tractor steering in strip spraying. This made it possible to achieve accurate and precise herbicide application, and thus ensured a significant reduction in herbicide use and a reduced risk of environmental pollution compared to conventional spraying.
6 Conclusion

The commercial production of carrots with the current technologies requires the use of herbicides in a relatively wide range. The decision to use pesticides should be preceded by a broad analysis of all available weed control methods and the possible effects of their use. The research and analysis herein of the proposed technology for precise herbicide application in the ridge carrot cultivation system allowed for the formulation of the following conclusions:

(1) The designed technical solution, enabling multifaced regulation of the spraying unit operation, allows for the precise application of plant protection products in ridge carrot cultivation.

(2) Empirical verification of the effectiveness of the developed technology, confirmed by statistical analyses of the obtained results, allows for a comparative assessment of this method with the conventional method of herbicide application used in this study. Both total and commercial yield and the quality as determined by the average weight of carrot root in both methods did not differ statistically.

(3) Precise application of herbicide reduces the amount of chemical used. This has a significant impact on environmental protection and improves the economic performance of carrot production.

(4) In the conducted research, no phytotoxicity of herbicides in relation to crops was reported, as shown by the lack of statistical differences in the yield between the weed control methods used. This was also noted during the visual assessment of carrot plants in the treatment groups.

(5) Further research should be carried out on technology for the precise application of herbicides bypassing crops. The aim of these studies should be to determine the possibility of shortening the grace period, without the potential danger of accumulation of chemical compounds in crops. In addition, attention should be paid to the danger of potential condensation of the working liquid on the inner surface of the herbicide shield and the penetration of these condensates near the root system of the crop.

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