Optimal chemigation duration model based on the crop and environment effects

Hui Wang, Wenpeng Shi, Wene Wang*, Xiaotao Hu, Gang Ling, Rong Wei

(*Key Laboratory of Agricultural Soil and Water Engineering in Arid Areas, Ministry of Education, Northwest A & F University, Yangling 712100, Shaanxi, China*)

Abstract: Herbicides with drip irrigation (chemigation) could control the herbicides application accurately as the irrigation technology, and could reduce the harm to humans and the environment. However, the herbicide concentration is not consistent in the advancing process along the drip irrigation tape of different lengths, which not only influences the crop growth and results in herbicide residue. In this study, the crop and environmental effects of chemigation were discussed, potassium permanganate was used to replace herbicides, and a laboratory test was conducted to determine the best application duration. Based on this result, the maize field experiment of chemigation under plastic mulch was carried out to compare the effects of maize growth index, yield and herbicide residue for determining the optimal chemigation mode. The result shows that there is no significant difference in the application uniformity among treatments, but the leaf area index (LAI), yield, and double-ear rate of maize under continuous application (CA) were higher than those under periodic application (PA) and no application (NA) significantly. One month after the application, the acetochlor residue of the two modes was less than 1%, which would not cause pollution to the surrounding environment. And there was a significant linear regression relationship between the length of drip irrigation tape and the optimal application duration under the same acetochlor dosage.

Keywords: chemigation, irrigation mode, maize, environment

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1 Introduction

With the sustainable development of agriculture, the use of herbicides has been increasing. However, as the main way of pesticide application, the spray is easy to harm the workers through inspiration. Pesticide would move with the wind and may even penetrate the soil and enter the river or underground water with rain or irrigation water, causing widespread diffusion and posing a threat to the environment and other organisms. Chemigation is a mixture of pesticide and water application technology. It can apply pesticides according to the needs of crop growth and plant protection accurately, timely, and appropriately[1-3], not only save time, workforce, and water, increase production and income, but also be safe for the non-target creature[4]. In recent years, preliminary experimental studies on pesticide drip irrigation have also been carried out in China[5-7] . The results show that it can decrease the waste of water resources, control the leakage of pesticides in agricultural production effectively, and reduce the harm to workers and pollution to the environment.

Moreover, drip irrigation is not limited to the use of pesticides, and herbicides can also control weeds and diseases timely, bringing farmers more economic benefits. Some experiments[8-10] has built herbicide with drip irrigation system on different crops, and the results showed the chemigation was feasible, which could not only effectively prevent weed growth but also significantly improve crop economy and agronomic traits, and had no negative effect on other non-target organisms. Some scholars also point out that herbicides have negative effects when controlling weeds, so the development and use of herbicides in the future will reduce their toxicity and improve efficiency[11]. Overall, chemigation could have minimal herbicide losses, which is an obvious advantage compared with conventional sprinkler irrigation.

Drip irrigation under plastic mulch has been mostly adopted in maize in the Hexi Corridor region of China. The use of it reduces irrigation water evaporation greatly and creates a favorable environment for the growth and development of crops and roots. However, weeds around the crops cannot be removed by conventional methods because of the plastic mulch. Herbicide drip irrigation under mulch can apply herbicide effectively, remove weeds under the mulch and save manpower without affecting normal irrigation. At present, chemigation has been studied widely to control crop diseases[7,12,13], but there are few studies on herbicide application. And most of the existing research is focused on the screening and control effects of herbicides[6,14]. The influence of drip irrigation on herbicide uniformity and its influencing factors are seldom considered.

During herbicide application with drip irrigation (chemigation is used in the following paragraphs), the dose and concentration of herbicides should be within a certain range to kill the target weeds without harming the crops. And the discharge, herbicide

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Biographies: Hui Wang, PhD candidate, research interest: water saving irrigation theory and technology, Email: huiwang_@nwsuaf.edu.cn; **Wenpeng Shi**, Master candidate, research interest: water saving irrigation theory and technology, Email: 1156646414@qq.com; **Wene Wang**, PhD, Professor, research interest: water saving irrigation theory and technology, Email:wangwene@nwsuaf.edu.cn**;** **Xiaotao Hu**, PhD, Professor, research interest: water saving irrigation theory and technology, Email: huxiaotao11@nwsuaf.edu.cn; **Gang Ling**, Master candidate, research interest: Hydraulics and river dynamics, Email: 2690883602@qq.com; **Rong Wei**, PhD candidate, research interest: water saving irrigation theory and technology, Email: 1023049623@qq.com.

***Corresponding author: Wene Wang**, PhD, Professor, research interest: water saving irrigation theory and technology. Key Laboratory of Agricultural Soil and Water Engineering in Arid Areas, Ministry of Education, Northwest A&F University, Yangling 712100, Shaanxi, China. Tel: +86-15209241621, Email: wangwene@nwsuaf.edu.cn.

concentration, and application duration all affect application uniformity[15]. Herbicides are transported by water flowing along the drip irrigation tape in the irrigation process. At the beginning of the application, the liquid concentration increases to a stable value gradually. According to the micro-irrigation uniformity design requirements, the flow difference of the emitters in the drip irrigation tape is no more than 20%, so it can be considered that the emitter discharge is the same throughout the drip irrigation tape. Therefore, increasing application duration is theoretically beneficial to maintaining good application uniformity. But when the dosage is constant, prolonging duration means that the liquid concentration needs to be reduced, affecting weed control. To ensure the uniformity of chemigation and achieve a positive application effect, it is necessary to find the best application duration with different lengths of drip irrigation tapes.

Chemigation affects the growth and yield of maize, and herbicide residue could cause environmental pollution. According to the optimal application duration test of different drip irrigation tapes, the planting test of maize under mulch was designed to analyze the weed control effect, application uniformity, herbicide residue, and other indicators. Under the premise of ensuring maize growth and being friendly to humans and the environment, the suitable application mode and duration were explored.

2 Materials and method

2.1 Test site and treatment

2.1.1 Application duration experiment

Due to the long drip irrigation tape laid in the field, the water flow in the drip irrigation tape takes a long time, which easily leads to the low uniformity of herbicide. The acetochlor travel time in drip irrigation tape of different lengths can be discussed through laboratory experiments. Acetochlor would irritate eyes and skin and its detection and preparation require special equipment that is complex, time-consuming, and expensive. However, the density and water-carrying capacity of potassium permanganate are close to acetochlor (more details are in 3.1), and it has lower toxicity. Instead of acetochlor, potassium permanganate was tested to determine the best application duration. The experiment was carried out in the Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest Agriculture and Forestry University, Shaanxi, China. The water used was local tap water, pH was 7.92, and electrical conductivity was 243 uS/cm. The test layout is the same as the field test (Figure 1), including a water source, filter, water pump, self-made applicator, connecting tape, valve, and pressure gauge mainly.

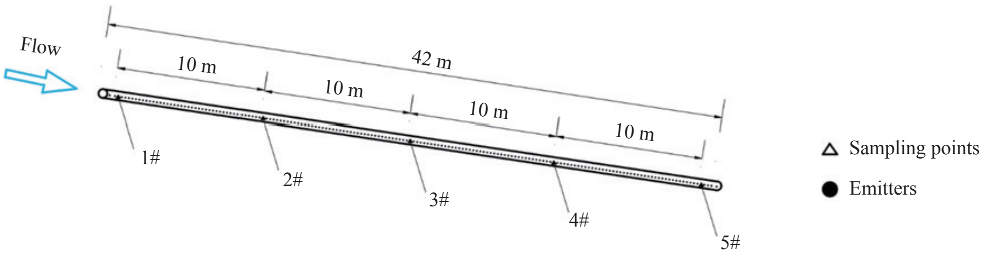


Figure 1 Sampling points of drip irrigation tape

The actual length of drip irrigation tape is 42 m and the calculated length is 40 m. The self-made dosing device is composed of an application barrel, stirring motor, and metering pump. The capacity of it is 100 L, the flow adjustment range of the metering pump is 0-20 L/h, and the adjustment gradient is 0.5 L/h. The rated test pressure is 55 kPa. Specific parameters of the drip irrigation tapes are shown in Table 1 (Drip irrigation tape was the same for all experiments in this paper). All the herbicides used were 50% acetochlor ($C_{14}H_{20}ClNO_2$) emulsions.

Table 1 Parameter of drip irrigation tapes

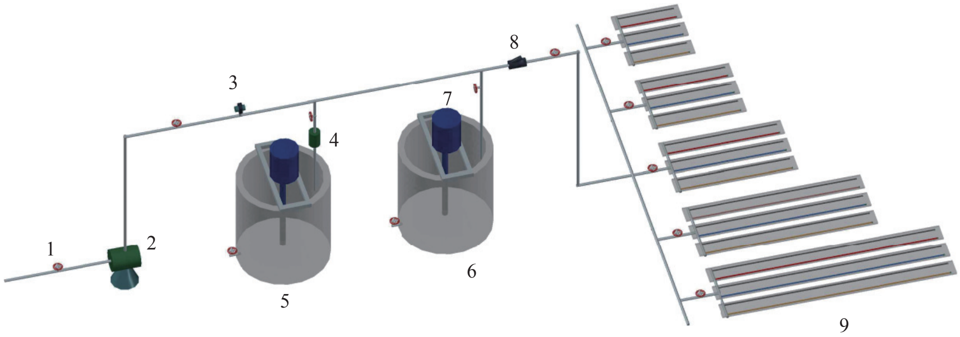
Type of the tape	Diameter of tape/mm	Thickness/ mm	Spacing of emitters/ cm	Rated pressure/ kPa	Rated discharge/ $L \cdot h^{-1}$
Labyrinth drip irrigation tape	16	0.2	30	100	3.5

2.1.2 Application mode field experiment

The field experiment was conducted from May to September 2018 at Shiyang River Experimental Station, Wuwei, Gansu Province, China. According to the local irrigation system, the seeds were sown on May 5, 2018 and harvested on September 10, 2018. The total growth period was 128 d. Acetochlor is a selective pre-bud treatment herbicide and has a long validity period. Therefore, only an application was made before the seedlings emerge, and the application date was May 6, 2018. The ions are mainly HCO^{3-}, HSO^{4-}, Cl^-, Ca^{2+}, K^+, and Mg^{2+} in the local irrigation water, which will not react with the acetochlor, and the pH is between 7.3-9.5. The experimental crop was "Xianyu 335", and a row of maize is planted under a mulch. The maize plant spacing was 0.3m, and the mulch width was 1.2 m.

As shown in Figure 2, integrated drip irrigation technology under mulch was used, including a water source, pump, filter, self-made applicator, and drip irrigation equipment. The filter equipment is a 120 mesh filter. A fertilization system was added to ensure the normal development and growth of experimental maize. To avoid errors caused by emitter blockage affecting the uniformity, the chemigation system was separated from the fertilization system. The chemigation system is only used for acetochlor application, and the drip irrigation tapes are replaced after each irrigation period. The fertilization proportion in the test was 4% and the rated test pressure was 55 kPa.

The field experiment set five lengths of drip irrigation tapes, two application modes, and a control group, with a total of 15 treatments. The continuous application was a common chemigation mode, while no application was used as a control group. Moreover, some studies have discussed the effect of periodic application[16]. To compare different acetochlor drip irrigation modes, the periodic application is added as a test mode. The amount of water and fertilizer applied is the same as the fertigation and acetochlor irrigation tapes, and the laying methods of all-length drip irrigation tapes are the same, as shown in Figure 2. The total application amount of acetochlor was 3000 mL/hm², and the same amount of acetochlor was applied to different tape length levels. The detailed test treatment was listed in Table 2 and Table 3.



Note: 1. Water inlet valve; 2. Pump; 3. Pressure gauge; 4. Measuring pump; 5. Acetochlor application barrel; 6. Fertilizer application barrel; 7. Mixer; 8. Filter; 9. Test area. Description: 1) According to the level of drip irrigation tapes, the experimental field was divided into 5 plots, each plot was 42 m×3.6 m, and 3 rows of mulch were laid, each row of mulch was laid with two drip irrigation tapes of fertilization and chemigation, a total of 6 drip irrigation tapes. 2) In the test area, the black drip irrigation tape represents fertigation tapes; The red drip irrigation tape represents periodic application tapes; The blue drip irrigation tape represents continuous application tapes; The yellow drip irrigation tape represents no application tapes.

Figure 2 Field experiment layout

Table 2 Treatments in the field experiment

Applications	Length/mm	Labels for the application modes	Applications	Length/mm	Labels for the application modes	Applications	Length/mm	Labels for the application modes
Continuous application (AC)	40	40CA	Periodical application (PA)	40	40PA	No application (NA)	40	40NA
	30	30CA		30	30PA		30	30NA
	20	20CA		20	20PA		20	20NA
	15	15CA		15	15PA		15	15NA
	10	10CA		10	10PA		10	10NA

Table 3 Field treatment of drip irrigation with different lengths

Length/m	Control area of each drip irrigation strip/m²	50% theoretical amount of acetochlor emulsion/g	The theoretical amount of acetochlor per unit mass in soil/mg·kg⁻¹	Actual application duration/s	Actual periodic flow q_1/L·h⁻¹	Actual continuous flow q_2/L·h⁻¹	Actual dosage V/L	Actual configuration concentration c/g·L⁻¹	50% acetochlor emulsion is required for the actual configuration of 10 L liquid/g
40	12	3.60	3.45	211	20	10	1.53	2.35	23.47
30	9	2.70	3.45	323	20	10	1.22	2.22	22.18
20	6	1.80	3.45	432	20	10	1.20	1.50	14.99
15	4.5	1.35	3.45	436	20	10	0.90	1.50	14.99
10	3	0.90	3.45	549	20	10	0.58	1.54	15.42

Note: Field trial application duration was set according to the results obtained in the laboratory experiment. The application duration was rounded to take into account the practical difficulties.

2.2 Measurement index and determination methods

2.2.1 Potassium permanganate sampling

Take a 40 m long drip irrigation tape as an example. The relative positions (0, 1/4, 1/2, 3/4, and 4/4) of drip irrigation were taken as sampling points, as shown in Figure 2. Open the applicator after the pressure stabilizes at the rated test pressure. Potassium permanganate flowed from the head to the end along the flow direction of drip irrigation tape and then flowed out of the emitter. The duration was 5.5 min in total, which is controlled by the application tank switch.

The sampling duration includes application duration (330 s) and after-application duration (130 s), with a total of 460 s. Potassium permanganate solution dripping from the emitter at the sampling point was collected through a 100 mL measuring glass, and the electrical conductivity of the samples was measured by a conductivity meter. Sampling was performed at five sampling points simultaneously. At 1 min after the switch is turned on, each sample was collected every 5 s, and the measuring cup was replaced immediately after collection to get the next sample, a total of 12 samples. During 2-5.5 min after the switch is turned on, the emitter discharge was stable, so each sample was collected every 15 s, with a total of 18 samples. After finishing the application process (turn off the self-made applicator), the remaining liquid in the drip irrigation tape will still flow into the field with the water, so each sample was collected every 5 s within 130 s. The whole process included 270 samples. To avoid the influence of temperature on the concentration and conductivity, the temperature was strictly controlled at 20°C during the indoor test.

2.2.2 Potassium permanganate concentration determination

The potassium permanganate concentration was obtained by the concentration-conductivity standard curve. The conductivity meter was KEDIDA CT-3031 with a range of 0-1999 uS/cm and an accuracy of 1 uS/cm. To ensure the weighing accuracy and accelerate the dissolution of potassium permanganate, potassium permanganate particles were grinded, and 10 portions of 0.01 g potassium permanganate powder were weighed accurately through a ten-thousandth precision scale. In keeping with the actual irrigation conditions, potassium permanganate was dissolved in irrigation water. The conductivity value of tap water was measured first, and then the potassium permanganate powder was added to 500 mL tap water in sequence. After each addition, stir to dissolve thoroughly, and measure the conductivity. During the whole test, the room temperature was controlled at about 20°C and the temperature difference was less than 1°C, so the influence of temperature on the conductivity could be ignored. According to the conductivity of potassium permanganate solution measured at different concentrations, Figure 3 and the conversion equation are obtained.

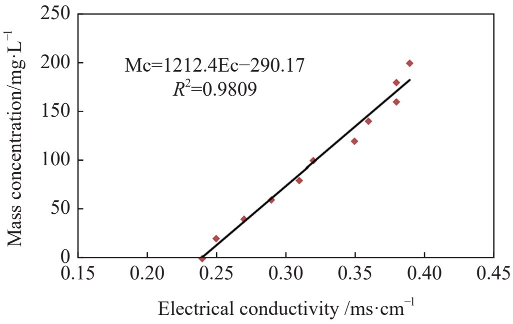


Figure 3 $KMnO_4$ standard curve

2.2.3 Maize growth index and herbicide residue determination

Maize Leaf area index (LAI): During the pustulation period and mature period of corn, the leaf area index (LAI) was measured at the same sites weekly. Leaf area index = maize leaf length × leaf width × 0.7.

Acetochlor residues in the soil: After 30 d of application, soil layers were taken (40cm, a total of 4 layers) at the middle of each application drip irrigation tape every 10 cm in depth, and the acetochlor content in each soil layer was determined by ultrasonic extraction. The acetochlor concentration was determined by ultra-performance liquid chromatography (UPLC).

The yield, hundred-grain weight, and double-ear rate of maize were measured after harvest.

2.3 Data analysis

Microsoft Excel was used for basic calculation, and SPSS 22.0 was used for the significance analysis of paired *t*-test. The purpose of the paired t-test is to analyze the population mean difference of normal samples among different application treatments. In the analysis, $p<0.05$ was considered statistically significant.

3 Analysis and results

3.1 Feasibility of using potassium permanganate instead of acetochlor

Due to the high ionization degree of potassium permanganate, its migration in water can be observed directly and traced effectively. Its concentration can be converted by the electrical conductivity directly, which is measured by a conductivity meter. Using potassium permanganate instead of acetochlor in the test is convenient for on-site detection and can reduce the pollution of herbicides to people and the environment. Therefore, a control test was conducted on the migration of potassium permanganate and acetochlor in a 40 m drip irrigation tape.

Figure 4 shows the concentration changes and migration of acetochlor and potassium permanganate overtime respectively. As can be seen from Figure 4, when the emitter discharge tended to be stable, the acetochlor concentration in the liquid fluctuated around 8.5 g/L, that is, the normal acetochlor concentration was 8.5 g/L. When the switch was turned on, part of the acetochlor migrated to the 0 m sampling point quickly, and the concentration was 2.54 g/L at this time, which had not reached the normal concentration. Subsequently, the acetochlor concentration increased rapidly and reached the normal concentration at about 10 s. At 25 s, acetochlor was transported to the 10 m sampling point with water and reached the normal concentration within the next 10 s.

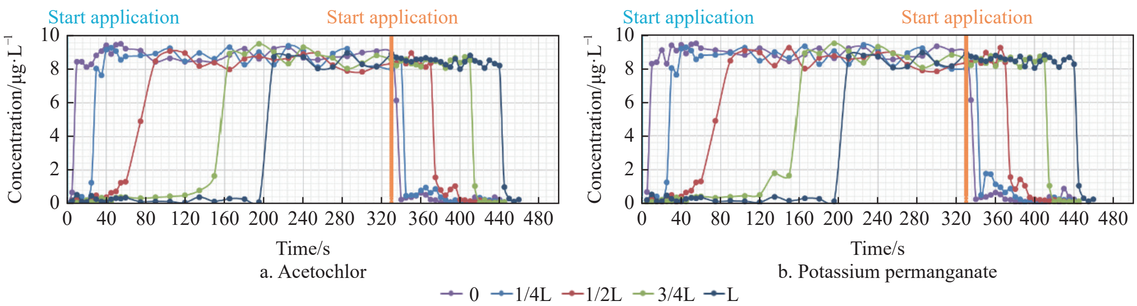


Figure 4 Changes of acetochlor concentration in 40 m irrigation tape

Then, the acetochlor migration rate slowed down, appearing at the 20m sampling point in the 60 s, and reaching the normal concentration after 30 s. Finally, the acetochlor migration rate decreased with the migration distance gradually, and it appeared at the 30 m and 40 m sampling points at 135 s and 210 s, respectively. When the acetochlor application finished, there was still water flowing in the drip irrigation tape, and the solution concentration would decrease gradually until all the outflow became clear water. As shown in Figure 5, the acetochlor concentration at each sampling point began to decline at 330 s, 340 s, 370 s, 410 s, and 440 s, and decreased rapidly to 0 in the 30 s, 30 s, 20 s, 5 s, and 5 s, respectively.

After application, potassium permanganate was detected at 0 m, 10 m, 20 m, 30 m, and 40 m of drip irrigation zone at 5 s, 25 s, the

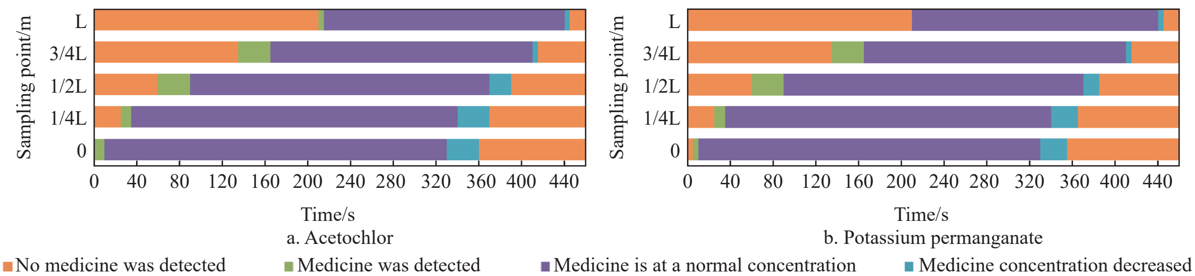


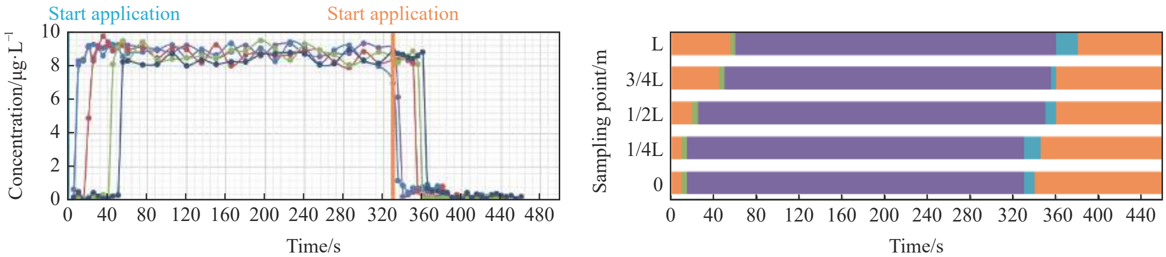
Figure 5 Duration of acetochlor migration in 40 m irrigation tape

60 s, 135 s, and 210 s, respectively, and reached the normal concentration quickly within 5 s, 10 s, 30 s, 30 s, and 0 s. Then, potassium permanganate began to decrease at 330 s, 340 s, 370 s, 410 s, and 440 s, respectively and decreased to 0 rapidly. By comparing Figure 5, the migration and concentration changes of acetochlor and potassium permanganate in the drip irrigation process are the same. The migration of acetochlor and potassium permanganate with water application mainly depends on the hydraulic performance of drip irrigation tape. Therefore, if the drip irrigation tape and operating conditions are the same, potassium permanganate can be used instead of acetochlor to carry out the application concentration change test along the process, and the results would not be affected. Potassium permanganate is less toxic, the method of sampling and detection is simple and the cost is low, so it is suitable to be used as a substitute for the polluting and toxic acetochlor, which can shorten the test time and reduce the test cost, and avoid the damage caused to the health of the test personnel.

In addition, according to the potassium permanganate concentration curve, the normal potassium permanganate concentration is 8.7 g/L, and the optimal application duration of potassium permanganate in 40m drip irrigation tape is 9.62 min, and the relative error between it and acetochlor is 1.62%. Therefore, it is reasonable to calculate the optimal application time using potassium permanganate instead of acetochlor.

3.2 Optimal application duration of drip irrigation tape

Field experiments show that the length of drip irrigation tape would affect the acetochlor application uniformity at the same application duration. When a drip irrigation system is used in the field, seeking the best application duration is beneficial to improve application uniformity. Figure 6 shows the variation of potassium permanganate concentration in drip irrigation tape of each length. Taking the 40 m drip irrigation tape as an example, the acetochlor content in each sample was calculated and accumulated into the total acetochlor content. The total acetochlor content of samples at 0 m, 10 m, 20 m, 30 m, and 40 m was 2854.9 μg, 2699.2 μg, 2536.1 μg, 2314.4 μg, and 2134.7 μg, respectively. The deviation coefficient C_V of acetochlor content at the head and end of drip irrigation was 0.7477.

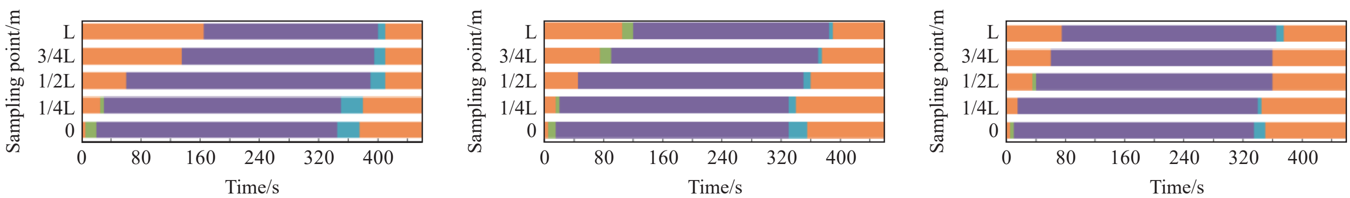


a. Concentration changes b. Migration

Figure 6 Concentration changes and migration of acetochlor in 10 m drip tape

Due to the requirements of micro-irrigation, the corresponding head pressure difference of the emitter in each micro-irrigation unit should not exceed 20%. Therefore, the expected uniformity of irrigation should not be less than the minimum uniformity of drip irrigation tape (80%) in the application process.

To simplify the model, it is assumed that the emitter discharge along the drip irrigation tape is equal. It can be seen from the concentration change (Figure 6) that the liquid concentration at the sampling point of 0 m and 40 m can reach 8.5 g/L, but the duration from 0 to normal concentration and from normal concentration to 0 is different (Figure 7). Therefore, the accumulative difference of application duration caused by liquid propulsion at different sampling points can be reduced effectively by prolonging application duration and increasing the proportion of normal concentration application duration in total application time at different sampling points. Under the requirement of minimum uniformity, the additional acetochlor dose was 746.1 μg, which needed 87.78 s, so the total application time was 417.78 s.



a. 30 m drip tape b. 20 m drip tape c. 15 m drip tape

Figure 7 Acetochlor migration in different sampling points

However, the actual discharge is different in the irrigation process, and the irrigation specification requires that the discharge change is no more than 10%. Considering that the capillary head loss should be less than 20% of the working pressure, the comprehensive correction coefficient (1.32) is adopted to correct the actual acetochlor loss in the irrigation process and Table 4 is obtained.

Table 4 Optimal application schedule for drip irrigation tapes of different lengths

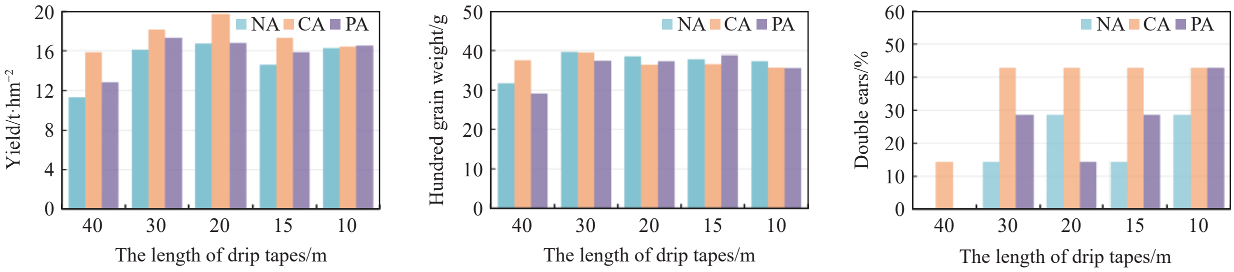
Length of tapes/m	Preset application time/s	Extended application time/s	Total application duration/s	Total duration after correction/s
10	330	–170.11	159.89	211.05
15	330	–85.52	244.48	322.72
20	330	–2.76	327.24	431.96
30	330	0.00	330.00	435.60
40	330	87.78	415.76	548.80

3.3 Optimal acetochlor application modes of drip irrigation

3.3.1 Crop effects

The effects of chemigation on crops are mainly reflected in weed control effect and uniformity. Weeds plunder the nutrients for crop growth, and the herbicides application to inhibit the weeds growth can enable crops to obtain more sufficient nutrients for normal growth and development. The main growth indexes of crops: leaf area index, yield, hundred-grain weight, double-ear rate, and the uniformity of weed in the field can be used to characterize the herbicides efficacy effectively. Due to the toxicity of acetochlor, it is difficult to measure the application uniformity in the field. The uniformity can be reflected by the weeds growth at different sampling points indirectly.

Figure 8 shows the double-ear rate, hundred-grain weight, and yield of three application modes, respectively. Under different lengths of drip irrigation tape, continuous application increased the total yield and double-ear rate significantly. When the length of drip irrigation tape was 40 m, the hundred-grain weight of continuous application was significantly greater than that of the other two modes, while there was no obvious difference in the hundred-grain weight of drip irrigation tape with other lengths. However, when the length of drip irrigation tape was 10 m, the yield indexes of continuous application and periodic application were the same. The leaf area index (LAI) of maize before the application was measured under different treatments. Although the overall change in LAI was similar (Figure 9), there were significant differences in the values of different application treatments. The difference between this value and the maximum LAI value measured can be used to obtain the increase of LAI under acetochlor dosage. LAI increment of continuous application ranged from 1.19 to 2.97, which was much higher than that of no application and periodic application. Periodical application is only slightly larger than non-application, indicating that periodical application also has a certain effect. But for the application effect, the continuous application is more appropriate.



a. Yield b. Hundred-grain weight c. Double-ears rate

Figure 8 Increasing amount of maize growth index in different length drip irrigation tapes for 30 d

Figures 10 and 11 show the weeding effect and uniformity at the relative positions of different drip irrigation zones. According to the fresh weeds weight obtained after application, acetochlor application did inhibit the growth of weeds. When the length of the drip irrigation tape was shorter (10 m, 15 m), the continuous application had a better weeding effect. When the length was longer (30 m, 40 m), the periodic application mode was better. When the length was 20 m, there was little difference between the two treatments. In terms of application uniformity, the continuous application was superior to the periodic application under each length. In general, with the increase in the length, the weeding effect and uniformity of acetochlor decreased gradually. The difference in application modes decreased with the decrease in the length. It indicated that the length of drip irrigation tape did affect the chemigation uniformity. The shorter length of drip irrigation tape leads to more uniform application, higher herbicide utilization, and crop yield.

Meanwhile, it can be seen from Figure 9 that the length of drip irrigation tape also has an impact on LAI changes. Under chemigation, the backward shift degree of the leaf area index peak changed with the change of drip irrigation tape length. The longer the length of drip irrigation tape, the less regressive degree. Moreover, the numerical differences of LAI at different locations decreased with the decrease in the length. The reason is that with a long drip irrigation tape, the pressure difference between the head and tail is large, leading to a larger difference in the discharge between emitters, that is, the irrigation uniformity is low. As a result, the uniformity of chemigation was low, and weeds in the tail could not be effectively removed, so the LAI and the uniformity of weed growth would also have a great difference.

The numerical difference of LAI at different locations decreased as the length decreased. The reason is that when the drip irrigation tape is longer, the pressure difference between the head and end is large, leading to a large discharge difference between the emitters, that is, the uniformity of irrigation is low. Therefore, the low uniformity of chemigation leads to ineffective weed removal. LAI and weed growth uniformity will also be very different.

3.3.2 Environment effects

After chemigation, pesticide residue will cause serious harm to the environment and organisms. Under different treatments, the acetochlor residues in the soil increased first and then decreased with the increase in soil depth (Figure 12). In general, acetochlor residues were the highest in the soil layer at 0-20 cm depth, because acetochlor drops into the soil surface and mainly moves through the soil with water infiltration. With the increase of soil depth, the amount of acetochlor in the soil layer with water decreased gradually and reached 100 ng/kg finally.

However, in the 0-10 cm soil layer, acetochlor was almost zero, which was caused by the degradation mode of acetochlor. The degradation of acetochlor in soil mainly includes photodegradation[17] and microbial degradation[18-20], and there are many factors that affect the degradation rate, among which soil microbes are the most important[18]. In the 0-10 cm soil layer, acetochlor was mainly degraded by light and microorganisms. In addition, due to the direct contact between air and soil surface, there was sufficient sunshine and moisture, which accelerated the degradation rate, resulting in less acetochlor residual in the 0-10 cm soil layer. In the 10-20 cm soil layer, acetochlor degradation mainly relied on microbial degradation due to a lack of sunlight and water, which slowed down the degradation rate by microorganisms. In addition, the herbicide carried by irrigation water infiltrates downward from the 0-10 cm soil layer, and part of the herbicide enters the 10-20 cm soil layer. As a result, 20 cm is the peak position of acetochlor residues in the soil.

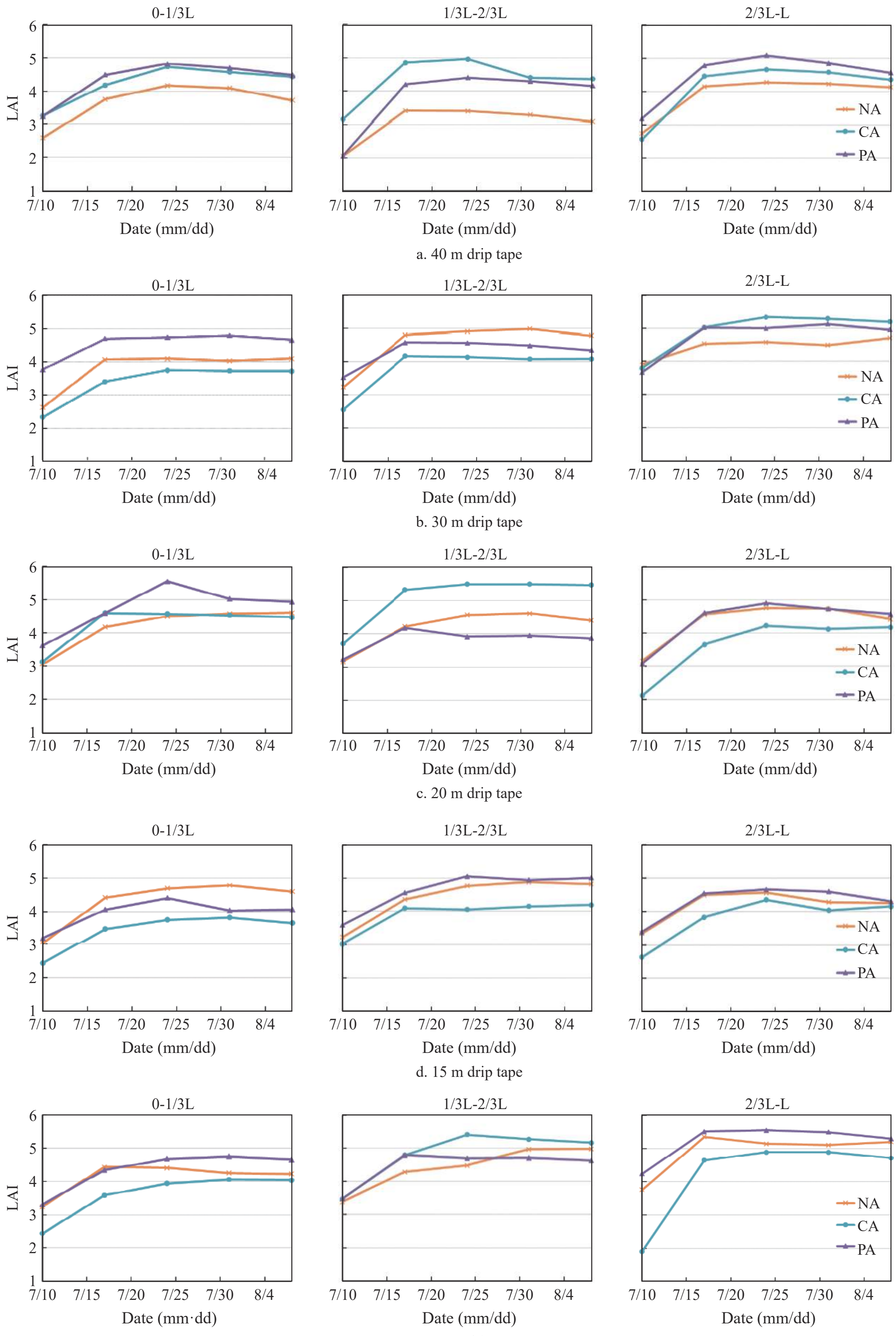


Figure 9 Leaf area index change of maize with different application methods (from left to right in the order of head, middle, and tail of each line)

The residual acetochlor content is less than 10% of the original acetochlor content, and it can be considered that acetochlor has been completely degraded[17,21]. The soil of the test site is sandy soil with few microorganisms. Besides topsoil, acetochlor degradation mainly depends on microbial degradation, and the water-holding capacity of tested soil is less than 60%. So, the estimated half-life of acetochlor is greater than 7.9 d[19,22], and the degradation time of 90% acetochlor should be greater than 26.24 d.

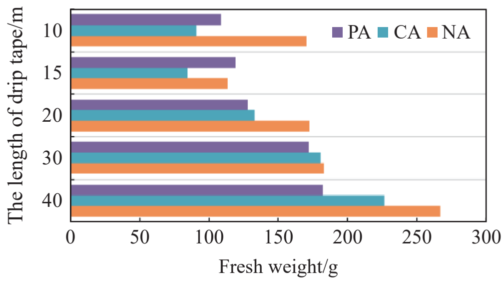


Figure 10 Average fresh weight of weeds at relative positions of different drip irrigation zones

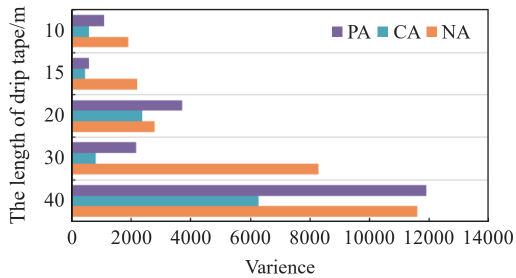


Figure 11 Variance of fresh weight of weeds at relative positions of different drip irrigation zones

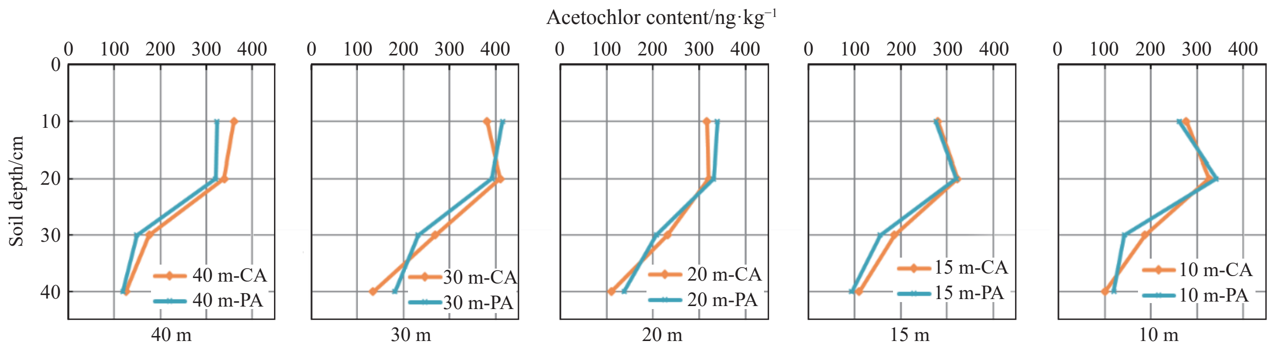


Figure 12 Acetochlor residues in different depths of soil layers

After 30 d of application, the soil was taken and the residual acetochlor in the soil was determined by liquid chromatograph, which was less than 10% of the original content, indicating that acetochlor had been completely degraded and would not pollute the soil environment. Acetochlor residues are listed in Table 5. The residual of the three application modes is all below 10%, indicating that the three application modes have no impact on the environment.

Table 5 Cumulative pesticide residues in soil

Length of drip irrigation tape/m	Application modes	Soil depth/cm				Cumulant/ ng·kg⁻¹	Residual ratio/%
		0-10	10-20	20-30	30-40		
40	CA	359.8	338.5	175.5	125.3	999.1	0.29%
	PA	322.8	320.0	148.9	118.5	910.2	0.26%
30	CA	381.2	409.9	269.3	133.9	1194.3	0.35%
	PA	414.7	392.2	231.5	181.4	1219.9	0.35%
20	CA	316.3	320.6	231.0	109.8	977.7	0.28%
	PA	339.7	331.0	206.8	137.4	1014.9	0.29%
15	CA	280.8	322.8	185.9	109.6	899.1	0.26%
	PA	276.7	320.4	155.6	93.6	846.3	0.25%
10	CA	276.3	325.7	187.0	100.2	889.2	0.26%
	PA	260.4	341.2	141.8	119.2	862.6	0.25%

4 Discussion

4.1 Maize leaf area index change

Figure 9 shows the changes in maize leaf area index (LAI) after acetochlor application at different growth stages. The overall LAI growth was roughly the same under different lengths and treatments. Leaf area index (LAI) increased first and then decreased slightly[23]. This is a normal growth phenomenon of maize at the mature stage. Maize transfers part of the nutrients supplied to the leaf surface to the grain to ensure its normal growth and development[4,5,24,25].

Although the overall changes of LAI were similar, the LAI peak value of continuous and periodic application was delayed significantly compared with those of no application. Leaf area index (LAI) peaked from July 17 to July 24 under no application mode and then decreased gradually. However, the peak value at different treatments and positions in drip irrigation zones appeared between July 24 and July 31 after applying herbicide. The delay of continuous application was greater. The reason for the delayed peak is that the herbicide inhibited the weeds growth and increased the available nutrients in the field, so the grain reduced the need for leaf nutrients. This also indirectly proved the herbicidal effect and the promotion effect on maize growth of acetochlor.

However, the delayed peak value did not occur in the middle of the drip irrigation zone under the periodic application. For example, the overall change in 30 m length drip irrigation tape was the same. With continuous application, the maize leaf area index measured at the beginning, middle, and tail of the drip irrigation tape all had varying degrees of peak value backward. However, under periodic application, the peak value in the middle of 30 m drip irrigation tape did not change backward. This is due to the self-irrigation characteristics of the periodic application. The periodic application mode is produced by drawing on the pulse irrigation method, which would produce a wave-like pulse flow inside the drip irrigation tape[23]. In addition, the long drip irrigation tape leads to insufficient mixing of herbicide and irrigation water, resulting in worse uniformity at different locations of the drip irrigation tape. Therefore, the phenomenon of the large difference in LAI occurred at different locations.

4.2 Quantitative relationship between drip irrigation tape length and application duration after the dosage introduction

Section 3.1 has illustrated the minimum application duration of different drip irrigation tapes based on uniformity. The field trial application duration was set according to the results obtained in the laboratory experiment. To laterally test the model (without introducing total dose required, *W*) obtained from the laboratory experiment, part of the data (fresh weed weight, dry matter weight, and daily leaf area index (LAI) of maize) obtained from the field experiment was substituted into the model. The validation results are shown in Figure 13. The accuracy is only between 0.6 and 0.7.

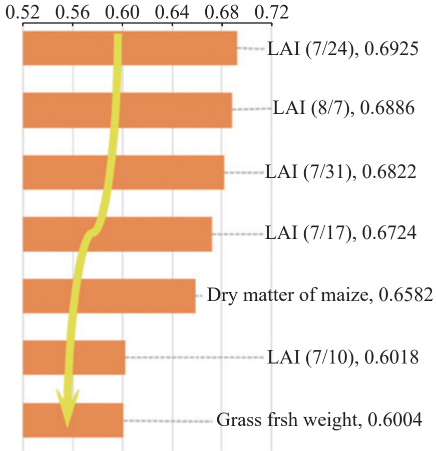


Figure 13 Model (without W) validation with field data

So, we try to introduce the dosage (W) into the model to improve the accuracy. Dosage is an important factor that must be considered in actual fieldwork. During application, the amount of acetochlor applied at the end was usually lower than that at the head. Therefore, to meet the requirement of minimum dosage, the whole application process was divided into three parts (as shown in Figure 14) according to the liquid migration at the sample points at the tail of each drip irrigation tape: T_1 is the duration for the liquid concentration to reach the normal level from the beginning of application at the last sampling point; T_2 is the duration for the liquid concentration maintained at the normal level at the last sampling point; T_3 is the duration for the liquid concentration to drop from normal concentration to 0 after application at the last sampling point; T_4 is a special period contained in T_2, which is the duration for the liquid detected at the normal concentration at the last sample point after turning off the fertilizer.

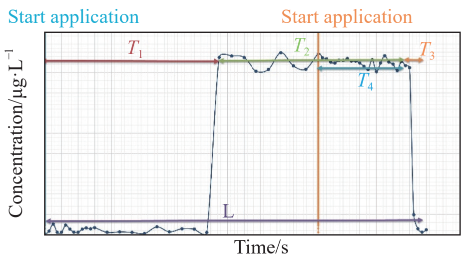


Figure 14 Application process division of drip irrigation tape

According to the multivariate independent Frideman analysis (p=0), which is less than the significance level. Therefore, it can be considered that the length of drip irrigation tape has a significant influence on the acetochlor concentration at the sampling points at different locations over time. IBM SPSS 22 was used to perform a fitting analysis on the duration of the liquid propelling process at each sampling point and the length of drip irrigation tape, and the results show that the duration is related to the hydraulic performance of drip irrigation tape used in chemigation:

$$T_1 = 5.2586L + 4.0517(R^2 = 0.987) \tag{1}$$

$$T_2 = W/(\alpha P^x) \tag{2}$$

$$T_3 = 2.7845L - 0.0431(R^2 = 0.9234) \tag{3}$$

where, α is the characterization coefficient, α=3600·C·k; x is the flow index; k is the discharge coefficient; P is the work pressure, MPa; W is the total dose required, g; C is herbicide concentration, g/L.

As the concentration changes rapidly in the drip irrigation tape, it can be considered that the application dosage goal is mainly reached at T_2. T_2 can be determined by the dosage to be satisfied and the liquid concentration. The normalized residuals satisfy the Gaussian distribution. The fitting degree is high, and the model autocorrelation residuals are small. p (0.020) is less than the significance level of 0.05, so it can be confirmed that under the same application dosage, the length of drip irrigation tape has a very significant explanation for the optimal application duration.

The final result obtained after the total application dose is introduced is different from the result without the application dose (Table 6). In the field application, the application uniformity should be improved based on meeting the basic application dosage requirements. Therefore, a larger value should be taken between the results of the two calculation models.

Table 6 Optimal application schedule for drip irrigation tapes of different lengths

Length of tapes/m	Calculated application duration without W/s	The application duration with W/s	Final results/s
10	211.05	302.53	302.54
15	322.72	315.85	322.72
20	431.96	326.29	431.96
30	435.60	355.88	435.60
40	548.80	377.77	548.80

It should be noted that acetochlor and its metabolites may cause serious health and environmental problems, such as cancer, genetic diseases, reproductive disorders, and aberrations. However, according to the research results, the advance of herbicide in drip irrigation tape is related to the hydraulic characteristic of drip irrigation tape and has no relationship with the herbicide type and the location. Therefore, the research results and optimal applying duration model can still be used in other herbicides.

Based on the establishment of the optimal applying duration model, although some results have emerged, there are problems that need further study: (1) the estimation model and regression coefficient of different pesticides have not been verified. (2) The range of models with different kinds of drip irrigation tapes, the placement mode, and the working pressure need to be expanded.

5 Conclusions

The rational use of pesticides is an urgent problem in China. Based on the environmental and crop effects, the pesticide application model was discussed. The results showed that continuous application could effectively remove weeds, delay leaf senescence and promote crop growth. In addition, under continuous application, LAI changes at different positions in the drip irrigation area were minimal, indicating good application uniformity. The yield and double ear rate of maize were significantly increased after continuous application, so it was considered to be a more suitable way of chemigation.

The distribution and migration of potassium permanganate and acetochlor were the same during irrigation. The results showed that the pesticide migration was determined by the drip irrigation tape used and was related to the hydraulic characteristics of it. And the concentrations and cumulative doses of potassium permanganate and acetochlor were the same at each sampling point. It is proved that potassium permanganate is feasible to replace acetochlor in irrigation experiments, which not only saves cost but also avoids harm to researchers. After the model was determined, the optimal chemigation duration in 40 m, 30 m, 20 m, 15 m, and 10 m drip irrigation tape was 302.54 s, 322.72 s, 431.96 s 435.60 s, 548.80 s, respectively. It also lays a foundation for improving the chemigation uniformity and promoting the rationality of pesticide application.

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