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Article

Magnetic field as an environmentally friendly tool increases the effectiveness of pesticides: A case study of acaricide spirodiclofen against *Tetranychus urticae* (Acari: Tetranychidae)

Behnam Nezhadakbarimahani[1], Aurang Kavousi[1*], Jaefar Nikbakht[2] and Mohammad Hossein Rasoulifard[3]

1. *Department of Plant Protection, Faculty of Agriculture, University of Zanjan, Iran; E-mails: behnam.mahani@gmail.com, akavousi@ znu.ac.ir*
2. *Water Engineering Department, Faculty of Agriculture, University of Zanjan, Iran; E-mail: nikbakht.jaefar@znu.ac.ir*
3. *Department of Chemistry, Faculty of Sciences, University of Zanjan, Zanjan, Iran; E-mail: m_h_rasoulifard@znu.ac.ir*

[*] Corresponding author

ABSTRACT
Applying reduced doses of pesticides has advantages such as resistance management, environmental pollution reduction, and control costs. Very few studies show that passing the water used for pesticide applications through a magnetic field can improve the pesticides' efficiency. In this study, the effect of a magnetic field on the acaricidal activity of spirodiclofen was evaluated against *Tetranychus urticae*. Treatments included distilled water and well water for preparing the suspensions after passing through a constant magnetic field of 0.42 Tesla. Furthermore, additional treatments were made by passing the prepared suspensions through the magnetic field. Mites were counted right before the sprays on days 7, 14, and 21. The treatment efficiencies were calculated by using the Henderson-Tilton formula. Except for 2 of 12 cases in which the efficiencies were negative, in the rest of the experiments, the magnetic field enhanced the efficiency of the studied acaricide. The highest values were recorded for two treatments including magnetizing the mixture of well water and acaricide treatment and magnetized distilled water plus acaricide treatment between days 7 to 21 (approximately 77 %). This study suggests the usefulness of magnetic fields as an environmental-friendly method to increase the effectiveness of the studied plant protection agent.

KEYWORDS: Chemical control, Henderson-Tilton formula, magnetic field, pest management, pesticide use reduction, water quality.

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INTRODUCTION

Magnetized water is commonly used in agriculture to improve crop yield in several ways (Sarraf *et al*. 2020). However, its use remains very little known in the field of plant protection. The water used as a diluent in chemical plant protection possesses properties that may negatively affect pesticide effectiveness in controlling pests. Among the various water properties, these factors encompass pH levels, water hardness (involving minerals such as calcium and magnesium in solution), and the presence of suspended soil particles, often referred to as "dirty water" (Tharp and Sigler 2013). The

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properties of the spray mixture can be modified by different types of chemical agents – adjuvants (Adamczewski and Matysiak 1997; Woźnica and Milkowski 1999; Wachowiak and Kierzek 2002) as well as by water conditioning installations (Orłowski and Dobromilska 1998). Evaluation of the effectiveness of a magnetic field in the modification of the chemical and physical properties of spray mixtures for a few pesticides for the control of red spider mite (*Tetranuchuse urticae* Koch) with four different acaricides (Magus 200 SC, Omite 30 WP, Ortus 05 SC, and Talstar 100 EC) and grain weevil (*Sitophilus granarius* (L.); Col.: Curculionidae) with Karate 025 EC, Sumi-Alpha 050 EC, Talstar 100 EC, and Winylofos 550 EC using different degrees of magnetized water has been studied in two separate experiments and the results in some cases were contradicting and the authors speculated that the differences were a consequence of a different polarity of applied magnetizers (Górski and Wachowiak 2004; Górski *et al*. 2009). The effect of magnetized water used to prepare a spray liquid on the effectiveness of plant protection agents was also observed by Wachowiak and Kierzek (2002). Karimi *et al*. (2012) also conducted some field trials to investigate the effects of magnetized water on improving the efficiency of some herbicides. Pest control effects of magnetized pesticides tested in greenhouse cucumbers showed different results with different magnetic field strengths (Shenga *et al*. 2013).

Considering the limited and scarce studies in this field, along with the presence of several variables that may impede the generalization of research results, further experimentation is required to substantiate the positive influence of magnetic fields in enhancing the effectiveness of pesticides. Consequently, this study aimed to address this gap by focusing on a pesticide that lacked previous similar investigations, thereby introducing an innovative aspect. Furthermore, the study conducted a simultaneous and comparative analysis using both well water with a high degree of hardness and distilled water. Importantly, the impact of the magnetic field on the water-pesticide mixture was also taken into account, a factor often overlooked in prior studies.

MATERIALS AND METHODS

Plants

A homogenous batch of clean-heathy red bean seeds (*Phaseolus vulgaris* cv. Naz) was obtained from Zanjan Provincial Bureau of Agricultural Research and soaked in water for 24 hours then planted in plastic pots (25 cm in diameter, 20 cm in height) filled with a mixture of five parts garden soil and four parts of sand and one part natural fertilizer and at the bottom of each container a layer of coarse gravel (16–32 mm) added for better air-circulation and drainage. Plants were maintained at 25 ± 1 °C, 65 ± 5% relative humidity (RH), and a 16:8 (L:D) h photoperiod. Two-spotted spider mites were obtained from a laboratory colony reared on *P. vulgaris* at University of Zanjan, Plant Protection Research Laboratory located in Zanjan, Iran. Mites were mass-reared on plants kept at the above mentioned conditions. Old mite-damaged plants were replaced with new bean plants when needed.

Treatments

The treatments of the present study were: **Water quality** at two levels including distilled water and well water; **Magnetic field** in three levels including: Passing the water through the magnetic field first and then preparing the pesticide mixture; preparing the mixtures of pesticide and non-magnetic waters first and then passing them through the magnetic field; and preparing the water and pesticide mixtures without crossing through the magnetic field (control treatments). Experiments were performed in three replications. (Górski and Wachowiak 2004; Górski *et al*. 2009). When the plants reached the trifoliate stage, 15 same-aged adult females were chosen and transferred individually with a fine paintbrush for each plant (five mites per leaf).

Different treatments used are shown by the following abbreviations: DWA (distilled water plus acaricide), WWA (well water plus acaricide), MDWA (magnetized distilled water plus acaricide), MMDWA (magnetized mixture of distilled water plus acaricide), MWWA (magnetized well water plus acaricide), MMWWP (magnetized mixture of well water plus acaricide).

Pesticide preparation

Spirodiclofen (Envidor® 240 SC) was used at the LC_{50} of 3.1 mg (a.i./liter) which was prepared in 400 mL total volume and contained 1.5 mL (commercially recommended dose) of a spreader adjuvant (PC GATE®). The adjuvant was used for uniform coverage of the pesticide application and as a result, the homogeneity of the results.

After preparing each treatment, the target pots were separated from the rest of the pots and the pesticide was applied in a separate room. The isolated pots were kept at that place for 15 minutes and then transferred to the original location. Spraying was done by a hand sprayer until the separation of the droplets from the leaves surface (run off) (Osborne 1984).

Magnetic field properties

To create a constant magnetic field of 0.42 Tesla, a magnetic water softener manufactured by Paya Iran Trade Company was used. The device consists of two fixed ceramic magnets of 4200 Gauss MF enclosed in a polyethylene tube of 50 mm in diameters. For preparing the treatments, according to the type of treatment, the mixed concentrations were passed through the magnetic field five times (considering the magnetic field series condition), at a moderate speed.

Tests procedure

Two weeks after planting the red bean seeds, the top leaves were trimmed and only three primary leaves per plant in a pot were kept. Then the plants were infested by five same-aged adult female *T. urticae* mites on each leaf (Pavela 2016). Seven days after infestation, the number of mites, except eggs, on each leaf was counted with the help of a hand magnifier with 40× magnification power (Benzi *et al*. 2009). Based on the particular treatment of pots, the applications were done afterward (Labanowska 2006; Pavela 2016). One week after the first application, the mites were counted again on each leaf, and then the pots were sprayed according to the protocol for the second time. Seven days after the second application, motile forms were counted for the last time.

Data analysis

To show the relationship between stimulus and response and calculate the percentage of impact, the efficiency formula of Henderson-Tilton was used:

$$Ef\ \% = \left[1 - \left(\frac{X_{iT}}{X_{iC}}\right)\left(\frac{X_{0C}}{X_{0T}}\right)\right] \times 100 \qquad (1)$$

where, X_{0C} and X_{0T} are the mean numbers of motile forms in unsprayed and treated plots before treatment, and X_{iC} and X_{iT} are the mean numbers of motile forms in unsprayed and treated plots at i^{th} assessment after treatment, respectively (Henderson and Tilton 1955).

The change in population density (CPD %) was calculated as follows (Marčić *et al*. 2012):

$$CPD\ \% = \left[\frac{(X_i - X_0)}{X_0}\right] \times\ 100 \qquad (2)$$

where, X_0 is the mean number of motile forms before spraying, and X_i is the mean number of motile forms at i^{th} assessment after spraying. Positive values imply an increase.

Minitab® 17.1.0 statistical software was used for the statistical analysis of the data. Analysis of variance was performed after the normality test in a completely randomized design and the means were compared using Tukey's test.

Physicochemical analysis

Changes in physicochemical contents after conditioning the suspensions were analyzed. Levels of pH, EC, and TH were recorded using the available facilities at the University of Zanjan, Mineral Chemistry Laboratory located in Zanjan. Results are presented in Table 1.

Table 1. Effect of magnetic field on physicochemical properties of treatments.

Treatments*	Factors				
	pH	EC† (µSiemens/cm)	TH‡ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)
DW	5.36	0	2	1	1
MDW	5.48	2	3	2	1
WW	7.78	2609	256	160	96
MWW	7.99	2490	260	115	145
DWA§	5.46	8	4	2	2
MDWA	5.86	3	8	4	4
WWA	7.83	2340	200	140	60
MWWA	7.92	2381	420	60	360
MMDWA	6.50	1	20	8	12
MMWWA	7.93	2527	880	420	460

*DW (distilled water), MDW (magnetized distilled water), WW (well water), MWW (magnetized well water), DWA (distilled water plus acaricide), MDWA (magnetized distilled water plus acaricide), WWA (well water plus acaricide), MWWA (magnetized well water plus acaricide), MMDWA (magnetized mixture of distilled water plus acaricide), MMWWA (magnetized mixture of well water plus acaricide). § The acaricide mixtures were composed of 3.1 mg/l A.I of 24 % commercial formulation of Spirodiclofen and 1.5 ml of a spreader adjuvant (PC GATE®) in the total volume of 400 ml. †EC – Electrical conductivity, ‡TH – Total Hardness

Electrolytic conductivity

EC was measured in µS/cm using Milwaukee EC59 Martiny's digital EC meter, which also measures TDS (Total dissolved solids) and temperature in °C or °F in addition to EC with automatic calibration all in a waterproof casing. The EC59 device shows the results on a dual-level LCD with a 3,999 µS/cm range of EC and data was recorded after the numbers were stabilized while holding the pen in different suspensions.

pH parameter

pH levels were determined using a high-precision laboratory bench pH meter (Sana model SL-901) with a measuring range of −1.999–19.999 pH and ± 0.01 pH accuracy level. Data were concluded after the numbers on the display in our electrochemistry device became stabilized.

Total hardness (TH)

Water hardness is defined as the measured content of divalent metal cations. Dissolved calcium and magnesium are the only two divalent cations found at appreciable levels in most waters. In determining TH levels using the titration method, first titration gives the results for calcium hardness and the second titration gives total hardness. The difference between these values is the magnesium hardness level.

RESULTS AND DISCUSSION

Physicochemical analysis

The physicochemical and biological properties of the water used in the application mixture can affect pesticide efficiencies (Górski *et al*. 2009). Magnetic activation of water may result in changes in its chemical properties (Chibowski *et al*. 2003).

In this study, some properties of the preparations used in the treatments were measured before and after passing through a constant magnetic field. Based on the results, a slight increase in the concentration of calcium ions in distilled water but a notable decrease (from 160 to 115 mg/l) in calcium ion content was found in well water without mixing with the acaricide (WW). On the contrary, the magnetic field caused an increase (from 96 to 145 mg/l) in the magnesium ion concentration of the well water (WW) (Table 1).

In general, according to the literature, the magnetic field does not cause significant changes in the chemical composition of water. A slight increase in iron (Fe) and a decrease in zinc (Zn) contents have been shown (Górski *et al*. 2009). Conversely, Coey and Cass (2000) have reported the decrease in iron and manganese concentration as the only significant change due to magnetic treatment. Pang and Deng (2008) relate the magnetized effects of water to factors such as the magnetized time, the intensity of the magnetic field, and the temperature of water.

Based on our results, the magnetic field generally increased pH levels. For EC, both increased and decreased records were obtained (Table 1). Fathi *et al* (2006) also observed that in the first 10 minutes of magnetizing the treatments maximum changes occurred and the magnetic field increased the pH level of water. The reports by Górski *et al.* (2009) and Górski *et al.* (2004) showed different results. They suggested that differences in results may be a consequence of a different polarity of applied magnetizers. We tested a novel hypothesis to see whether there are differences in the magnetic treatment of the “whole pesticide mixture preparation” in comparison with the magnetic treatment of the “only water used for the mixture”. Remarkably, both Ca and Mg concentrations increased when the whole pesticide mixture was treated by the magnetic field: for instance, the Ca concentration increased from 60 mg/l in “magnetized well water” plus acaricide treatment (MWWA) to 420 mg/l in “magnetized mixture of well water plus acaricide” treatment (MMWWA) (Table 1). As will be discussed later, there were significant differences in acaricidal activity due to the two different methods of treatment as well.

Acaricidal efficiency and population density change

The average number of motile mites in different treatments is shown in Table 2. According to the table, the pest population for three treatments of MDWA, MMDWA, and MMWWA showed a steady decrease over the experiment. Meanwhile, for the other three treatments population rates fluctuated after the applications. The two treatments of MMWWA and MDWA had the most negative effect on population rates; on day 21 of the experiment the population of motile forms had a statistically significant difference in comparison to the control treatments with the mean numbers of 43 and 45 per treatment, respectively. In the corresponding control treatments (WWA and DWA) the number of motile forms was 187 and 185, respectively.

The highest percentage for density change (−80%) was recorded for the MWWA treatment between days 7 to 21 and the lowest rate of change in population density (−0.89%) was observed in distilled water without magnetic field treatment (DWA). This value was −77 % for magnetized distilled water plus pesticide treatment (MDWA) at the same interval.

The efficiency comparison of different treatments at three-time intervals is shown in Table 3. The maximum and minimum treatment efficiency values were recorded for MMWWA in the third interval and MWWA in the first interval, with 77 % efficiency and −35 % efficiency, respectively.

In treatments diluted with distilled water, the efficiency was positive in all intervals, but for magnetizing the whole solution after preparation (MMDWA) we did not observe a significant change as we recorded for well water in the MMWWA treatment.

According to the literature reviews, it is shown that magnetization can affect pesticide efficiency in a positive way (Rao 2000; Górski and Wachowiak 2004; Górski *et al*. 2009; Rashed-Mohassel and Aliaverdi 2012; Abd El-Wahab 2016). In the present research, we observed analogous results that magnetic activation of water may change its chemical properties and affect the efficiency of the tested pesticide. However, in the treatment where we mixed the acaricide and magnetized well water (MWWA), the efficiency of the overall application within the intervals of days 7 to 14 and 7 to 21 was negative (Table 3).

Table 2. Population density of two-spotted spider mites during the experiment and percentage of change in population density within 7 days' intervals.

Treatments*	Mean number of mites motile forms†				Percentage of change in population density (CPD%)					
	Day 0	Day 7	Day 14	Day 21	(0–7)	(0–14)	(0–21)	(7–14)	(14–21)	(7–21)
DWA	15	187.00 ± 3.00[a]	245.7 ± 21.40[a]	185.3 ± 21.90[a]	1146.7	1537.8	1135.6	31.37	−24.56	−0.89
WWA	15	214.67 ± 6.89[a]	139.50 ± 44.50[ab]	187.00 ± 17.00[a]	1331.1	830.00	1146.7	−35.02	34.05	−12.89
MDWA	15	202.67 ± 8.76[a]	67.50 ± 2.50[b]	45.00 ± 3.00[bc]	1251.11	350.00	200.00	−66.69	−33.33	−77.80
MMDWA	15	232.67 ± 27.00[a]	217.33 ± 17.00[a]	158.67 ± 18.00[ab]	1451.11	1348.89	957.78	−6.59	−26.99	−31.81
MWWA	15	225.00 ± 12.70[a]	170.00 ± 24.00[ab]	218.33 ± 42.70[a]	1400.0	1033.33	1355.56	−24.44	28.43	−2.96
MMWWA	15	217.33 ± 1.45[a]	87.67 ± 6.06[b]	43.00 ± 3.46[c]	1348.9	484.44	186.67	−59.66	−50.95	−80.21

* DWA (distilled water plus acaricide), WWA (well water plus acaricide), MDWA (magnetized distilled water plus acaricide), MMDWA (magnetized mixture of distilled water plus acaricide), MWWA (magnetized well water plus acaricide), MMWWA (magnetized mixture of well water plus acaricide). † Mean number of motile forms per pot.
† Mean values followed by the same letters in each column indicate no significant difference ($P \leq 0.05$) according to the Tukey test.

Table 3. Efficiency percentage of treatments within three-time intervals.

Treatments*	Efficiency percentages calculated by Henderson-Tilton's formula (EF%)		
	d7–d14	d14–d21	d7–d21
MDWA	74.65	11.64	77.65
MMDWA	28.95	3.23	31.19
MWWA	−35.58	19.64	−11.39
MMWWA	25.99	69.31	77.29

* MDWA (magnetized distilled water plus acaricide), MMWWA (magnetized mixture of well water plus acaricide), MWWA (magnetized well water plus acaricide), MMDWA (magnetized mixture of distilled water plus acaricide)

We investigated the effect of a constant magnetic field of 0.42 Tesla on the efficiency of spirodiclofen diluted with two different water qualities. From the overall results obtained in this study, for the two treatments of MMWWA and DWA the efficiency levels increased significantly and the pest population rates were reduced significantly during the intervals as well (Table 3). Within the interval days 7 to 14 of the experiment, we observed the most reduction in population density of mites' motile forms for MDWA treatment by −66%. Meanwhile, during the same period, a 31% change in population density (CPD) was recorded for DWA treatment (Table 2). For the time period between the second application and day 21 of the experiment the highest change in the populations' rates was obtained from WWA treatment and the lowest for MMWWA treatment (Table 2); over the experiment, the lowest and highest percentage of change in populations density were observed in DWA (−0.89%) and MMWWA (−80%) treatments, respectively.

Many factors are involved in the effects of magnetization on water properties (Knez and Pohar 2005; Pang and Deng 2008) and various changes occur in treated water (Coey and Cass 2000; Pang and Deng 2008). Researchers who have reported the enhanced efficiency of pesticides due to using magnetized water, studied the water properties as well but not comprehensively. Górski *et al*. (2009), found increased efficiency of several pesticides by just changing the polarity of the magnetic device for the identical products. They found by physicochemical analysis of the water that there was no significant difference in the amount of Ca, Mg, Na, and Cl in magnetized water compared to ordinary tap water. Also, in their experiments, there were no significant changes in pH and EC levels but surface tension was increased by magnetic treatment. Despite Górski's experiments, Rashed-Mohassel and

Aliverdi (2012) reported a decrease in the surface tension of water after passage through a magnetic field. In addition to some commonly known changes in the properties of water due to magnetic fields, some strange phenomena such as the "irreversible effect of infrared absorption" have been reported (Pang and Deng 2008). Coey and Cass (2000) and Knez and Pohar (2005) showed that magnetic field influences the polymorph composition of $CaCO_3$ leading to increases in the aragonite/calcite ratio. Based on the literature, the properties of water under the magnetic field are not fully known (Coey and Cass 2000; Knez and Pohar 2005; Pang and Deng 2008). Besides, waters of different sources may have different responses to the field. Because of these facts, in the few studies on the efficacy of pesticides mixed with magnetized water, the mechanisms of improved performance of the treatments have not been discussed and shown. However, due to changes in the quality of water used for agriculture due to drought which itself is a result of climate change (Fallahati *et al*. 2020), and the importance of water quality-pesticide interactions (Klokocar Smit *et al*. 2002; Soares *et al*. 2020), studying the magnetic treatment as a safe method to enhance the pesticidal effect is suggested. In parallel with such studies, investigations to reveal the mechanism of positive effects of using magnetized water are suggested.

Due to variations in water composition, differences in the chemical structure of pesticides, diverse formulations (including formulation types and adjuvants used), as well as variations in the concentration of active ingredients among different formulations, it is not possible to generalize the impact of a magnetic field on the efficiency and effectiveness of all types of pesticides and formulations. Therefore, to endorse the use of a magnetic field, it is essential to conduct multiple studies involving various water types, pesticides, formulations, and even different types of pests. Furthermore, even if multiple studies confirm the significant impact of this technology on pesticide effectiveness, it is crucial to investigate the potential side effects of pesticides on non-target organisms when subjected to a magnetic field.

CONCLUSIONS

Results from this study indicate that magnetizing the application mixture could be more effective and this is a turning point for practically utilizing magnetic devices. However, the phenomenon of a positive effect of magnetic field on pesticides has not been fully investigated yet and it requires further studies with different plant protection agents and their proportions in the tank mixture. With more investigation in this area, we can solve some of the environmental pollution and pest resistance problems due to usage of high doses of pesticides, and reduce the subsequent health issues. By increasing the efficiency of treatments using a magnetic field as a clean source, we can avoid using high doses of plant protection agents that can cause pest resistance. Regarding the mechanism of the magnetic field effect, some authors considered only magnetizing the diluent but we observed a better performance for the treatment in which we passed the prepared mixture containing the acaricide (MMWWA) through the magnetizing device. Further multidisciplinary studies are required to understand the mechanism of action in magnetizing the treatments for different pesticides in controlling common pests. The negative effects of climate change on the quality of water used in agriculture makes this technique necessary in some regions.

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میدان مغناطیسی به عنوان ابزاری سازگار با محیط زیست اثربخشی آفتکش‌ها را افزایش می‌دهد: مطالعه موردی کنه‌کش اسپیرودایکلوفن علیه *Tetranychus urticae* (Acari: Tetranychidae)

بهنام نژاد اکبری ماهانی[1]، اورنگ‌کاوسی[1*]، جعفر نیکبخت[2] و محمدحسین رسولی‌فرد[3]

۱. گروه گیاه‌پزشکی، دانشکدهٔ کشاورزی، دانشگاه زنجان، زنجان، ایران؛ رایانامه‌ها: behnam.mahani@gmail.com، akavousi@znu.ac.ir

۲. گروه علوم و مهندسی آب، دانشکدهٔ کشاورزی، دانشگاه زنجان، زنجان، ایران؛ رایانامه: nikbakht.jaefar@znu.ac.ir

۳. گروه شیمی، دانشکدهٔ علوم، دانشگاه زنجان، زنجان، ایران؛ رایانامه: m_h_rasoulifard@znu.ac.ir

* نویسندهٔ مسئول

چکیده

کاربرد دزهای کاهش یافته آفت‌کش‌ها مزایایی مانند مدیریت مقاومت، کاهش آلودگی محیطی و کاهش هزینه‌ها دارد. مطالعات بسیار معدودی نشان می‌دهد که عبور آب مورد استفاده برای کاربرد آفتکش‌ها از میان میدان مغناطیسی می‌تواند کارایی آفت‌کش‌ها را بهبود ببخشد. در این مطالعه، اثر یک میدان مغناطیسی بر فعالیت کنه‌کشی اسپیرودایکلوفن علیه کنه تارتن دولکه‌ای *Tetranychus urticae* ارزیابی شد. تیمارها شامل آب مقطر و آب چاه برای تهیه سوسپانسیون‌ها پس از عبور از یک میدان مغناطیسی ثابت ۰/۴۲ تسلا بودند. همچنین، تیمارهای دیگری با عبور سوسپانسیون آماده از میدان مغناطیسی استفاده شدند. کنه‌ها بی درنگ پیش از سمپاشی‌ها در روزهای ۷، ۱۴ و ۲۱ شمارش شدند. اثربخشی تیمارها با استفاده از فرمول هندرسون-تیلتون محاسبه شد. به جز دو مورد از ۱۲ حالت که کارایی‌ها منفی بودند، در بقیه موارد میدان مغناطیسی باعث افزایش اثربخشی کنه‌کش شد. بیشترین مقادیر برای دو تیمار مخلوط آب چاه و کنه‌کش تحت تاثیر میدان مغناطیسی و آب مقطر تحت‌تاثیر میدان مغناطیسی مخلوط با کنه‌کش بین روزهای ۷ تا ۲۱ (کارایی حدود ۷۷ درصد) ثبت شدند. این مطالعه مفید بودن میدان مغناطیسی به عنوان یک روش سازگار با محیط زیست در افزایش اثربخشی کنه‌کش مورد مطالعه را نشان می‌دهد.

واژگان کلیدی: کنترل شیمیایی، فرمول هندرسون-تیلتون، میدان مغناطیسی، مدیریت آفات، کاهش مصرف آفتکش‌ها، کیفیت آب.

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