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ORIGINAL ARTICLE

Magnetized irrigation water: a method for improving the efficacy of pre-emergence-applied metribuzin

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Abstract

The yield of many crops can be increased by irrigating them with magnetically treated water (MTW). The aim of our research was to determine if the efficacy of a soil-applied herbicide such as metribuzin against weeds could be affected by MTW. A split-plot randomized complete block experiment was designed with two main plots, including potato (*Solanum tuberosum* L.) irrigated with equal volumes of MTW and non-MTW. Sub-plots were weedy control, weed-free control (hand-weeded), and pre-emergence application of metribuzin at 420 and 525 g a.i. · ha^{-1}. Generally, MTW induced the seed germination and vegetative growth of *Amaranthus blitoides* S.Watson and *Convolvulus arvensis* L., resulting in a reduction of the total tuber yield of potato from 1.47 to 1.18 kg · m^{-2}. MTW improved the efficacy of weed control strategies, resulting in an improvement of the total tuber yield and the water use efficiency of potato. The total tuber yield when metribuzin was applied at 420 g a.i. · ha^{-1} with MTW (3.51 kg · m^{-2}) was more than when metribuzin was applied at 525 g a.i. · ha^{-1} with non-MTW (2.76 kg · m^{-2}). It can be concluded that the use of MTW can be a safer crop production method by reducing the required dosage of metribuzin to control weeds. Considering the fact that the use of MTW without herbicide application increased the density of weed species, this method should be limited to a scenario where weeds can be effectively controlled.

Keywords: germination, herbicide, water use efficiency

Introduction

Potato (*Solanum tuberosum* L.) is a crop belonging to the Solanaceae family native to Central and South America. It is the world's fourth most important food crop after wheat, rice, and maize and it is commonly perceived as a fundamental source of carbohydrate in the diet of people (Zhang *et al*. 2017). Over the past decade, although world potato cultivation area has decreased from 18.1 million ha in 2008 to 17.5 million ha in 2018, an increase in production from 327.2 to 368.1 trillion kg tubers has occurred (FAO 2018). Thus, a shifting has occurred from extensive to intensive potato cultivation systems, relying on huge amounts of inputs such as water and herbicides. Since the world water crisis and the environmental side-effects of herbicides have a risk in terms of their impact on society, it is necessary to enhance the water use efficiency (WUE) of crops and the efficacy of herbicides against weeds.

The emergence of potato takes a relatively long time compared to weeds due to the deeper planting of tubers, resulting in a serious quality and quantity loss of tubers (Zimdahl 2004). This growth characteristic of potato in comparison to weeds can provide an excellent opportunity to use a non-selective post-emergence herbicide (diquat, glufosinate, glyphosate, and paraquat). Such herbicides have little or no activity in soil and burn down all emerged weeds before there is any emergence of sown potato. In addition to the above-mentioned herbicides and endothall used as a pre-harvest herbicide, there are 10 selective herbicides labeled for use in potato. Four post-emergence herbicides (clethodim, cycloxydim, rimsulfuron, and sethoxydim) and six pre-emergence herbicides (EPTC, linuron, metolachlor, pendimethalin, trifluralin, and metribuzin). The latter, metribuzin, is a soil or foliage acting herbicide used as a pre- or post-emergence treatment (Monaco *et al.* 2002). Such a wide window for metribuzin application in potato (from before planting to after emerging) has made it the most important potato herbicide to control a variety of grass and broad-leaved weeds. It can also be used selectively in sugarcane, tomato, and soybean.

Metribuzin acts by inhibiting photosynthesis at photosystem II. It is a weak basic herbicide with a relatively high water solubility of approximately 1220 mg $\cdot$ l^{-1} at 20°C (Monaco *et al.* 2002). Therefore, metribuzin (Zhang *et al.* 2014) and its metabolites (Kjær *et al.* 2005) are subject to considerable leaching in soils. This can be an example of endo-drift (the a.i. fallen into the target area, but leached). Thus, the leaching of an herbicide can not only pollute groundwater but also decrease herbicide efficacy (López-Piñeiro *et al.* 2013; Aliverdi and Borghei 2021). Shifting from extensive to intensive potato cultivation systems (FAO 2018) can presumably increase the use of metribuzin and intensify its non-target effects.

In Iran, metribuzin is commonly used as a pre-emergence herbicide at 525 g a.i. $\cdot$ ha^{-1} in potato. On the label, it says that if metribuzin is used as a pre-emergence herbicide, the required irrigation is to ensure the herbicide effect. Recently, a new irrigation technique using magnetically treated water (MTW) has been introduced to improve the yield in various potato varieties by up to 6.7% (Ahmed and Abd El--Kader 2016), 10.5% (Hachicha *et al.* 2016), 33.1% (Hozayn *et al.* 2016), and 34% (Abdel-Aziz *et al.* 2017). In this technique, water is magnetized by passing through an iron tube covered with a ring magnet, leading to some changes in the physical characteristics of water such as solvent capacity (Liu *et al.* 2019), conductivity (Grewal and Maheshwari 2011), evaporability (Toledo *et al.* 2008), surface tension (Rashed-Mohassel *et al.* 2009), pH (Fathi *et al.* 2006), and viscosity (Chang and Weng 2006). These changes in the physical characteristics of water can improve soil water holding capacity due to less evaporability of MTW (Surendran *et al.* 2016; Ali *et al.* 2017) and/or increased nutrient availability in soil due to the more solvent capacity of MTW (Hozayn *et al.* 2016) and the low nutrient leaching (Surendran *et al.* 2016), resulting in a better crop yield. However, the changed properties of water return to the original status 8 days after magnetization (Coey and Cass 2000).

All previous studies have focused on the effect of MTW on the yield of crops. To do this, the fields have been hand-weeded to provide an environment without weeds. As a result, there is no information as to how weeds respond to MTW under field conditions. Furthermore, it is not clear whether the efficacy of a soil-applied herbicide is affected by MTW or not. As a preliminary investigation, the current study was conducted to investigate the response of weeds to metribuzin in potato irrigated with MTW.

Materials and Methods

Experimental location

A 2-year field experiment was conducted in Qazvin, Iran (36°16′ N; 50°00′ E; 1279 m above sea level) in 2018 and 2019. The soil was a clay loam with 0.9% organic matter, 7.4 pH, and 1.45 dS m^{-1} electrical conductivity. The mean monthly air temperature and relative humidity during the growing seasons are presented in Table 1. In the third week of March of both years, after applying 22 kg $\cdot$ ha^{-1} P and 83 kg $\cdot$ ha^{-1} K, the field was plowed and then disked twice. In the first week of June of both years after applying 46 kg $\cdot$ ha^{-1} N, the field was harrowed and hand-planted with intact tubers of potato (*S. tuberosum* L. cv. Agria) with approximately 4 cm diameter and 50 g weight and a 20-cm planting distance on 75-cm-spaced rows at 15-cm depth. The tubers were chemically disinfected with pencycuron (Monceren 25% WP) at 3 g a.i. 10 $\cdot$ kg^{-1} tubers.

Experiment design and layout

The experimental layout was a split-plot arranged as a randomized complete block design with three replications. Water type was the main plot, weed control strategy was the sub-plot. Two main plots were: (I) non-MTW and (II) MTW. In each main plot, four

Table 1. The mean monthly air temperature and relative humidity in the growing season

	2018				2019			
	June	July	August	September	June	July	August	September
Air temperature [°C]	22.3	26.0	26.1	22.8	25.4	27.2	27.1	20.6
Relative humidity [%]	44.3	32.1	34.0	41.9	37.2	29.4	34.9	43.5

The long-term yearly precipitation is 343 mm at the experimental site. In both years, there was no rainfall event during the experiment sub-plots were: (1) weedy control (non-treated), (2) weed-free control (hand-weeded with a garden hoe in all growing season), (3) and (4) pre-emergence application of metribuzin (Sencor WP70%, Bayer CropScience, Germany) at 420 and 525 g a.i. · ha^{-1}, respectively. In other words, there were eight treatments arranged in two major fields, with four sub-plots each and replicated three times. A sketch of the experimental set-up is shown in Figure 1. Each sub-plot (3.75 × 4 m) had five east-west rows with 4 m length. Three rows for sampling and two rows for considering marginal effects were applied. Each sub-plot had 150 plants. The herbicide treatments were applied in 250 l of water · ha^{-1} at 300 kPa using a battery-operated knapsack sprayer equipped with an Albuz MVI-14502-VK Flood nozzle the next morning after planting. Then the first irrigation was done immediately. Air temperature and relative humidity at the time of herbicide application were 15°C and 54% in 2018 and 13°C and 48% in 2019, respectively. Based on a local calendar, the field was irrigated every 10 days in June, every 7 days in July and August, and again every 10 days in September using a surface drip irrigation system designed with two separate ports. One port was for the main plot of non-MTW and the other port was for the main plot of MTW. A control valve and a flow meter were installed at the inlet of each port. Water was magnetized after the flow meter at the inlet port of the MTW plot. To do this, a 1 inch magnetic water softener (Ansar Industrial Group 2019) 35 cm long and 0.68 Tesla magnetic field force was installed after the flow meter. A drip line was fixed on each row. The spacing between droppers was 20 cm and each had a discharge of 4 l · h^{-1} at 100 kPa. Each year, a total of approximately 5900 m^3 · ha^{-1} water was delivered to each main plot throughout the growing seasons. The amount of water applied to each sub-plot per irrigation event was approximately 34 mm.

Data collection

Fifty-five days after herbicide application, the weed species within four 0.25 m^2-quadrats placed systematically in each sub-plot (except for weed-free sub-plot duo to hand-weeding) were identified, counted, clipped about 0.5 cm above the soil surface, oven-dried at 70°C for 48 h, and weighed. The field was predominantly infested with redroot pigweed (*Amaranthus retroflexus* L.), prostrate pigweed (*Amaranthus blitoides* S.Watson), and field bindweed (*Convolvulus arvensis* L.). A very low density of puncture vine (*Tribulus terrestris* L.) and common saltwort (*Salsola kali* L.) was observed at the experimental site and therefore, they were not included in the analysis of data. One week before harvest, all the fields were treated with paraquat at 600 g a.i. · ha^{-1} (Gramoxone SL 20%, Syngenta, Belgium) in 400 l of water · ha^{-1} at 300 kPa using

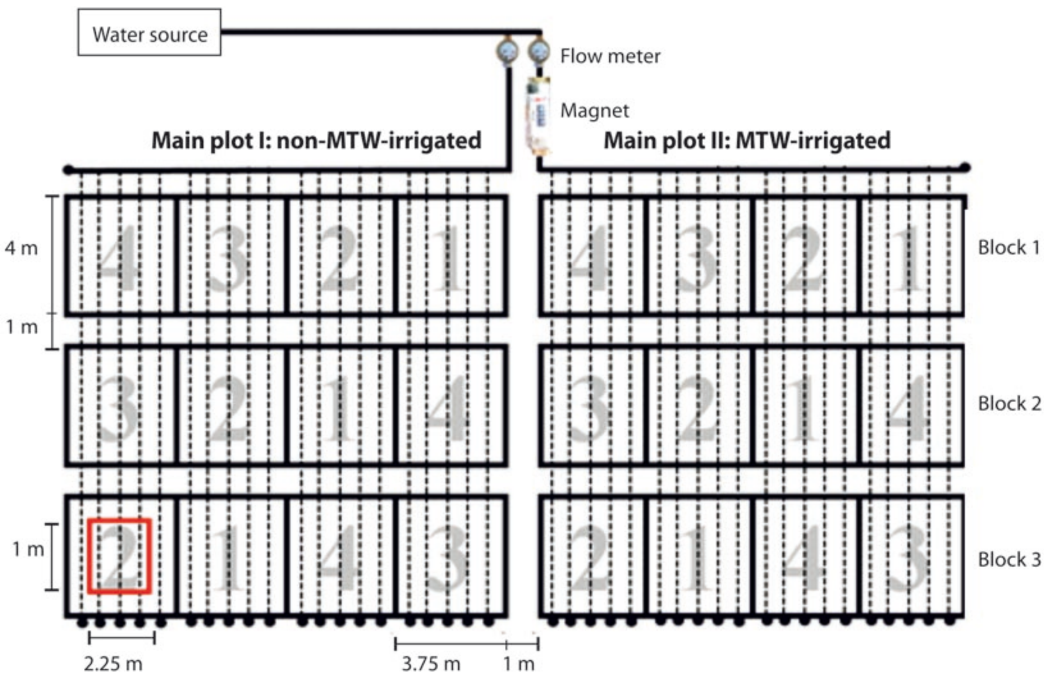

Fig. 1. A sketch of the experimental set-up. In each main plot, there were four sub-plots: 1 – weedy control (non-treated), 2 – weed-free control (hand-weeded in all growing seasons), 3 and 4 – pre-emergence application of metribuzin at 420 and 525 g a.i. · ha^{-1}, respectively. One harvested plot was 2 × 2.25 = 4.5 m^2

a battery-operated knapsack sprayer equipped with an ASJ TFS-11002-VP Flat Fan nozzle. In both years, the tubers were hand-harvested from 2 m of three central rows of each sub-plot and washed to remove soil in the fourth week of September. Then, the total tuber yield and the yield by grade ha^{-1} were determined for marketable No. 1 tubers weighing ≥113 g with no defects, marketable No. 2 tubers weighing ≥113 g with slight defects, undersized tubers weighing <113 g with no defects, and malformed tubers affected by soft rot with an area >2% of the tuber (Hutchinson *et al.* 2004). WUE ($kg \cdot m^{-3}$) was calculated as the total tuber yield ($kg \cdot ha^{-1}$) divided by the water application rate ($m^3 \cdot ha^{-1}$).

Statistical analysis

With checking normality data for each measured variable based on the Shapiro-Wilk statistical test, their normal distribution was stabilized ($1 > W > 0.9$). Thus, they were not transformed and subjected to analysis of variance (ANOVA) using PROC MIXED in SAS software version 9.4. Then, the data for the 2 years were pooled together to analyze as one with six replications because repetition was not significant. When an *F*-test showed statistical significance for the simple main effects (water type and weed control strategy), their means were separated by Fisher's Least Significant Difference (LSD) test at the 0.05 probability level.

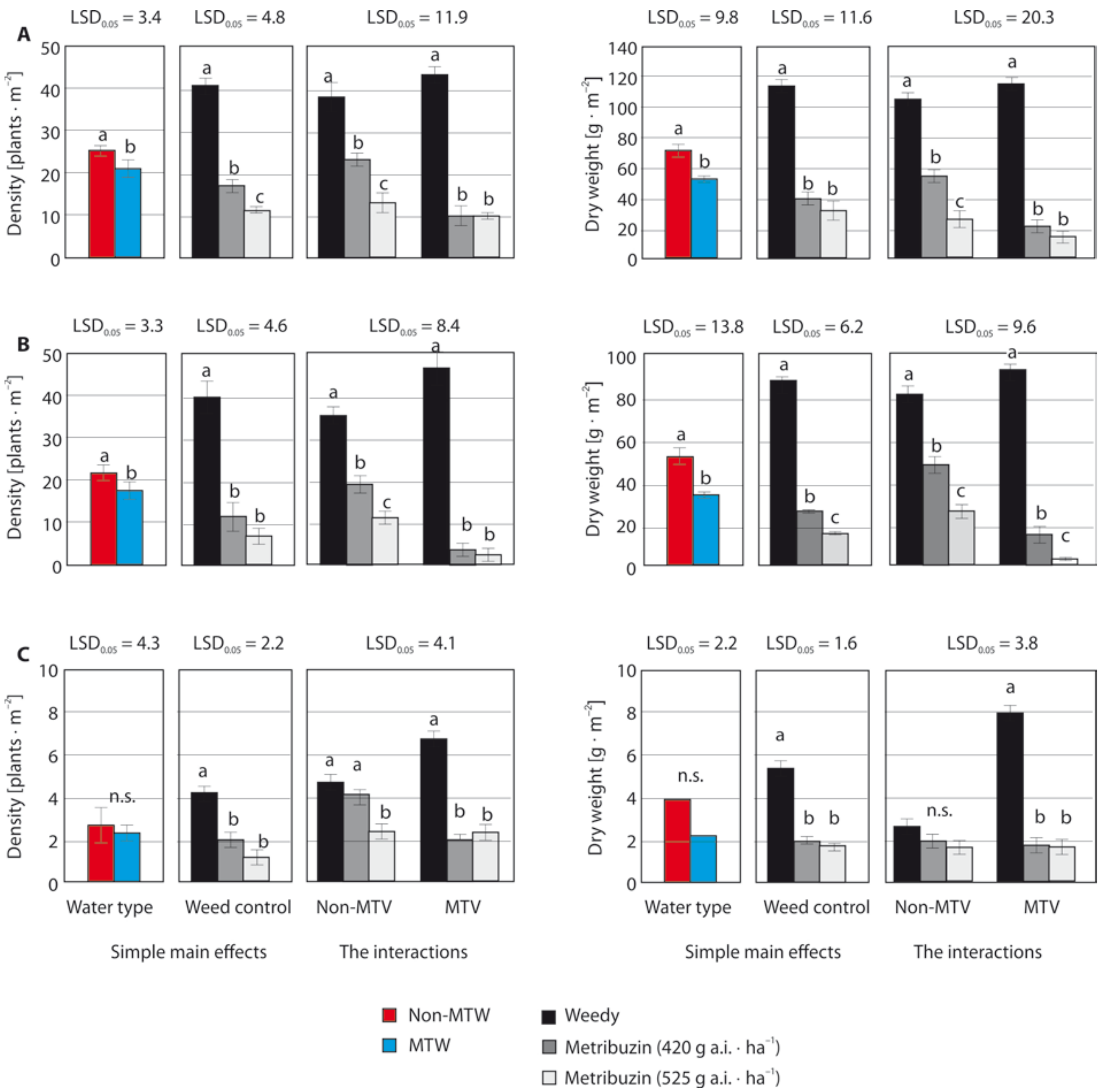

Fig. 2. A – the density and dry weight of *Amaranthus retroflexus*, B – *Amaranthus blitoides*, and C – *Convolvulus arvensis* under weedy and pre-emergence application of metribuzin at 420 and 525 g a.i. · ha^{-1} conditions when the field was irrigated with magnetically treated water (MTW) or non-MTW. Statistics for each water type individually were obtained using the SLICE option of PROC MIXED in SAS. Bars labelled with the same letter are not significantly different ($p < 0.05$)

Moreover, when an *F*-test showed statistical significance for the interaction of water type × weed control strategy, the means of each weed control strategy level within each water type level were separated using the SLICE option.

Results and Discussion

ANOVA showed that among three weed species, the density and dry weight of *A. retroflexus* (Fig. 2A) and *A. blitoides* (Fig. 2B) were significantly affected by the simple effect of water type. The density and dry weight of all three weed species were significantly affected by the simple effect of weed control strategy (Fig. 2A–C). The interaction of water type and weed control strategy was significant for the density and dry weight of all three weed species (Fig. 2A–C). The slicing of the data across water type showed that under weedy conditions, the density of *A. blitoides* and the dry weight of *A. blitoides and C. arvensis* were significantly higher in MTW-irrigated plots (II_1 treatment) than in non-MTW-irrigated plots (I_1 treatment). This led to a greater reduction in the total tuber yield (Fig. 3E); 68.2% loss with MTW as compared to weed-free sub-plot (II_2 treatment), but 52.1% loss with non-MTW as compared to weed-free sub-plot (I_2 treatment). These results indicated that the competitiveness of weeds with potato increased with MTW. It is well-reviewed by Teixeira da Silva and Dobránszki (2014) that MTW can induce seed germination and vegetative growth in various crops (such as celery, cowpea, flax, maize, pea, snow pea, and wheat). In other laboratory studies, it was established that the seed of *Amaranthus tricolor* L., *Amaranthus gangeticus* L., *Amaranthus blitum* L. (Krishnaraj *et al.* 2017), *Brachiaria decumbens* Stapf (Carbonell *et al.* 2004), *Pinus tropicalis* Morelet (Morejón *et al.* 2007), *Oryza sativa* L. (Flórez *et al.* 2004) can be induced to germinate by treatment with MTW. In a greenhouse study, Alkassab and Albach (2014) reported that the plant height, leaf area, leaf number, and branch number plant^{-1} of field mustard (*Sinapis arvensis* L.) increased with MTW, resulting in a significant increase in seed yield plant^{-1}. The seedbank of weeds can be depleted more quickly if the seeds of weeds can be stimulated and then those germinated and emerged can be adequately controlled (Gallandt 2006). Since the emerged seedlings of three weed species in the field were significantly stimulated with MTW, the current results suggested that this novel irrigation technique may also be applied as a novel method to deplete weed seedbanks more quickly if the emerged seedlings can be effectively controlled.

In the non-MTW main plot, with the exception of the density of *C. arvensis* (Fig. 2C), increasing the dose of metribuzin from 420 to 525 g · ha^{-1} decreased significantly the density and dry weight of all three weed species (I_3 vs I_4 treatment; Fig. 2A and C). Whereas, in the MTW main plot, with the exception of the dry weight of *A. blitoides* (Fig. 2B), increasing the dose of metribuzin from 420 to 525 g · ha^{-1} did not impact the density and dry weight of all three weed species (II_3 vs II_4 treatment; Fig. 2A and C). When 420 g · ha^{-1} metribuzin was applied, the density of *A. retroflexus*, *A. blitoides*, and *C. arvensis* decreased with MTW compared to non-MTW (I_3 vs II_3 treatment) from 23.3 to 10.6 m^{-2} (Fig. 2A), 18.6 to 3.6 m^{-2} (Fig. 2B), and 4.0 to 2.1 m^{-2} (Fig. 2C), respectively; while, the dry weight of *A. retroflexus* and *A. blitoides* decreased with MTW. These results indicated that when the field was irrigated with MTW, the efficacy of metribuzin was improved, resulting in a reduction in weed biomass, as well as an improvement in the quality and quantity of tubers (Fig. 3A–E). When 525 g · ha^{-1} metribuzin was applied, only the density and dry weight of *A. blitoides* were significantly decreased by MTW-irrigation (I_4 vs II_4 treatment; Fig. 2B). It was clearly seen that the efficacy of 525 g · ha^{-1} metribuzin to reduce the density and dry weight of all weed species when the field was irrigated with non-MTW was significantly similar to the efficacy of 420 g · ha^{-1} metribuzin when the field was irrigated with MTW. In a previous study, Surendran *et al.* (2016) measured soil moisture at 0–40 cm depth after the 1st and 3rd days of drip irrigation with MTW and non-MTW and reported that soil moisture at all depths was significantly higher with MTW than non-MTW. Considering the fact that the higher viscosity of MTW has already been shown by Chang and Weng (2006), Surendran *et al.* (2016) concluded that the water molecules are more cohesive after passing through a magnetic field. Consequently, the water molecules can attach to soil particles firmly, resulting in a significant decrease in the amount of water passing down through a soil profile. The leaching of an herbicide is defined by Zhang *et al.* (2014) as the downward movement of an herbicide dissolved in water through a soil profile. Principally, one factor affecting the leaching of herbicides is the amount of water passing down through the soil profile. Although the leaching of metribuzin was not studied in the study, I hypothesized that the soil depth to which metribuzin is leached might be decreased by MTW as a result of a reduction in the amount of water passing down through the soil profile. Therefore, more herbicide molecules probably remain in the soil surface layers, resulting in increased activity of metribuzin against weeds. However, more research is required to verify our hypothesis.

ANOVA showed that the tuber yield in all grades (Fig. 3A–D) and the total tuber yield (Fig. 3E) were significantly affected by the simple main effects (water type and weed control strategy). Moreover, the interaction effect between them was significant. The slicing

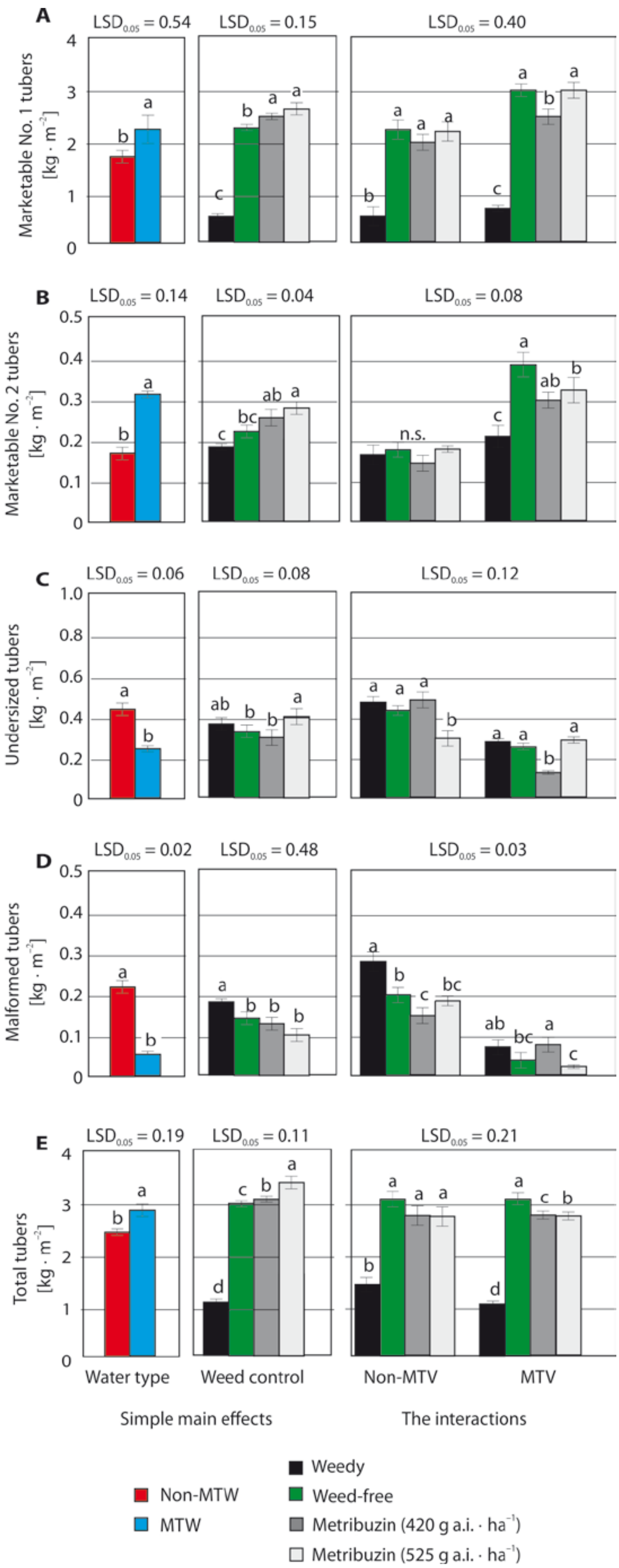

Fig. 3. The qualitative and quantitative yield of potato tubers under weedy, weed-free and pre-emergence application of metribuzin at 420 and 525 g a.i. · ha^{-1} conditions when the field was irrigated with magnetically treated water (MTW) or non-MTW. Marketable No. 1 tubers weighing ≥113 g with no defects, No. 2 tubers weighing ≥113 g with slight defects, undersized tubers weighing <113 g with no defects, and the surfaces of malformed tubers were affected by soft rot >2%. Statistics for each water type individually are obtained using the SLICE option of PROC MIXED in SAS. Bars labelled with the same letter are not significantly different ($p < 0.05$)

of the data across water type showed that in the non--MTW main plot, there were no differences in the total tuber yield obtained from the sub-plots of weed-free (I_2 treatment) and metribuzin at both doses (I_3 and I_4 treatments). Whereas, in the MTW main plot, the total tuber yield in the weed-free sub-plot (II_2 treatment) was more than in the sub-plots with metribuzin at both doses (II_3 and II_4 treatments). At both herbicide doses, a significant increase in total tuber yield occurred when the field was irrigated with MTW due to the increased activity of metribuzin against weeds (Fig. 2A–C). Moreover, under weedy conditions, the total tuber yield in MTW-irrigated plot (1.18 kg · m^{-2}) was less than in non-MTW-irrigated plot (1.47 kg · m^{-2}) (II_1 vs I_1 treatment; Fig. 3E). In contrast, under weed-free conditions, the total tuber yield in MTW-irrigated plot (3.72 kg · m^{-2}) was more than in non-MTW-irrigated plot (3.07 kg · m^{-2}) (II_2 vs I_2 treatment). The results showed that there is a tendency for the MTW-irrigated treatments to give higher yields. On the other hand, the more the herbicide dose, the better the weed control. A similar trend for marketable No. 1 and 2 tuber yields was also observed. The quantity of potato tubers (marketable No. 1, 2, and total tubers), when a weed control strategy was applied, was more with MTW--irrigation than with non-MTW-irrigation. Moreover, the results clearly showed that the quantity of tubers in potato when metribuzin was applied at 420 g a.i. · ha^{-1} with MTW was more than when metribuzin was applied at 525 g a.i. · ha^{-1} with non-MTW. Under all weed control strategies, a significant decrease in undersized tubers yield occurred with MTW-irrigation. A similar trend for malformed tubers yield was also observed, except with metribuzin application at 525 g a.i. · ha^{-1}. Generally, these findings indicate that an improvement in the quality of potato tubers (undersized and malformed tubers) occurred when the field was irrigated with MTW (Fig. 3C and D). Perhaps, this finding might be related to better control of weeds (Fig. 2A–C) and/or soil pathogens. To date, the efficacy of any herbicide had not been tested with MTW. It has already been shown that the quality of crops can be improved with MTW. Abdel-Nabi *et al*. (2019) demonstrated that garlic irrigated with MWT can be less tainted by soil pathogens (*Pseudomonas* sp., *Rhizoctonia* sp., and *Fusarium* sp.) than garlic irrigated with non-MWT.

ANOVA showed that the WUE of potato was significantly affected by the simple main effects of water type and weed control strategy. Moreover, the interaction effect between them was significant. Although an equal amount of water was delivered to each sub-plot, the total tuber yield of potato obtained was different (Fig. 3E). This indicates that there was a significant difference in the WUE of potato between treatments. Under weedy conditions, the WUE of potato in MTW--irrigated plots (2.0 kg · m^{-3}) was less than in non--MTW-irrigated plots (2.5 kg · m^{-3}). While, in the hand-weeded sub-plots, the WUE of potato irrigated with MTW (6.3 kg · m^{-3}) was more than with non-MTW (5.2 kg · m^{-3}). Moreover, when metribuzin was applied at both doses, the WUE of potato was improved with MTW. Previous studies indicated that the WUE of potato (Ahmed and Abd El-Kader 2016; Hachicha *et al*. 2016; Hozayn *et al*. 2016; Abdel-Aziz *et al*. 2017) was improved with MTW. The improvement observed in the WUE of potato irrigated with MTW can most likely be attributed to an improved soil water holding capacity (Surendran *et al*. 2016; Ali *et al*. 2017) due to less evaporability of MTW (Toledo *et al*. 2008) and/or an improved availability of soil nutrients (Hozayn *et al*. 2016), especially in the case of phosphorus (Noran *et al*. 1996), due to the more solvent capacity of MTW (Liu *et al*. 2019).

Conclusions

Based on the current results, the use of MTW can be an acceptable method to produce a safer and more marketable crop. In fact, it has no side-effects and can even reduce the dosage of metribuzin. It can also improve the WUE in potato. Moreover, the use of MTW can improve the quality of tubers in potato. However, it should be noted that the use of MTW can also increase the density of weeds in the field. Therefore, the use of MTW should be limited to a scenario where weeds can be effectively controlled. More studies are needed to make it possible to make general conclusions about other soil-applied herbicides.

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