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Co–application effect of herbicides and micronutrients on weeds and nutrient uptake in flooded irrigated rice: Does it have a synergistic or an antagonistic effect?

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ABSTRACT

In submersed rice fields, weeds are considered the main source of nutrients removal. Hence, reduction in yield and grain quality is realized. Thus, a two–year field experiment was performed to find out the best cooperative effect between herbicides and micronutrients for controlling rice weeds with yield in mind. Two herbicides (halosulfuron–methyl and bentazone) and three micronutrients (Fe, Mn and Zn) were arranged in a strip plot design with three replicates. Results exhibited that in plots treated by halosulfuron–methyl, the control treatment (without fertilizing) showed the maximum reductions in weed N, P and K uptake, however, it statistically equaled Fe and Mn treatments in weed N uptake and Mn, Fe and Zn treatments in weed K uptake. With controlling weeds by halosulfuron–methyl herbicide, Zn treatment was as similar as Fe and Mn treatments for increasing plant height, straw yield and grain yield of rice. The interactions of halosulfuron–methyl x Zn treatment (for N and P in rice grain) and halosulfuron–methyl x Zn or Fe treatments (for P in rice grain) had synergistic effects. Moreover, the highest increases in Fe, Mn and Zn contents in rice grains were recorded with halosulfuron–methyl plus Fe, Mn and Zn treatments, respectively. In conclusion, rice producers should be aware of the synergism and co–operative effects between herbicides and micronutrients. The synergistic effect could be exploited for reducing the hazardous impacts of weeds, and hence, it raises yield potentiality and quality.

1. Introduction

There is no doubt that the micronutrients such as iron (Fe), manganese (Mn) and zinc (Zn) are so important for people's health around the world. Lack of proper human nutrition are mainly caused by not having enough Fe and Zn (Welch and Graham, 2004). Human acquire such nutrients from different food sources, especially plant ones. In this respect, rice (*Oryza sativa*) is the prime food and supplies energy to almost half of the world's population, and this reality reflects the significance of rice in terms of food security. Among cereal crops, rice occupies the first rank for providing world's dietary calories (FAO, 2020). Rice constitutes the fundamental source of Zn in nourishment in developing countries (Cakmak, 2012). Rice grains contain about 4–24 mg Fe kg^{-1} and 14–58 mg Zn kg^{-1} according to the genotype (Gregorio, 2002). However, the intensive agriculture and agrochemical misuse resulted in micronutrient deficiencies (NAAS, 2018; Kopittke et al., 2019). Besides macronutrients, the micronutrients also are so significant for rice growth and development. In this regard, foliar spraying of Fe was exploited to improve available Fe and crop productivity (Mahender et al., 2019). Since the photolysis of H_2O molecules is catalyzed by Mn, the photosynthesis is enhanced by Mn supply (Millaleo et al., 2010) and could maintain leaf greenness level, causing an increase in rice yield potential (Timotiwu and Dewi, 2014). Because of the pivotal act of Zn in numerous physio–biochemical and metabolic pathways (Broadley et al., 2007), positive correlations among the availability of Zn in soil and rice plant biomass, Zn uptake, and Zn concentration were reported (Seth et al., 2018). Accordingly, supplying rice plants with proper amounts of Fe, Mn and Zn is a crucial action for sustaining crop productivity and quality.

On the other hand, in flood irrigation system, rice plants are subjected to biotic stress due to the presence of undesirable plants, i.e. weeds. Weed infestation is one of the most severe issues in rice which caused yield losses. If weeds are not properly controlled, they capture distinctive amount of nutrients, which result in significant loss of yield

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and economic returns. In this regard, weeds removed approximately 367.8, 220.0 and 291.0% of N, P and K from rice field (Raj and Syriac, 2017). Because of weed competition with rice for moisture, nutrients, light and space, about 50.4–80.0% reduction in grain yield was manifested (Mahajan and Chauhan, 2015; Parthipan and Ravi, 2016) and reduced benefit cost ratio by 60.7% (Riaz et al., 2018). Although the application of herbicides may cause pressure on the crop plants, their use is inevitable. Herbicide–based weed control is the best applicable choice for weed management programs in rice due to labor scarcity with high wage rate (Singh et al., 2006). Moreover, tested herbicides application in rice remarkably suppresses the growth of broad–leaved weeds (Dangol et al., 2020; Kaur et al., 2019).

Accordingly, fertilizer application and weed control practices should be managed in a good manner in crop management. However, relaying on herbicide and crop species, the use of fertilizer with herbicides can perform either negative or positive action on their strength (Bernards et al., 2005). In this context, no reduction in herbicidal efficiency was obtained as a result of the concurrent use of fertilizers (copper, iron, manganese and magnesium) and herbicides (Makvandi et al., 2007). Adding manganese to herbicide solution of glyphosate caused reduction in controlling several weed types (Bailey et al., 2002; Bernards et al., 2005). A synergistic influence on crop yield could be achieved due to integrated effect of herbicide and nutrient applications (Gauvrit, 2003). Unlike, mixing nitrogen and boron with glyphosate did not possess baneful effect on growth target weeds (Scroggs et al., 2009).

Nevertheless, knowledge about co–application of rice herbicides and plant micronutrients effect on weed control is so limited. The controversy about the type of interference (synergism or antagonism) between herbicides and nutrients is one of the major concerns in rice production. Also, crop safety to combination of herbicides and micronutrients is another concern. The current study hypothesizes that plant nutrition and herbicide application may have interactive impacts on weed growth and rice yield. Therefore, our current research aimed to [(a)] assess the relation between the micronutrient type and the efficiency of herbicide against weeds, and [(b)] evaluate rice yield performance and grain nutritional status to three micronutrients in combinations with two herbicides.

2. Materials and methods

2.1. Site attributes

Plants of rice (*O. sativa*) cv. Giza–178 were grown in field under flooded conditions at the Experimental Research Station, Agricultural Research Centre, Dakahlia Governorate, Egypt, (31° 36″ N, 30° 57″ E), during the growing seasons of 2015 and 2016 (from May, 15th to September, 20th). The experimental soil at the research location comprised of 17.0% sand, 15.8% silt and 67.2% clay. Moreover, the soil solution had pH of 7.8, EC of 2.8 dS m^{-1} as well as the available N, P and K were 31.0, 8.60 and 520.0 mg kg^{-1}, respectively. According to US Soil Taxonomy (Soil Survey Staff, 1999), the soil is characterized as Typic Torriorthents. The means of weather parameters such as air temperature, wind speed, relative humidity and solar radiation were 29.7 and 28.3 °C, 4.35 and 4.27 m s^{-1}, 56.1 and 65.4% and 28.1 and 27.2 MJ m^{-2} day^{-1} in 2015 and 2016 seasons, respectively.

2.2. Agronomic practices

Before land preparation, the soil ploughed two times. Prior to the last plough, single calcium superphosphate (15.5% P_2O_5) at a rate of 160 kg ha^{-1} and the first portion of ammonium sulfate (20% N) at a rate of 160 kg ha^{-1} were added as basal. After that, the field land was leveled and divided into plots with size of 16 m^2 (4 m × 4 m). Then, as commonly practiced locally, the plots were filled by irrigation water with a layer of 5–7 cm and rice seeds at a rate of 130 kg ha^{-1} were distributed in water on 15 Ma y in both seasons. Irrigation program was applied along the growth period of rice as alternating between watering for along 4 days and drainage for along 6 days. At 30 and 50 days after sowing (DAS), rice plants received the second and third portions of ammonium sulfate (160 kg ha^{-1} for each), respectively. The field was submerged under a water layer of 5–10 cm according to the growth stage. Water was drained from the field two weeks before harvesting.

2.3. Experimental treatments

The performance of weeds and rice were investigated under three micronutrients [Fe, Mn and Zn, in addition to the control (without micronutrient application, tap water only)] as well as two herbicides [halosulfuron–methyl and bentazone, in addition to unweeded treatment (weeds were left over the entire period of crop growth)]. Fe (240 g ha^{-1}), Mn (240 g ha^{-1}) and Zn (2.4 kg ha^{-1}) in chelated form (EDTA, Ethylenediaminetetraacetic acid) were separately sprayed twice, at 40 and 55 DAS. Fe EDTA chelated 13%, Zn EDTA chelated 15% and Mn EDTA chelated 13% were produced by Van Iperen International, Netherlands. Halosulfuron–methyl (Inpul® 75% WG, Nissan Chemical Industries, Japan) at a rate of 48.0 g ha^{-1}, and bentazone (Basagran® 48% AS, BASF Chemical Co., Germany) at a rate of 3.6 L ha^{-1} were sprayed at 12 and 15 DAS, respectively. The herbicides and micronutrients were applied using a manual back−pack knapsack sprayer fitted with a flat-fan nozzle and calibrated to deliver 480 L water ha^{-1}.

2.4. Assessments

The abundant weed floras at the trial location were broad–leaved weeds comprising 55.5% of *Eclipta prostrata* and 44.5% of *Portulaca oleracea*. At 85 DAS weeds were surveyed and collected from a square meter of each experimental unit (plot) and air dried. After that, weed samples were oven dried at 70 °C till the constant weight to assess the dry weight. Moreover, N, P and K contents of weeds were estimated (Cottenie et al., 1982). Consequently, weed N, P and K uptake were computed by multiplying nutrient content by dry weight.

At full maturity stage (on 20 September in both seasons), rice crop was harvested manually from random spot (1 × 1 m) area per treatment. Crop traits, involved plant height, number of fertile grains $panicle^{-1}$, straw yield ha^{-1} and grain yield ha^{-1} (at 14% moisture), were measured.

Each of N, P and K content of rice grains were estimated (Cottenie et al., 1982) and their uptake were calculated by multiplying nutrient content by dry grain yield. Also, each of Fe, Mn and Zn in rice grains was extracted as described by Soltanpour and Schwab (1977). Extracted solution was determined against a standard using ICP instrument Prodigy 7. The ICP Specified by Optical Design High Energy EchellePoly chromator connected with a detector CMOS. The analytical wavelengths of Fe, Mn and Zn assessment were 259.940, 257.610 and 213.857 nm, respectively.

2.5. Experimental design and analysis

Treatments were distributed in a strip–plot in completely randomized block design in three replications applying the model presented in formula 1 (Casella, 2008). Prior to analysis of variance (ANOVA), the collected data were subjected to homogeneity test (Levene's test). Since the outputs proved that the homogeneity and normality of the data are satisfied for running further a 2–way ANOVA, the combined ANOVA for the data of the two seasons was performed. Costat software program, Version 6.303 (2004) was applied. Means separation was performed only when the F–test indicated significant ($P < 0.05$) differences among the treatments using Duncan's multiple range test (alphabetical letters).

$$Y_{ijk} = \mu + \tau_i + \beta_j + (\beta\tau)_{ij} + \gamma_k + (\beta\gamma)_{jk} + (\tau\gamma)_{ik} + (\beta\tau\gamma)_{ijk} + \varepsilon_{ijk} \ldots\ldots\ldots.(1)$$

Where:

Y_{ijk} is response, μ is overall mean effect, τ is the treatment, β and γ are the blocks, and $\beta_j \sim N(0, \sigma^2_{\beta})$, $\gamma_k \sim N(0, \sigma^2_{\gamma})$, $\varepsilon_{ijk} \sim N(0, \sigma^2_{\varepsilon})$, all independent.

{Assuming that the block factor to be random and the other factors to be fixed; independence between all errors}

3. Results

3.1. Effect of herbicides and micronutrients application on weed dry weight and weed nutrient uptake

As presented in Table 1, different herbicidal impacts on rice weeds between halosulfuron–methyl and bentazone were obtained. Halosulfuron–methyl was the superior for suppressing dry weight of *E. prostrate*, *P. oleracea* and total weeds as well as weed N uptake and weed P uptake. Halosulfuron–methyl caused 98.4, 90.8, and 90.5% reductions in total weed dry weight, weed N uptake and weed P uptake, respectively, compared to the unweeded. While, the counterpart reductions by bentazone were 91.9, 87.3 and 86.4%, respectively. Statistically, halosulfuron–methyl was as similar as bentazone in decreasing weed K uptake which amounted to 88.9% and, 86.8% reductions, respectively.

The lowest values of the studied weed traits were recorded with no fertilization (the control treatment). However, variations in *E. prostrate* dry weight of Fe, Mn or Zn treatments and *P. oleracea* dry weight of Mn treatment were not significant as compared the control treatment (Table 1). Moreover, total weed dry weight produced with Mn or Fe treatments as well as weed N uptake and weed K uptake obtained with Mn treatment were as similar as the control treatment. While, Mn treatment came in the second order after the control for recording the maximum reduction in weed P uptake. On the contrary, the highest values of dry weight of *P. oleracea* and total weeds as well as weed N, P and K uptake were observed with Zn treatment which statistically leveled with Fe and Mn treatments in all weed traits, except weed P uptake.

Concerning the interaction effect between herbicides and micronutrients, in unweeded treatments, application of Zn or Fe treatment (for dry weight of *E. prostrate*, *P. oleracea* and total weeds), Zn treatment (for weed N and P uptake) as well as Zn, Fe or Mn treatments (for weed K uptake) showed the highest values (Table 1). However, there was no significant difference found with weed dry weight when the micronutrient applications were followed by the herbicide treatments. The observed reductions with halosulfuron–methyl x Fe or Mn treatments (in weed N uptake) as well as halosulfuron–methyl x Fe, Mn or Zn treatments and bentazone x no fertilizing (in weed K uptake) were as similar as halosulfuron–methyl x no fertilizing.

3.2. Effect of herbicides and micronutrients application on agronomic traits of rice

The measured agronomic traits of rice markedly responded to herbicides application (Table 2). Herein, the increases in plant height, number of fertile grains panicle^{-1}, straw yield and grain yield were greater with halosulfuron–methyl than bentazone.

Zn treatment along with Fe treatment were the efficient fertilizers for enhancing plant height (4.4 and 2.4%), number of fertile grains panicle^{-1} (5.6 and 4.1%), straw yield (18.2 and 13.9%) as well as grain yield (20.3 and 15.6%), respectively, compared to the control (without fertilizing). Mn treatment came in the second order in this respect.

As anticipated, leaving weeds in unweeded treatment led to reductions in rice agronomic traits (Table 2). This was more pronounced in the control (without fertilizing) along with Fe and Mn treatments for plant height and Mn treatment for grain yield. The lowest reductions in rice agronomic traits in unweeded plots were obtained with spraying of Zn treatment. With controlling weeds by halosulfuron–methyl, all tested micronutrients possessed similar enhancements in agronomic traits exceeding the control (without fertilizing), except Mn treatment for number of fertile grains panicle^{-1}.

3.3. Effect of herbicides and micronutrients application on nutrient constituents of rice grains

Macro– and micro– nutrient constituents of rice grains (Table 3) significantly responded to herbicides application. Halosulfuron–methyl was the efficient herbicide for increasing N, P, K, Fe, Mn and Zn content in rice grains surpassing bentazone and unweeded treatment.

Zn application was the effective treatment for promoting the

Table 1
Dry weight, N uptake, P uptake and K uptake of rice weeds as affected by herbicide and micronutrient applications.

Variable		Weed dry weight (g m^{-2})			Total N uptake %	Total P uptake %	Total K uptake %
		Eclipta prostrata	*Portulaca oleracea*	Total			
Herbicide, H							
Halosulfuron–methyl		2.17 ± 0.25^{c}	1.65 ± 0.33^{c}	3.82 ± 0.22^{c}	4.83 ± 0.17^{c}	4.28 ± 0.24^{c}	7.35 ± 0.18^{b}
Bentazone		8.32 ± 0.22^{b}	10.68 ± 0.42^{b}	19.00 ± 0.38^{b}	6.65 ± 0.17^{b}	5.97 ± 0.31^{b}	9.01 ± 0.20^{b}
Unweeded		130.3 ± 2.05^{a}	104.52 ± 1.64^{a}	234.82 ± 3.69^{a}	52.22 ± 0.63^{a}	45.28 ± 0.51^{a}	66.10 ± 0.80^{a}
Micronutrient, M							
Fe		47.62 ± 14.5^{a}	39.68 ± 11.48^{a}	87.30 ± 26.0^{ab}	21.32 ± 5.31^{b}	18.95 ± 4.61^{b}	27.85 ± 6.68^{a}
Mn		46.25 ± 14.2^{a}	38.50 ± 11.17^{ab}	84.75 ± 25.3^{ab}	20.77 ± 5.29^{bc}	17.85 ± 4.63^{c}	27.25 ± 6.63^{ab}
Zn		48.49 ± 14.7^{a}	40.24 ± 11.62^{a}	88.73 ± 26.3^{a}	22.55 ± 5.45^{a}	20.23 ± 4.58^{a}	28.59 ± 6.71^{a}
Control		45.43 ± 13.9^{a}	37.38 ± 11.05^{b}	82.81 ± 25.0^{b}	20.29 ± 5.26^{c}	17.02 ± 4.59^{d}	26.26 ± 6.55^{b}
HxM							
Halosulfuron–methyl	Fe	2.90 ± 0.92^{e}	1.13 ± 1.30^{e}	4.03 ± 0.47^{e}	5.03 ± 0.10^{fgh}	4.68 ± 0.24^{g}	7.66 ± 0.28^{def}
	Mn	1.93 ± 0.31^{e}	1.81 ± 0.35^{e}	3.74 ± 0.44^{e}	4.55 ± 0.25^{gh}	3.70 ± 0.17^{h}	7.16 ± 0.28^{ef}
	Zn	2.25 ± 0.22^{e}	2.20 ± 0.30^{e}	4.45 ± 0.51^{e}	5.73 ± 0.35^{efg}	5.81 ± 0.21^{f}	8.13 ± 0.26^{cdef}
	Control	1.63 ± 0.19^{e}	1.45 ± 0.03^{e}	3.08 ± 0.19^{e}	4.03 ± 0.16^{h}	2.95 ± 0.12^{i}	6.43 ± 0.29^{f}
Bentazone	Fe	7.66 ± 0.44^{d}	11.83 ± 0.91^{d}	19.50 ± 0.71^{d}	6.71 ± 0.18^{de}	6.36 ± 0.25^{f}	9.28 ± 0.26^{cd}
	Mn	8.23 ± 0.39^{d}	10.60 ± 0.81^{d}	18.83 ± 0.65^{d}	6.26 ± 0.32^{ef}	5.08 ± 0.21^{g}	8.76 ± 0.34^{cde}
	Zn	9.16 ± 0.48^{d}	11.01 ± 0.82^{d}	20.17 ± 0.90^{d}	7.66 ± 0.17^{d}	8.06 ± 0.36^{e}	10.01 ± 0.36^{c}
	Control	8.21 ± 0.38^{d}	9.30 ± 0.62^{d}	17.51 ± 0.49^{d}	5.96 ± 0.20^{ef}	4.36 ± 0.21^{gh}	$7.98 \pm 0.15d^{ef}$
Unweeded	Fe	132.31 ± 3.61^{ab}	106.08 ± 2.89^{ab}	238.40 ± 6.50^{ab}	52.23 ± 1.19^{b}	45.8 ± 0.86^{b}	66.60 ± 2.15^{a}
	Mn	128.59 ± 4.69^{bc}	103.10 ± 3.76^{bc}	231.70 ± 8.48^{bc}	51.51 ± 1.30^{bc}	44.76 ± 1.08^{c}	65.83 ± 1.34^{ab}
	Zn	134.07 ± 4.29^{a}	107.50 ± 3.44^{a}	241.58 ± 7.73^{a}	54.26 ± 1.28^{a}	46.83 ± 1.06^{a}	67.63 ± 1.48^{a}
	Control	126.45 ± 4.09^{c}	101.39 ± 3.28^{c}	227.84 ± 7.38^{c}	50.88 ± 1.14^{c}	43.75 ± 0.91^{d}	64.36 ± 1.42^{b}

N: nitrogen, P: phosphorus, K: potassium, Fe: iron, Mn: manganese, Zn: zinc. In each column, numbers followed by the different letters are statistically significant at 95% level of probability; Values are the mean of 3 replicates ± standard errors.

Table 2

Plant height, number of fertile grains panicle^{-1}, straw yield and grain yield of rice as affected by herbicide and micronutrient applications.

Variable		Plant height (cm)	Number of fertile grains panicle $^{-1}$	Straw yield (t ha^{-1})	Grain yield (t ha^{-1})
Herbicide, H					
Halosulfuron–methyl		77.30 ± 0.49^{a}	93.68 ± 0.51^{a}	12.76 ± 0.18^{a}	11.66 ± 0.16^{a}
Bentazone		71.58 ± 0.67^{b}	88.62 ± 0.65^{b}	10.86 ± 0.19^{b}	10.56 ± 0.24^{b}
Unweeded		63.54 ± 0.73^{c}	63.99 ± 0.89^{c}	8.41 ± 0.16^{c}	5.86 ± 0.13^{c}
Micronutrient, M					
Fe		71.09 ± 1.58^{ab}	82.92 ± 3.14^{ab}	11.00 ± 0.46^{ab}	9.78 ± 0.65^{a}
Mn		70.31 ± 1.55^{b}	81.73 ± 3.21^{bc}	10.63 ± 0.48^{b}	9.03 ± 0.62^{b}
Zn		72.44 ± 1.51^{a}	84.08 ± 3.09^{a}	11.42 ± 0.45^{a}	10.18 ± 0.63^{a}
Control		69.39 ± 1.50^{b}	79.65 ± 3.43^{c}	9.66 ± 0.41^{c}	8.46 ± 0.59^{c}
HxM					
Halosulfuron–methyl	Fe	78.01 ± 0.95^{a}	94.34 ± 1.07^{ab}	13.18 ± 0.21^{ab}	11.88 ± 0.25^{ab}
	Mn	77.36 ± 0.85^{ab}	93.18 ± 0.91^{bc}	12.88 ± 0.24^{b}	11.61 ± 0.25^{abc}
	Zn	78.25 ± 1.05^{a}	95.28 ± 0.93^{a}	13.45 ± 0.25^{a}	12.31 ± 0.17^{a}
	Control	75.59 ± 0.95^{b}	91.92 ± 0.86^{c}	11.53 ± 0.23^{c}	10.85 ± 0.36^{c}
Bentazone	Fe	71.90 ± 1.23^{cd}	89.22 ± 0.97^{d}	11.05 ± 0.32^{d}	11.37 ± 0.46^{bc}
	Mn	70.65 ± 1.48^{d}	88.46 ± 1.17^{de}	10.70 ± 0.44^{d}	9.86 ± 0.24^{d}
	Zn	73.12 ± 1.28^{c}	89.92 ± 1.53^{d}	11.72 ± 0.21^{c}	11.66 ± 0.24^{abc}
	Control	70.68 ± 1.51^{d}	86.90 ± 1.47^{e}	9.97 ± 0.15^{e}	9.34 ± 0.18^{d}
Unweeded	Fe	63.36 ± 1.21^{f}	65.22 ± 1.46^{fg}	8.76 ± 0.31^{f}	6.08 ± 0.17^{ef}
	Mn	62.93 ± 0.86^{f}	63.55 ± 1.36^{g}	8.31 ± 0.17^{g}	5.62 ± 0.15^{fg}
	Zn	65.95 ± 2.31^{e}	67.05 ± 2.12^{f}	9.09 ± 0.29^{f}	6.57 ± 0.23^{e}
	Control	61.90 ± 0.81^{f}	60.15 ± 1.02^{h}	7.48 ± 0.13^{h}	5.20 ± 0.17^{g}

Fe: iron, Mn: manganese, Zn: zinc. In each column, numbers followed by the different letters are statistically significant at 95% level of probability; Values are the mean of 3 replicates ± standard errors.

accumulation of macronutrients in rice grains (Table 3). Herein, Zn treatment showed increases amounted to 2.0, 5.7 and 17.3% for N, 11.0, 27.9, 50.1% for P as well as 4.2, 11.3, 21.6% for K greater than Fe, Mn and control treatments, respectively. On the other hand, the maximum values of Fe, Mn and Zn content in rice grain were obtained with Fe, Mn and Zn treatments, respectively (Table 3). In this context, the application of Fe, Mn and Zn treatments increased Fe, Mn and Zn content in rice grain by 40.1, 76.7 and 63.9%, compared to the control, respectively.

Overall, the significant interaction between herbicides and micronutrients revealed that the combinations of halosulfuron–methyl x Zn treatment (for N and P in rice grain) and halosulfuron–methyl x Zn or Fe treatment (for P in rice grain) had the effective complementary effects in this respect (Table 3). By calculating the difference (subtraction of the nutrient uptake by weeds and the crop) of grain N, P and K uptake and weed N, P and K uptake (Fig. 1), the outputs clarified that halosulfuron–methyl x any micronutrient and halosulfuron–methyl x Zn or Fe treatments are promising combinations due to their higher positive values towards the crop. Moreover, the highest increases in grain Fe, Mn and Zn contents were recorded with halosulfuron–methyl plus Fe, Mn and Zn treatments, respectively (Table 3).

4. Discussion

4.1. Weeds

The current research proved that micronutrients e.g. Zn, Fe and Mn had beneficial effects on rice weeds growth and their nutrient uptake. Zn treatment was the most efficient for enhancing N and P uptake by weeds. Plant biological processes e.g. synthesis of proteins and metabolism of nucleic acid, which affect plant growth and development, require Zn (Han et al., 2004; Broadley et al., 2012). In field application of nutrients, weeds as crop plants receive fertilizers and can exploit a part of crop's food. Thus, the positive effect of micronutrients toward weeds, in addition to the biotic stress of weeds, represents a serious issue in crop fertilization management. In this situation, introducing the suitable weed control methods is a crucial act. Our finding clarified that application of herbicides led to distinctive reductions in weed biomass and weed nutrients uptake. Herein, both halosulfuron–methyl and bentazone exhibited significant control of rice weeds by reducing the dry weight, and hence nutrients uptake was reduced. Halosulfuron–methyl is a sulfonylurea herbicide effectively controls broadleaf weeds (Senseman 2007). The key enzyme (acetolactate synthase, ALS) in the pathway of branched chain amino acids in plants is inhibited by sulfonylurea herbicides (Ray 1984). Bentazone as an inhibiting herbicide can discourage the photosynthetic electron transport in photosystem II, exciting an oxidative stress (Zhu et al., 2009), suppressing the growth of sensitive plants as broad–leaved weeds. Therefore, the growth and nutritional status of rice weeds were negatively affected because of herbicides application (Table 1). Moreover, results proved that halosulfuron–methyl was more efficient in inhibiting the broad–leaved weeds than bentazone, since weed dry weight, weed N uptake and weed P uptake which produced from halosulfuron–methyl herbicide –treated plots were less.

The interactive effect of herbicides and micronutrients showed that neither halosulfuron–methyl or bentazone has substantial interactional impacts with micronutrients on weed dry weight. However, the accumulation of N, P and K in weeds were influenced by herbicides x micronutrients. In plots treated with halosulfuron–methyl, the control treatment (no fertilizer application) recorded the maximum reduction in weed N, P and K uptake, without significant variations between Fe and Mn treatments (for weed N uptake) and among Fe, Mn and Zn treatments (for K uptake). This refers to that the micronutrients may obstruct the absorption and utilization of N and K by weeds in the presence of halosulfuron–methyl herbicide.

4.2. Rice crop

Due to excellent herbicidal efficiency of halosulfuron–methyl for managing rice weeds (Table 1), nutrients and other environmental factors became more available to rice plants. Accordingly, application of halosulfuron–methyl showed higher values in plant height, number of fertile grains panicle^{-1}, straw yield and grain yield (Table 2) as well as grain nutrient contents (Table 3). Because of nutrient uptake by weed is inversely proportional to nutrient uptake by crop (Ramachandiran et al., 2012), the suppressive impact of herbicides on weeds gave rise to an increment in accumulation of nutrients by rice plants (Payman and Singh 2008).

In general, Fe, M n and Zn treatments caused remarkable increases in rice yield and its traits (Table 2) as well as grain nutritional status (Table 3) compared to the control treatment. Several factors are

Table 3

Some macro– and micro– nutrient contents in rice grains as affected by herbicide and micronutrient applications.

Variable		Macronutrient %			Micronutrient content (mg kg^{-1})		
		N	P	K	Fe	Mn	Zn
Herbicide, H							
Halosulfuron–methyl		1.92 ± 0.024^{a}	0.569 ± 0.018^{a}	1.99 ± 0.027^{a}	44.5 ± 1.44^{a}	42.1 ± 1.95^{a}	38.7 ± 1.59^{a}
Bentazone		1.74 ± 0.020^{b}	0.461 ± 0.016^{b}	1.85 ± 0.036^{b}	40.1 ± 1.25^{b}	35.7 ± 1.83^{b}	31.7 ± 1.25^{b}
Unweeded		1.63 ± 0.014^{c}	0.383 ± 0.012^{c}	1.60 ± 0.031^{c}	33.8 ± 0.68^{c}	29.8 ± 1.85^{c}	28.9 ± 1.35^{c}
Micronutrient, M							
Fe		1.81 ± 0.034^{b}	0.507 ± 0.022^{b}	1.89 ± 0.045^{b}	47.9 ± 1.77^{a}	30.5 ± 1.29^{c}	33.3 ± 1.38^{b}
Mn		1.75 ± 0.033^{c}	0.440 ± 0.019^{c}	1.77 ± 0.044^{c}	37.2 ± 1.01^{c}	50.7 ± 1.48^{a}	29.8 ± 1.12^{c}
Zn		1.87 ± 0.030^{a}	0.563 ± 0.021^{a}	1.97 ± 0.043^{a}	38.5 ± 1.02^{b}	33.6 ± 1.31^{b}	43.1 ± 1.28^{a}
Control		1.63 ± 0.020^{d}	0.375 ± 0.015^{d}	1.62 ± 0.042^{d}	34.2 ± 0.82^{d}	28.7 ± 1.23^{d}	26.3 ± 0.73^{d}
HxM							
Halosulfuron–methyl	Fe	1.99 ± 0.014^{b}	0.621 ± 0.014^{b}	2.08 ± 0.029^{ab}	55.7 ± 0.96^{a}	36.5 ± 0.72^{e}	40.2 ± 0.93^{b}
	Mn	1.92 ± 0.008^{c}	0.540 ± 0.010^{c}	1.93 ± 0.027^{c}	41.1 ± 0.76^{cd}	57.5 ± 1.51^{a}	35.4 ± 1.08^{c}
	Zn	2.03 ± 0.014^{a}	0.666 ± 0.016^{a}	2.13 ± 0.018^{a}	43.2 ± 0.90^{c}	39.8 ± 0.75^{d}	49.5 ± 1.42^{a}
	Control	1.73 ± 0.020^{f}	0.448 ± 0.014^{def}	1.84 ± 0.028^{d}	38.2 ± 0.71^{e}	34.4 ± 0.53^{f}	29.8 ± 0.90^{e}
Bentazone	Fe	1.78 ± 0.015^{e}	0.493 ± 0.017^{d}	1.93 ± 0.019^{c}	49.5 ± 0.74^{b}	30.5 ± 0.72^{g}	32.4 ± 0.94^{d}
	Mn	1.73 ± 0.027^{f}	0.430 ± 0.009^{ef}	1.85 ± 0.020^{d}	38.4 ± 1.05^{e}	50.2 ± 1.36^{b}	28.8 ± 0.74^{e}
	Zn	1.85 ± 0.017^{d}	0.561 ± 0.011^{c}	2.03 ± 0.031^{b}	38.7 ± 0.67^{de}	33.3 ± 0.82^{f}	40.3 ± 1.50^{b}
	Control	1.61 ± 0.019^{h}	0.361 ± 0.017^{g}	1.58 ± 0.028^{g}	33.8 ± 0.70^{f}	28.8 ± 0.83^{h}	25.3 ± 0.68^{fg}
Unweeded	Fe	1.65 ± 0.004^{g}	0.406 ± 0.010^{f}	1.66 ± 0.045^{f}	38.6 ± 0.77^{de}	24.5 ± 1.36^{i}	27.2 ± 0.81^{ef}
	Mn	1.60 ± 0.008^{h}	0.350 ± 0.012^{g}	1.55 ± 0.049^{g}	32.2 ± 0.73^{fg}	44.3 ± 0.91^{c}	25.1 ± 0.56^{fg}
	Zn	1.73 ± 0.012^{f}	0.461 ± 0.009^{de}	1.74 ± 0.045^{e}	33.6 ± 0.52^{f}	27.6 ± 1.11^{h}	39.7 ± 0.63^{b}
	Control	1.55 ± 0.012^{i}	0.316 ± 0.011^{g}	1.45 ± 0.034^{h}	30.7 ± 0.45^{g}	22.9 ± 1.09^{i}	23.7 ± 0.53^{g}

N: nitrogen, P: phosphorus, K: potassium, Fe: iron, Mn: manganese, Zn: zinc. In each column, numbers followed by the different letters are statistically significant at 95% level of probability; Values are the mean of 3 replicates ± standard errors.

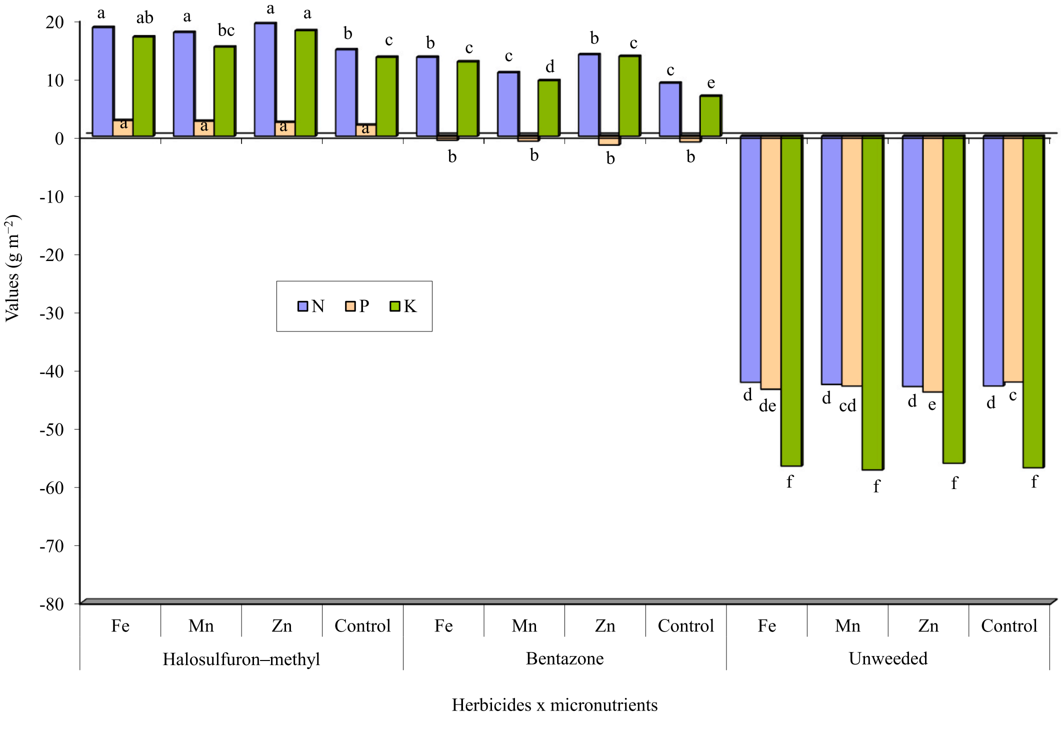

Fig. 1. The subtraction values output for N, P and K uptake between rice crop and associated weeds as affected by herbicide and micronutrient applications. Note: N: nitrogen, P: phosphorus, K: potassium, Fe: iron, Mn: manganese, Zn: zinc; Different letters indicate the significant difference at 95% level of probability; Values are the mean of 3 replicates ± standard errors.

affecting the availability of nutrients for crop growth. In alkaline soils with pH > 7.5 (as the soil of current study) the amount of soluble Fe is very low (Sánchez–Rodríguez et al., 2014). Hence, nutrient deficiency could be corrected by application of fertilization. Specifically, Zn and Fe treatments showed similar improvements higher than Mn. In this concern, Zn had a beneficial effect on several enzymes activity and improves the plant growth and development (Hassanpouraghdam et al., 2020). Zn has a vital function in significant biochemical and physiological processes (Han et al., 2004). Hence, crop yield is highly correlating with Zn nutrition in different plants especially under Zn–deficient conditions (Shukla and Tiwari 2016). Zn foliar application increased filled grain percentage in rice (Phuphong et al., 2018). Spraying of Zn corrected Zn deficiency and improved grain Zn content due to increasing translocation of Zn from flag leaves to grains (Wu et al., 2010; Noreen et al., 2019). The essentiality of the element Fe for the convenient growth of the plant could be imputed to its pivotal role in chlorophyll synthesis and activation of numerous enzymes in plant system. Significant increases in chlorophyll content, tillers number, 1000 grain weight, filled grains and rice grain yield were recorded in Fe−sufficient soils or with iron application (Daneshtalab Lahijani et al., 2020; Sakariyawo et al., 2020). Fe foliar application significantly improved plant height, tillers, dry matter accumulation and yield of rice (Kumar et al., 2018). Because of Fe spraying, 1000–grain weight and grain yield were increased, and unfilled grains were decreased (Dehaghi et al., 2015). Despite Mn treatment had lower impact than Fe and Zn treatments on rice yield, its importance in plant growth should not be neglected. Compared to the control (without fertilizing) treatment, Mn treatment increased straw and grain yields by 10.0 and 6.7%, respectively. Mn plays a role in activation of several plant enzymes and photolysis process of photosynthesis (Humphrise 2006; and Aref 2012).

In halosulfuron–methyl treated–plots, fertilizing with Fe or Zn achieved increases of 14.3 and 16.7% in straw yield and 9.5 and 13.5% in grain yield greater than non–fertilizing treatment (control), respectively. Each of Fe or Zn treatments recorded 50.5 and 47.9% increases in straw yield as well as 95.4 and 87.4% increases in grain yield from halosulfuron–methyl plots compared to unweeded ones. Such observations reflect the importance of the integral effect between herbicides and micronutrients on agronomic traits of rice (El–Metwally and Saudy, 2021). Whereas, quenching weed growth by herbicides improves the function and utilization of micronutrients. Also, micronutrients had the potentiality to enhance the competitive ability of crop plants and reduce the abiotic stress of associated weeds. Therein, due to foliar application of zinc and iron, remarkable enhancements in plant height, number of tillers hill^{-1}, dry weight, and leaf area index of rice were recorded (Singh and Singh 2018).

Despite the suppressive impacts of herbicides against weeds, herbicides may cause some pressures on crop plant (abiotic stress). Our findings proved that micronutrients could reduce such effect since herbicide x micronutrient treatments were more efficient for improving yield and quality of rice compared to herbicide x no micronutrient application. In this regard, the activation of specific enzymatic systems with Zn supply is because of Zn works as co–factor for catalyzing of superoxide dismutase (SOD) and carbonic anhydrase (CA) activity (Singh et al., 2019). Under different stresses, active oxygen species (ROS) such as superoxide radical ($O_2^{\bullet -}$), hydroxyl free radical ($OH^{\bullet}$), singlet oxygen ($^1O_2$) and hydrogen peroxide (H_2O_2) are elevated causing biological damaged leading to the death of plant cells (Hossain et al., 2014). SOD is the elementary sweeper enzyme shared in the detoxification of ROS and mutates superoxide to H_2O_2 and O_2 (Miller et al., 2007). Whereas CA is included in photosynthesis and work as a storage pool of Zn in leaf (Han et al., 2004). This led to producing higher photosynthates assimilates as well as Zn concentration in diversified plant organs (Bharti et al., 2014; Ma et al., 2017). SOD and CA are directly correlated with the plenty of Zn and introduce a positive association between their activities and Zn deficit (Mathpal et al., 2015). Zinc expedites the cumulation of IAA and consequently ROS were quenched by stimulating cellular division and enlargement (Torabian et al., 2016). Accordingly, micronutrients, particularly Zn, had the potency to relieve the herbicidal impacts on crop plants and enhance the productivity and quality. The complementary effect between halosulfuron–methyl x Zn treatment was confirmed, since its net N and K uptake was obtained (Fig. 1). This result might be attributed to higher potentiality in dry matter accumulation in grains.

5. Conclusion

Based on the ability of the tested micronutrients to enhance crop competitive ability against weeds, they could be arranged as follow: Zn > Fe > Mn. Hence, improving in yield and grain nutritional status was more evident with Zn treatment. Despite the non–significant interaction impact of herbicides and micronutrients on dry weight of rice weeds, there were synergism and co–application effects between halosulfuron–methyl herbicide and fertilizing rice by Zn or Fe owing to suppressing the accumulation of nutrients in weeds and achievable improvements in yield and grain nutrient uptake. Thus, we advise the farmers that the herbicide–based weed control methods in rice should be implemented in combination with the micronutrients, especially Zn. In fact, the potential interactive relationship between herbicides and micronutrients in rice requires further in−deep future study considering the physiological aspects of weeds and crops.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

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