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ORIGINAL PAPER

Effect of Iron, Zinc, and Manganese Nano-Form Mixture on the Micronutrient Recovery Efficiency and Seed Yield Response Index of Sesame Genotypes

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Abstract

Sesame genotypes have different potentiality to exploit the environmental growth factors, i.e., the available nutrients. So far, sesame genotypes have not received enough studies regarding their response to a mixture of micronutrients in nanostructures. Therefore, the current study aimed to investigate the response of some sesame genotypes under different rates of Fe, Zn, and Mn mixture in nano-form. Field experiment was established in a strip-plot design with three replicates during two successive seasons. The response of three sesame genotypes (Shandaweel3, Giza32, and Sohag1) was studied under two levels of iron (Fe), zinc (Zn), and manganese (Mn) package, 1:1:1 (0.25 and 0.50 g L^{-1} as nanoparticles, FeZnMn-nano), in addition to control treatment, 0.00 g L^{-1}, (tap water). Sesame yield attributes, oil and protein content, micronutrient uptake, micronutrient recovery efficiency, and seed yield response index were estimated. Sohag1 genotype was the most efficient for producing the maximum capsule number $plant^{-1}$, seed yield $plant^{-1}$, and seed yield ha^{-1} as well as protein yield ha^{-1}. The increase in seed yield ha^{-1} was 15.5% owing to 0.50 g L^{-1} FeZnMn-nano, compared to the control treatment. The maximum values of micronutrient uptake were recorded with Sohag1 genotype surpassing Shandaweel3 and Giza32 genotypes. Spraying of 0.50 g L^{-1} FeZnMn-nano recorded 25.6 and 30.5% increases for Fe uptake and Zn uptake, respectively. Sohag1 genotype × 0.50 g L^{-1} FeZnMn-nano was the efficient interaction treatment for enhancing Fe and Zn uptake. Sohag1 genotype showed the maximum values of Fe and Zn recovery efficiency. Each of Sohag1 genotype and Shandaweel3 genotype whether with 0.50 g L^{-1} FeZnMn-nano or 0.25 g L^{-1} FeZnMn-nano treatments achieved the highest values of Fe and Zn recovery efficiency. Both Sohag1 and Shandaweel3 genotypes are belonging to efficient and responsive (ER) group, being exceeded the averages of seed yield at zero micronutrients rate and seed yield response index. Genotypic variations associated with the application of Fe, Zn, and Mn as nano-mixture introduced a promising solution for remediation of micronutrients deficiency symptoms in sesame. Under arid regions, i.e., Egyptian conditions, fertilizing Sohag1 genotype by 0.50 g L^{-1} FeZnMn-nano could achieve cost-effective mean to overcome Fe, Zn, and Mn deficiency with higher productivity.

Keywords Nanofertilizers · Nanotechnology benefits · Oilseed crops · Sesame nutrient uptake · Varietal differences

1 Introduction

Globally, about 40% of world population is suffering from malnutrition owing to insufficient supply of micronutrients, i.e., iron (Fe), zinc (Zn), and manganese (Mn), especially in developing countries (Welch and Graham 2002; Jha and Warkentin 2020).

Seed of sesame (*Sesamum indicum* L.) is considered an important source of oil (44–58%), protein (18–25%), carbohydrate (13.5%), and ash (5%). The seed contains all essential amino acids and fatty acids. It is a good source of vitamins and minerals such as calcium and phosphorus (Malik et al. 2003). Due to the presence of endogenous antioxidants such as sesamol, sesamolinol, and sesaminol, the edible oil of sesame has high degrees of stability and resistance to oxidative rancidity (Alpaslan et al. 2001). Among the various factors of crop management, proper level of micronutrients

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and improved sesame genotypes are playing a key role in boosting crop production.

Fe, Zn, and Mn are three of the most significant micronutrients required for favorable plant growth and development. The lack or excrescent concentration of these nutrients leads to negative impacts on crop production (Lynch 2019). In addition, soils in the semi-arid and arid climates are disposed to have a deficiency of a variety of micronutrients as iron, copper, zinc, and manganese (Clair and Lynch 2010). Approximately 80% of Fe is found in photosynthetic cells where it is essential for the biosynthesis of cytochromes, chlorophyll, the electron transport chain, and the construction of Fe-S clusters (Briat et al. 2007; Hänsch and Mendel 2009). Also, Varotto et al. (2002) reported that Fe atoms are one of the structural components of molecules linked with photosystem II (PS-II), photosystem I (PS-I), cytochrome complex, and ferredoxin molecule. This clarifies that Fe is directly entangled in the photosynthetic activity of crop plants and, consequently, their productivity (Briat et al. 2007). Zn is a significant micronutrient required for humans, animals, and plants in minor amount (Kabata-Pendias 2011; Shukla et al. 2018). The function of several enzymes (alcoholic dehydrase, carbonic anhydrase, carboxypeptidase, alkaline phosphate, and phospholipase) in the metabolism of nucleic acid, lipids, proteins, and carbohydrates mainly depends on Zn (Khan et al. 2002; Ullah et al. 2020). Zn has an efficient effect on enhancing photosynthesis, cell division, protein synthesis, gene transcription, and retains integrity of membranes (Broadley et al. 2007; Rehman et al. 2018). Hence, the final rice crop product was improved by Zn supply (El-Metwally and Saudy 2021). Since Mn serves as electron storage and delivery to the chlorophyll reaction centers, it is regarded as a component and a catalytically active cofactor of enzyme system involved in photosynthesis and several metabolic processes (Millaleo et al. 2010).

There is no doubt that crops growing in sandy soils with low fertility are subjected to nutritional stress affecting their productivity. Applying micronutrients to soil appears to be one of the most cost-effective means to overcome nutrient deficiency. With the scarcity of micronutrients in the soil, adequate supply of them is required for optimal growth and yield of crops (Singh 2009). Several methods of micronutrients supply to crop plants have been reported, for instance, foliar application (Haider et al. 2018a) and seed priming (Ullah et al. 2019) to enhance the crop growth and productivity. Soil application of micronutrients has been also kept a realistic mean of alleviating the micronutrient deficiencies in crop plants (Haider et al. 2018b). However, change in soil factor can alter the soil chemical and physical properties, i.e., pH, redox potential, and organic matter (Alloway 2009), thus affecting biological activities for root function like ion uptake and respiration (Marschner and Rengel 2012). It is well known that foliar application of micronutrients established remarkably higher absorption levels than soil application of micronutrients (Moghadam et al. 2011). Recently, exploiting nanoparticles spray (materials with a size range from 1 to 100 nm) through nanotechnology (Hema et al. 2016; Suguna et al. 2017) can be utilized in environmental applications (Zou et al. 2016; Khan et al. 2017). Nanoparticles contribute to nutrient use efficiency and plant growth (Rui et al. 2016; Pacheco and Buzea 2018; Tombuloglu et al. 2018; Singh et al. 2019a). Nanonutrient fertilizers exhibit high sorption capacity, surface area, and control release of nutrients to targeted sites; hence, these can be considered as smart nutrient delivery system (Rameshaiah et al 2015). Furthermore, nanofertilizers offer benefits in nutrition management through their strong potential to increase nutrient use efficiency and provide better yield and may also be used for enhancing abiotic stress tolerance (Naderi and Danesh−Sharaki 2013; Zulfiqar et al 2019).

Sesame yield is highly variable according to the growing environment, cultural practices, and cultivated genotypes. Significant variations in seed yield, oil content, and oil composition were obtained among sesame genotypes (Ali et al. 2016; El–khouly et al. 2018; Saudy et al. 2018). Accordingly, providing sesame plants with proper amounts of Fe, Mn, and Zn is a crucial action for sustaining crop productivity and quality.

Despite the combined effect of Zn with Fe/Mn were previously reported in some crops (Movahhedy-Dehnavy et al. 2009; Blasco et al. 2015; Khodabin et al. 2021; Pal et al. 2021), there is almost no information available about the significance of Fe, Zn, and Mn together, particularly as a nanomixture for the sesame crop. It was hypothesized that Fe, Zn, and Mn application in combination through nanotechnology tools will enhance productivity and seed biofortification of sesame genotypes. Therefore, this field study was conducted to evaluate the response of sesame genotypes to various rates of Fe, Zn, and Mn mixture in nano-form.

2 Materials and Methods

2.1 Study Area

A 2-year-field study was conducted in 2018 and 2019 growing seasons at Imam Mllik village, Kom Hamada, El–Beheira governorate, Egypt (30° 30′ N, 30° 20′ E). The soil of the research site was sandy and its physical and chemical properties are shown in Table 1. The experimental site belongs to the arid areas with hot-dry summers and no rainfalls. As an average of the two seasons, the values of daily air temperature, wind speed, relative humidity,

Table 1 Properties of soil at Imam Mllik village, Kom Hamada, El–Beheira governorate, Egypt

Parameter	Unit	Value
Physical properties		
Sand	%	88.0 ± 0.2
Silt	%	5.3 ± 0.1
Clay	%	6.7 ± 0.1
Chemical analysis		
pH (1:2.5)	–	7.8 ± 0.1
EC	dS m^{-1}	2.4 ± 0.3
Organic matter	%	0.79 ± 0.02
Total nitrogen	%	0.05 ± 0.0.02
Available P	mg kg^{-1}	12.0 ± 0.2
Available K	mg kg^{-1}	160.0 ± 2.4
Available Fe	mg kg^{-1}	1.01 ± 0.01
Available Zn	mg kg^{-1}	0.85 ± 0.03
Available Mn	mg kg^{-1}	1.06 ± 0.03
Ca^{+2}	meq L^{-1}	18.7 ± 0.7
Mg^{+2}	meq L^{-1}	6.7 ± 0.1
Na^{+}	meq L^{-1}	2.53 ± 0.03
K^{+}	meq L^{-1}	0.74 ± 0.03
Cl^{-}	meq L^{-1}	4.18 ± 0.02
HCO_3^{-}	meq L^{-1}	2.90 ± 0.06
$CaCO_3$	g kg^{-1}	56.1 ± 0.6

Values are the mean of 3 replicates ± standard errors

and solar radiation were 39.8 °C, 4.32 m sec^{-1}, 59.5% and 28.3 MJ m^{-2} day^{-1}, respectively. Wheat (*Triticum aestivum* L.) was the preceding cultivated crop in both seasons.

2.2 Trial Design and Implementation

The experiment was implemented in a strip-plot design with three replicates, where genotypes (Giza32, Sohag1, and Shandaweel3) occupied the vertical strips and micronutrient treatments distributed in the horizontal ones. The net plot size was 10.5 m^2; involving five ridges, 3.5 m length and 0.6 m width. The tested genotypes originated from Egypt as well as their pedigrees are GIZAWHIxTYPE9, BENGALIANxGIZA32, and GIZA32xNA130 for Giza32, Sohag1, and Shandaweel3, respectively. Giza32 plants have unbranched stem and bear one capsule in the leaf axil. This genotype is moderately tolerant to wilt disease. Both Sohag1 (branched) and Shandaweel3 (unbranched) plants bear three capsules in the leaf axil as well as these two genotypes are tolerant to wilt disease. Three levels of iron (Fe), zinc (Zn), and manganese (Mn) package, 1:1:1 (0.00, 0.25, and 0.50 g L^{-1} as nano particles, FeZnMn-nano) were applied. The micronutrients in the form of oxides were sprayed twice at 30 and 45 days after sowing (DAS). The spray solutions were applied using a knapsack sprayer had one nozzle with 480 L water ha^{-1} as a solvent/carrier. Transmission electron microscopy (TEM) images of nano-oxide crystals for Fe, Zn, and Mn are depicted in Fig. 1.

Calcium superphosphate (15.5% P_2O_5) at a rate of 360 kg ha^{-1} was incorporated during land preparation. Seeds of sesame genotypes were sown on 5 May 2018 and 1 May 2019 (about 10.0 kg ha^{-1}) with 10-cm distance between hills, and then sowing irrigation was applied. At 25 DAS, plants were thinned to two plants per hill followed

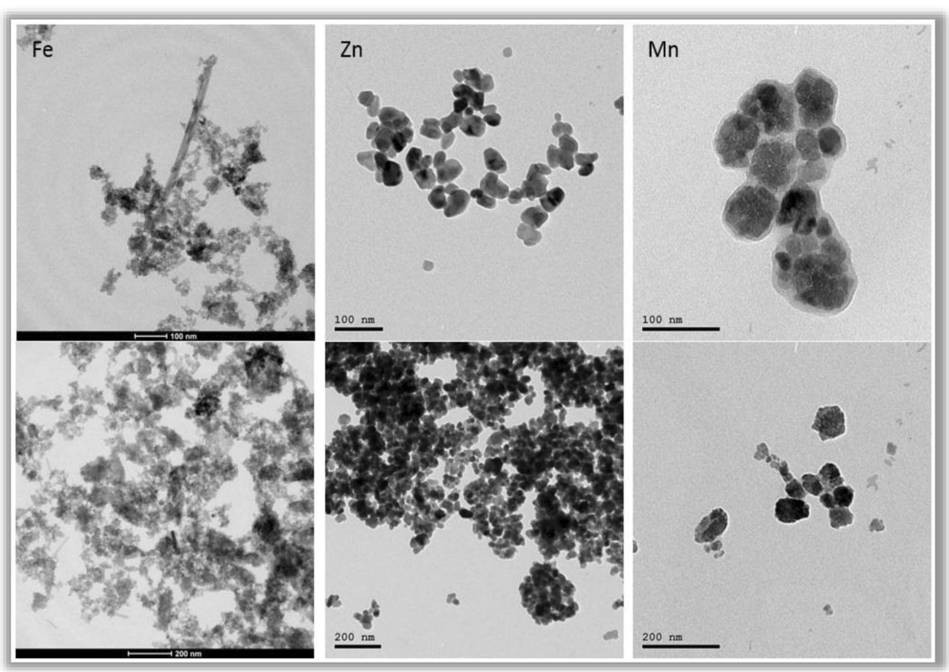

Fig. 1 Transmission electron microscopy (TEM) images of nano-oxide crystals for iron (Fe), zinc (Zn), and manganese (Mn) with sizes of 100 and 200 nm (nm)

by irrigation. Nitrogen fertilizer (in the form of ammonium sulfate, 20% N) was applied at the rate of 108 kg ha^{-1} in three equal portions, at sowing, 25 and 40 DAS. Also, plants received potassium sulfate (48% K_2O) at a rate of 120 kg ha^{-1}, 40 DAS.

Sesame plants were irrigated through trickle irrigation system. The irrigation system was set up consisting of control head (media and screen filters, pressure gauges, and control valves). Main line was PVC of 75.0 mm diameter up to 6.0 bar pressure and sub main line was PVC pipe of 50.0 mm diameter up to 6.0 bar pressure). Lateral lines were polyethylene tubes of 16 mm diameter (with built in emitters), 20.0 cm emitter spacing, and manufacturing emitter discharge 4.0 L h^{-1}, at operating pressure of 1.0 bar.

2.3 Assessments

2.3.1 Agronomic Traits

Flowering time was estimated based on the initial flowering of the first flower for whole plants per experimental unit. At maturity stage (on 27 August 2018 and 21 August 2019), ten plants were randomly selected from each plot to measure the means of fruiting zone length, capsules number plant^{-1}, seed yield per plant (g plant^{-1}), and weight of 1000 seeds. Moreover, sesame yield (kg ha^{-1}) was estimated by harvesting the whole plot size.

2.3.2 Seed Oil and Protein Content

According to AOAC (2012), seed oil content was measured (using Soxhlet Apparatus with hexane as an organic solvent) as well as total nitrogen was determined (using the modified micro Kjeldahl method). Hence, crude protein content was calculated by multiplying the total nitrogen by 5.7. After that, oil and protein yields ha^{-1} were computed through multiplying oil % and protein % by seed yield ha^{-1}, respectively.

2.3.3 Micronutrient Nutrient Uptake

Each of Fe, Zn, and Mn in sesame seeds was extracted as described by Soltanpour and Schwab (1977). Extracted solution was determined against a standard using ICP instrument Prodigy7. The ICP Specified by Optical Design High Energy EchellePoly chromator connected with a detector CMOS. The analytical wavelengths of Fe, Zn, and Mn assessment were 259.940, 213.857, and 257.610 nm, respectively. Fe, Zn, and Mn uptake (kg ha^{-1}) was calculated by multiplying seed nutrient content by seed yield ha^{-1}.

2.3.4 Micronutrient Recovery Efficiency

Recovery efficiency (*RE*) % of Fe, Zn, and Mn was computed according to Shivay et al. (2010), using formula 1 as follow:

$$RE\% = \frac{UN_t - UN_c}{N_a} \times 100 \quad (1)$$

where:

UN_t: seed nutrient uptake in treated plots, (kg ha^{-1}),

UN_c: seed nutrient uptake in control (no fertilizer applied) plots (kg ha^{-1}),

N_a: applied nutrient in treated plots (kg ha^{-1}).

2.3.5 Seed Yield Response Index

Seed yield response index (SYRI) was calculated for each genotype using formula 2 (Fageria and Barbosa Filho 1981) as follow:

$$SYRI = \frac{SY \text{ at high nutrient rate} - SY \text{ at low nutrient rate}}{High\ nutrient\ rate - Low\ nutrient\ rate}\left(kg\ seeds\ kg\ nutrient^{-1}\right) \quad (2)$$

where:

SY: seed yield kg ha^{-1}

Low nutrient rate = 0.00 kg ha^{-1}.

High nutrient rate = 0.24 kg ha^{-1} (equivalent 0.50 g L^{-1} nano-form).

According to the SYRI value, genotypes could be classified into four groups: (i) efficient and responsive (*ER*) that produce high seed yield at low as well as high rates of nutrient fertilizer; (ii) efficient and not responsive (ENR) that produce high seed yield at low nutrient rate with lower response to increase nutrient fertilizer than *ER*; (iii) not efficient but responsive (NER) that has low seed yield with response to increase nutrient fertilizer; and (iv) neither efficient nor responsive (NENR) that has low seed yield with low response to increase nutrient fertilizer.

2.4 Statistical Analysis

The collected data were subjected to homogeneity test (Levene 1960) and Anderson–Darling normality test (Scholz and Stephens 1987) before carrying out the analysis of variance (ANOVA). 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 (Casella 2008), using Costat software program, Version 6.303 (2004). Using, Duncan's multiple range test, means separation was done only when the *F*-test indicated significant ($P < 0.05$) differences among the treatments.

3 Results

3.1 Agronomic Traits, Oil, and Protein of Sesame

Agronomic traits, oil, and protein of sesame were significantly responded to the main effects of genotype (except weight of 1000 seed) and micronutrients application (except flowering time), while there was no significant effect of the interaction. The tested sesame genotypes were not similar in all agronomic traits (Table 2) and oil and protein yields (Table 3). In this respect, Sohag1 genotype was the most efficient for producing the maximum capsule number plant^{-1}, seed yield plant^{-1}, and seed yield ha^{-1} as well as protein yield ha^{-1}. Sohag1 genotype significantly equaled Shandaweel3 genotype in flowering time and oil yield ha^{-1} as well as Giza3 genotype in fruit zone length.

Concerning the effect of micronutrients fertilizer on agronomic traits of sesame, the results in Table 2 revealed that except flowering time, all yield parameters significantly responded to nanofertilizer form of the applied micronutrients. In this situation, application of 0.50 g L^{-1} FeZnMn-nano showed the highest values of fruit zone length, capsule number plant^{-1}, weight of 1000 seed, seed yield plant^{-1}, and seed yield ha^{-1}. However, the differences between 0.50 g L^{-1} FeZnMn-nano and 0.25 g L^{-1} of FeZnMn-nano were not significant for weight of 1000 seed, seed weight plant^{-1}, and seed yield ha^{-1}. Herein, the increase seed yield ha^{-1} was 15.5% owing to 0.50 g L^{-1} FeZnMn-nano, compared to the control treatment (tap water). Moreover, the potential of 0.50 g L^{-1} FeZnMn-nano treatment extended to improve oil yield by 13.3% and protein yield by 18.4%, compared to the control treatment (Table 3).

Table 3 Oil and protein yields of sesame as influenced by genotype and micronutrient

Variable	Oil yield (kg ha^{-1})	Protein yield (kg ha^{-1})
Genotype (G)		
Giza32	434.3 ± 14.6^{b}	192.7 ± 5.2^{b}
Sohag1	562.6 ± 18.1^{a}	261.2 ± 8.3^{a}
Shandaweel3	521.1 ± 14.1^{a}	223.0 ± 7.9^{b}
Micronutrient level (M)		
0.00 g L^{-1} FeZnMn	500.9 ± 13.7^{b}	213.2 ± 7.1^{b}
0.25 g L^{-1} FeZnMn-nano	449.6 ± 15.0^{b}	211.3 ± 9.7^{b}
0.50 g L^{-1} FeZnMn-nano	567.6 ± 20.4^{a}	252.4 ± 9.4^{a}
GxM	ns	ns

FeZnMn, iron, zinc, and manganese bundle. Values are the mean of 3 replicates ± standard errors. Different letters within columns indicates that there are significant differences at 0.05 level of probability; *ns*, non-significant

3.2 Micronutrient Uptake by Sesame

Micronutrient uptake of sesame seeds was significantly affected by the main effects of genotype and micronutrient fertilization (Table 4). In this context, the maximum values of micronutrient uptake were recorded with Sohag1 genotype surpassing Shandaweel3 and Giza32 genotypes by 1.13 and 1.38 times for Fe uptake, 1.14 and 1.42 times for Zn uptake, and 1.21 and 1.43 times for Mn uptake, respectively.

Table 2 Agronomic traits of sesame as influenced by genotype and micronutrient

Variable	Flowering time (DAS)	Fruit zone length (cm)	Capsule number plant^{-1}	Seed yield (g plant^{-1})	Weight of 1000 seed (g)	Seed yield (kg ha^{-1})
Genotype (G)						
Giza32	29.0 ± 0.4^{b}	128.8 ± 3.6^{a}	106.9 ± 3.2^{c}	26.4 ± 1.2^{c}	3.49 ± 0.06^{a}	845.3 ± 12.5^{c}
Sohag1	32.2 ± 0.5^{a}	128.7 ± 2.4^{a}	117.8 ± 1.7^{a}	45.2 ± 0.8^{a}	3.58 ± 0.06^{a}	1175.2 ± 24.0^{a}
Shandaweel3	33.3 ± 0.6^{a}	113.2 ± 2.7^{b}	114.7 ± 1.8^{b}	33.2 ± 0.8^{b}	3.76 ± 0.05^{a}	1042.4 ± 20.2^{b}
Micronutrient level (M)						
0.00 g L^{-1} FeZnMn	31.6 ± 0.7^{a}	111.3 ± 1.9^{c}	105.9 ± 1.8^{c}	31.1 ± 2.1^{b}	3.50 ± 0.05^{b}	950.8 ± 26.1^{b}
0.25 g L^{-1} FeZnMn-nano	31.6 ± 0.6^{a}	120.8 ± 2.0^{b}	113.1 ± 2.5^{b}	34.7 ± 2.0^{ab}	3.62 ± 0.06^{ab}	1013.5 ± 37.2^{ab}
0.50 g L^{-1} FeZnMn-nano	31.4 ± 0.6^{a}	138.6 ± 2.4^{a}	120.4 ± 2.2^{a}	39.1 ± 2.7^{a}	3.71 ± 0.06^{a}	1098.5 ± 40.8^{a}
GxM	ns	ns	ns	ns	ns	ns

DAS, days after sowing; *FeZnMn*, iron, zinc, and manganese bundle. Values are the mean of 3 replicates ± standard errors. Different letters within columns indicates that there are significant differences at 0.05 level of probability; *ns*, non-significant

Table 4 Iron (Fe), zinc (Zn), and manganese (Mn) uptake in sesame as influenced by genotype and micronutrient

Variable	Fe uptake (kg ha^{-1})	Zn uptake (kg ha^{-1})	Mn uptake (kg ha^{-1})
Genotype (G)			
Giza32	0.081 ± 0.001^{c}	0.055 ± 0.001^{c}	0.016 ± 0.0008^{c}
Sohag1	0.112 ± 0.004^{a}	0.078 ± 0.004^{a}	0.023 ± 0.0009^{a}
Shandaweel3	0.099 ± 0.004^{b}	0.068 ± 0.003^{b}	0.019 ± 0.0009^{b}
Micronutrient level (M)			
0.00 g L^{-1} FeZnMn	0.086 ± 0.003^{c}	0.059 ± 0.001^{c}	0.016 ± 0.001^{b}
0.25 g L^{-1} FeZnMn-nano	0.096 ± 0.004^{b}	0.066 ± 0.003^{b}	0.019 ± 0.001^{a}
0.50 g L^{-1} FeZnMn-nano	0.108 ± 0.005^{a}	0.077 ± 0.004^{a}	0.021 ± 0.001^{a}
GxM	*	*	ns

FeZnMn, iron, zinc, and manganese bundle. Values are the mean of 3 replicates ± standard errors. Different letters within columns indicates that there are significant differences at 0.05 level of probability; *significant; *ns*, non-significant

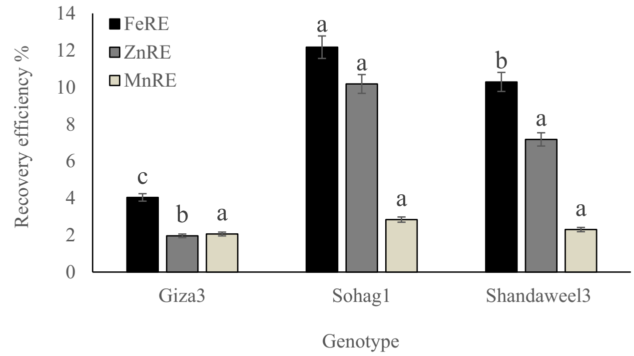

Fig. 2 Recovery efficiency of iron (FeRE), zinc (ZnRE), and manganese (MnRE) for the tested sesame genotypes. Values are the mean of 3 replicates ± standard errors. Bars with different letters are statistically significant at 0.05 level of probability

All micronutrient applications showed increases in Fe, Zn, and Mn uptake greater than the control treatment (Table 4). Spraying of 0.50 g L^{-1} FeZnMn-nano possessed higher values of Fe and Zn uptake recording increases of 25.6% (for Fe) and 30.5% (for Zn). Also, sprayings of 0.50 g L^{-1} FeZnMn-nano and 0.25 g L^{-1} FeZnMn-nano were statistically equaled and improved Mn uptake by 31.3 and 18.8%, respectively.

Significant interaction effect of genotype and micronutrient on Fe and Zn uptake was noticed (Table 5). Generally, treating Sohag1 genotype by 0.50 g L^{-1} FeZnMn-nano was the efficient interaction treatment for enhancing Fe and Zn uptake. Moreover, Shandaweel3 and Giza32 genotypes were more efficient to produce higher values of Fe and Zn uptake under application of 0.50 g L^{-1} FeZnMn-nano than other fertilizer treatments.

3.3 Micronutrient Recovery Efficiency

Recovery efficiency of iron (FeRE) and zinc (ZnRE) was significantly changed among sesame genotypes, while recovery efficiency of manganese (MnRE) did not affect (Fig. 2). Sohag1 genotype showed the maximum values of FeRE and ZnRE statistically equaled Shandaweel3 genotype in ZnRE. No significant variations in recovery efficiency of FeRE, ZnRE or MnRE between 0.50 g L^{-1} FeZnMn-nano and 0.25 g L^{-1} FeZnMn-nano treatments were recorded (Fig. 3).

Recovery efficiency of FeRE and ZnRE was significantly affected by sesame genotypes × micronutrient interaction, while recovery efficiency of MnRE did not respond (Fig. 4). As for the interaction, both of Sohag1 genotype and Shandaweel3 genotype whether with 0.50 g L^{-1} FeZnMn-nano or 0.25 g L^{-1} FeZnMn-nano treatments achieved the highest values of FeRE and ZnRE.

3.4 Seed Yield Response Index (SYRI) of Sesame

Based on 0.00 FeZnMn (0.00 g L^{-1}) kg micronutrients, as low nutrient rate, and 0.24 FeZnMn-nano (0.50 g L^{-1}) kg micronutrients, as high nutrient rate of Fe, Zn, and Mn bundle ha^{-1}, SYRI of sesame was computed.

Table 5 The significant interaction effect of sesame genotype and micronutrient on iron (Fe) and zinc (Zn) uptake

Variable	Giza32	Sohag1	Shandaweel3
	Fe uptake (kg ha^{-1})		
0.00 g L^{-1} FeZnMn	0.075 ± 0.0007^{f}	0.097 ± 0.0005^{c}	0.086 ± 0.0018^{d}
0.25 g L^{-1} FeZnMn-nano	0.079 ± 0.0016^{e}	0.113 ± 0.0021^{b}	0.097 ± 0.0022^{c}
0.50 g L^{-1} FeZnMn-nano	0.087 ± 0.0012^{d}	0.125 ± 0.0003^{a}	0.113 ± 0.0006^{b}
	Zn uptake (kg ha^{-1})		
0.00 g L^{-1} FeZnMn	0.053 ± 0.0015^{f}	0.065 ± 0.0013^{cd}	0.059 ± 0.0010^{def}
0.25 g L^{-1} FeZnMn-nano	0.054 ± 0.0022^{ef}	0.076 ± 0.0021^{b}	0.067 ± 0.0021^{c}
0.50 g L^{-1} FeZnMn-nano	0.060 ± 0.0007^{cde}	0.091 ± 0.0023^{a}	0.079 ± 0.0025^{b}

FeZnMn, iron, zinc, and manganese bundle. Values are the mean of 3 replicates ± standard errors. Different letters within columns indicates that there are significant differences at 0.05 level of probability; *ns*, non-significant

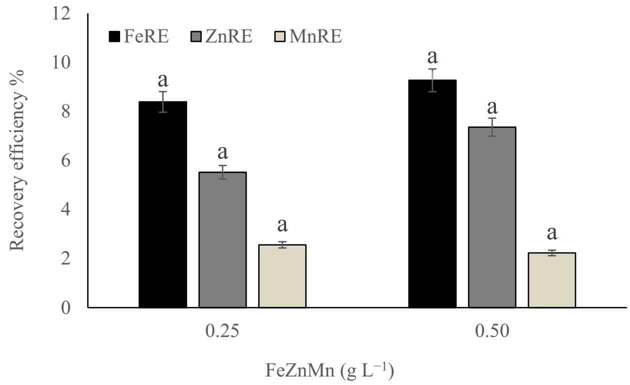

Fig. 3 Recovery efficiency of iron (FeRE), zinc (ZnRE), and manganese (MnRE) for sesame as affected by application of iron (Fe), zinc (Zn), and manganese (Mn) bundle (FeZnMn). Values are the mean of 3 replicates ± standard errors. Bars with similar letters are statistically non-significant at 0.05 level of probability

SYRI pointed out to the efficient genotype for producing higher seed yield at low nutrient rate and their response to increase nutrient fertilizer rates. In this connection, Fig. 5 illustrated that the average of sesame seed yield at zero micronutrients rate was 950.8 kg ha^{-1} as well as the mean of SYRI value for 0.24 FeZnMn-nano kg micronutrients was 615.4 kg seeds kg micronutrient ha^{-1}. Accordingly, both Sohag1 and Shandaweel3 genotypes were belonging to efficient and responsive (ER) group, being exceeded the averages of seed yield at zero micronutrients rate and SYRI, while Giza32 was neither efficient nor responsive (NENR), since the seed yield at zero micronutrients rate and SYRI were lower than the averages.

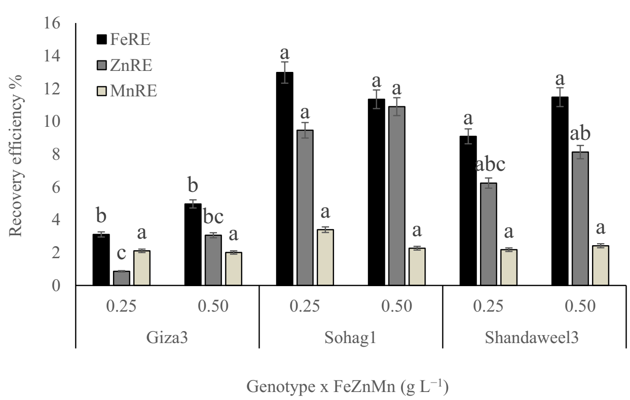

Fig. 4 Recovery efficiency of iron (FeRE), zinc (ZnRE), and manganese (MnRE) for the tested sesame genotypes under application of iron (Fe), zinc (Zn), and manganese (Mn) bundle (FeZnMn). Values are the mean of 3 replicates ± standard errors. Bars with different letters are statistically significant at 0.05 level of probability

4 Discussion

Findings of the current research clarified the differential response of sesame genotypes for agronomic traits (Table 2), oil and protein yields (Table 3), micronutrients uptake (Table 4), micronutrients recovery efficiency (Fig. 2), and SYRI (Fig. 5). This refers to the varied potential among sesame genotypes to utilize the absorbed micronutrient owing to their different genetic background. Saudy et al. (2018) stated that the higher leaf greenness produced by Sohag1 cultivar than other cultivars might have help it to absorb more solar radiation which could have led to enhanced assimilate production and consequently increased fruiting zone length, 1000-seed weight and seed yield. Different performances among sesame genotypes were also reported by Saudy and Abd El–Momen (2009) and Kashani et al. (2016). Moreover, varietal differences were observed between two cultivars of sesame in nutrient uptake (Laurentin and Rodriguez 2020).

It is interesting to clarify that the mixture of Fe, Zn, and Mn had promotive influences on sesame agronomic traits and yields (Tables 2, 3) and nutrient utilization, expressed in micronutrients uptake (Table 4). Since micronutrient combination treatment (Zn + Fe) improved net assimilation rate and crop growth rate (Heidarian et al. 2011), distinctive increases owing to micronutrients mixture application in yield traits (Table 2), and oil and protein yield of sesame (Table 3) were produced. Micronutrients have a major role in cell division and development of meristematic tissues, photosynthesis, respiration, and acceleration of plant maturity (Zeidan et al. 2010). Also, these elements play vital roles in CO_2 flowing out, improvement in vitamin A and immune system activities (Narimani et al. 2010). It is well known that Fe and Zn have a decisive role in various plant growth and developmental phases and in numerous biochemical reactions as well as in biosynthesis of RNA and DNA (Blasco et al. 2015). Fe is the inner component of cytochrome oxidase and protein ferredoxin which are fundamental for the nitrate and sulfate reduction, nitrogen assimilation, and energy generation (Honarjoo et al. 2013). Furthermore, Zn is involved in the major plant metabolisms, i.e., photosynthesis process, biosynthesis of auxins, carbohydrate and protein, cell division, maintaining cellular membrane stability, and sexual fertilization (Marschner 2012; Wasaya et al., 2017). Owing to Zn, as a crucial micronutrient, is included in several physio molecular functions, its existence has been shown to enhance crop growth and productivity (Haripriya et al. 2018; Singh et al. 2019b; El-Metwally and Saudy 2021). Song et al. (2015) stated that Zn is a central cofactor in vital biocatalytic enzymes and even has indirect roles in nucleic acid multiplication. Moreover, Mn plays a vital role in chlorophyll installation and involved in photochemical

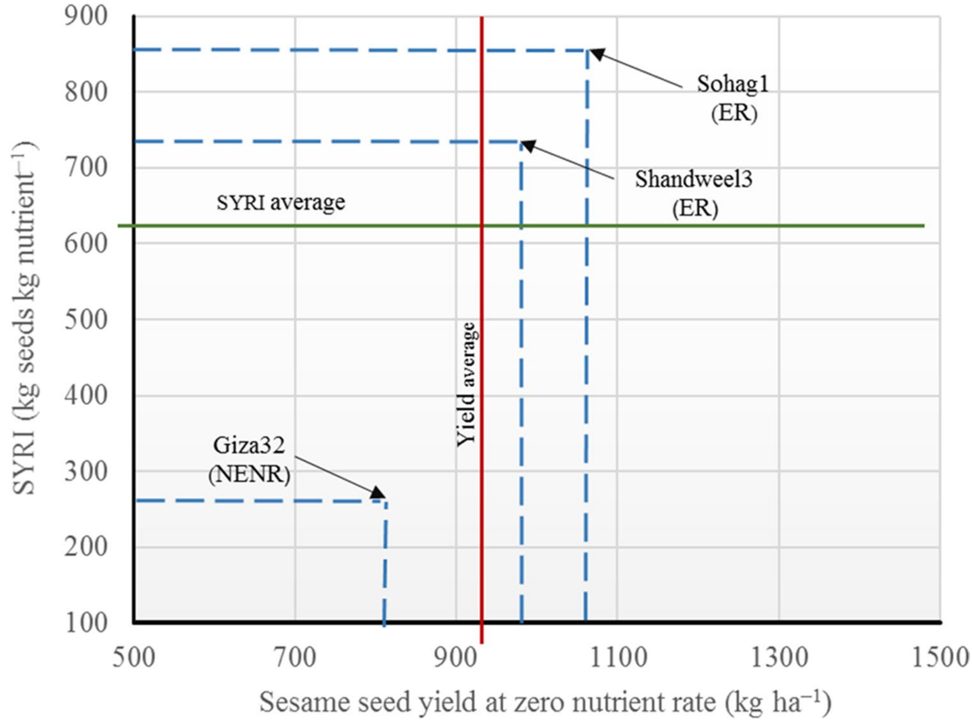

Fig. 5 Seed yield response index (SYRI) of the tested sesame genotypes fertilized by iron (Fe), zinc (Zn), and manganese (Mn) bundle at a rate of 0.24 FeZnMn-nano kg ha^{-1} (0.50 g L^{-1}). (ER, efficient and responsive; NENR, neither efficient nor responsive)

electron transfer reactions of plants (Yruela 2013). Additionally, Mn shares in water photolysis in photosynthesis apparatus (Andresen et al. 2018) and Mn ion can bind ATP to the enzyme complex (Zea et al. 2008). Accordingly, combined foliar application of Fe, Zn, and Mn achieved distinctive enhancements in sesame yield and its components (Tables 2, 3) and micronutrient uptake (Table 4). Enhancements in sesame yield and yield attributes were achieved owing to application of micronutrients mixture (Elayaraja 2018; Elayaraja and Sathiyamurthi 2020). Positive synergistic effects on photosynthesis, net assimilation rate, relative growth, seed yield, and oil yield were recorded with the combined application of Zn and/or Fe and Mn (Movahhedy−Dehnavy et al. 2009; Imran and Khan 2017; Roosta et al. 2018; Khodabin et al. 2021; Pal et al. 2021).

Since micronutrients in the form of nanoparticles have tiny size (Fig. 1), high sorption capacity, and diffusible nature with rapid and perfect absorption/uptake by the plants (Rameshaiah et al 2015), application of FeZnMn-nano could supply effectively the crop plants by their nutritional requirements (Raliya and Tarafdar 2013); thus, sesame yield and its components were improved with 0.50 g L^{-1} of FeZnMn-nano (Table 2). As reported by Prasad et al. (2012), plants the micronutrients in form nano quicker than the normal one. Compared to water-soluble ions, the penetration opportunities of nano-sized nutrients through the plant leaf surface, their ions across the cuticle were increased (Da Silva et al. 2006). Particles in nano-form have small size (1–100 nm) is clearly associated with the efficiency in their physicochemical features (Torabian et al. 2017). The activity of antioxidant enzymes as well as phenolics, proline, and chlorophyll contents positively responded to zinc-sulfate and nano-zinc oxide supply (Mohsenzadeh and Moosavian 2017). Significant improvements in growth and yield as well as the soil microbial counts and dehydrogenase activity were observed with nano Zn treatment (Bala et al. 2019).

Nano-micronutrients application not only improved the sesame yield attributes but also the micronutrients uptake (Table 4). The increases in Fe and Zn uptake were obviously produced with 0.50 g L^{-1} of FeZnMn-nano. All rates of nano-Fe, Mn, and Zn package achieved similar Mn uptake, exceeding the control treatment (Table 4). This refers to that the improvements in Fe and Zn uptakes are more correlated with the application of micronutrients than Mn uptake. Askary et al. (2017) pointed out that the nutrient solution containing nano-Fe increased fresh and dry weight of plant as well as K, P, Zn, Fe, and Ca content.

The calculation of SYRI proved the different potentiality of the tested sesame genotypes for absorbing and utilizing the available micronutrients in the plant media. Since seed yields of Sohag1 and Shandaweel3 genotypes were higher and seed yield of Giza32 genotype was lower than the average at nano-micronutrients application, this reflects the ability of both Sohag1 and Shandaweel3 genotypes to absorb the only source (soil) of micronutrients better than Giza32 genotype. The higher SYRI values, than the average, of Sohag1 and Shandaweel3 genotypes (Fig. 5) refer to their genetic potential to be responsive to nano-micronutrient additions. The higher values of SYRI (853.2 for Sohag1 and 729.2 for Shandaweel3) compared to the average of SYRI (615.4) under 0.24 nano kg micronutrients ha^{-1} refer to their better genetic potency to exploit and utilize micronutrients in soil and the exogenous supply. Differences in SYRI among crop genotypes were obtained by Noureldin et al. (2013) and Saudy et al. (2018)

5 Conclusions

Measuring micronutrients recovery efficiency and seed yield response index as recent parameters clarified varied performance of sesame genotypes. This genotypic variation, in addition to the unique properties of micronutrient nanoparticles should be exploited in nutrient addition program. In order to gain high profits of sesame cultivation, the farmers should keep in mind the relation between chosen genotype and micronutrient application. Thus, for efficient micronutrient use, fertilizing Sohag1 genotype by iron (Fe) plus zinc (Zn), and manganese (Mn), as nanoparticles bundle, at a rate of 0.50 g L^{-1} is advisable practice in sesame cultivation. Since Sohag1 genotypes had toughness in micronutrient utilization with efficient and responsive to micronutrients application, it is considered a promising genetic source in breeding programs to improve sesame varieties.

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Declarations

Conflict of Interest The authors declare no competing interests.

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