Cereal Research Communications (2022) 50:1269–1277
https://doi.org/10.1007/s42976-022-00251-8

ORIGINAL PAPER

Foliar zinc application for zinc biofortification in diverse wheat genotypes under low Zn soil

Salwinder Singh Dhaliwal[1] · **Vivek Sharma**[1] · **A. K. Shukla**[2] · **Vibha Verma**[1] · **S. K. Behera**[2] · **Prabhjot Singh**[1] · **Harkirat Singh**[1]

Received: 24 March 2021 / Accepted: 4 October 2021 / Published online: 7 February 2022

Abstract

The burgeoning population has forced farmers to grow wheat on light-textured low-zinc (Zn) soils which are otherwise not suitable for wheat cultivation. Growing Zn efficient wheat cultivars under such conditions along with Zn application is a sustainable approach to achieve higher Zn content and crop yield. Hence, screening of Zn efficient bread, durum and triticale wheat genotypes is necessary for their differential response toward foliar Zn application owing to their variable genetic characteristics. A field experiment was conducted on 16 (bread, durum and triticale) wheat genotypes with foliar application of Zn at different physiological stages for two years. Zinc application resulted in a maximum increase of grain and straw yield for the triticale genotype-TL2942 (48.2%) and bread genotype-PBW343U (68.4%) over the control. The grain and straw concentration of Zn increased to a maximum in the durum genotype-HD2967 (68.5%) and bread genotype-PBW 621 (51.2%) over the control. With respect to grain yield efficiency index (GYEI) and grain Zn accumulation efficiency index (ZAEI), PBWZn1 (95.8) and TL2969 (127.9), respectively, responded better to the Zn application. Based on GYEI and ZAEI, the genotypes TL2969, PDW291 were categorized as efficient and responsive, PBWZn1, HD2967, PBW621, PDW274, PBW343U efficient and non-responsive, PDW233, PDW314, PBW677, WHD943, TL2908, PBW725 inefficient and responsive as well as PBW550U, PBW550, TL2942 inefficient and non-responsive. The TL2969, PDW291 genotypes of wheat are most desirable for economical production due to higher yield and more Zn accumulation in low-Zn soil.

Keywords Wheat genotypes · Zinc accumulation · Grain yield · Grain and zinc efficiency index · Efficient and responsive genotypes

Introduction

Wheat (*Triticum aestivum* L.) is an important cereal crop consumed directly by humans. Wheat straw is also used as livestock feed and for industrial purposes like cardboard, packing etc. (Tian et al. 2018). In India, wheat is cultivated on 30 m ha area and provides a major portion of the human nutritional requirement of proteins, calories and micronutrients (GOI 2017; Cakmak and Kutman 2018). Bread wheat (BW) and durum wheat (DW) varieties are commercially important, whereas a triticale wheat variety is primarily grown for livestock feed. Bread wheat products mainly include bread, cookies, pastries etc. and DW is generally used for making pasta (Shewry 2018). Triticale wheat varieties produced from a man-made cross of durum wheat and rye, have been utilized in bio-ethanol production (Zhu 2018).

Over the past few decades, wheat consumption has not been able to meet the recommended dietary allowance for zinc (Zn) due to inherently low Zn concentration globally. Low Zn concentration in grain is found to be associated with declines in available nutrient levels in soils, as the soil serves as the primary source for plant nutrients (Dhaliwal et al. 2020). Over the past few decades, Zn deficiency was found to be prevalent in calcareous soils and soils having high pH, worldwide. The analysis of two hundred and forty-one thousand soil samples from different regions of India reported low-Zn content in 49% of Indian soils. The problem is more prevalent in the north Indian region with

---

Communicated by M. Taylor.

✉ Salwinder Singh Dhaliwal
ssdhaliwal@pau.edu

[1] Department of Soil Science, Punjab Agricultural University, Ludhiana 141004, India

[2] Indian Institute of Soil Science, Bhopal 462038, India

rice–wheat cropping systems due to inadequate soil management (Hussain et al. 2013). Thus, researchers have paid much attention to produce crops with the optimum level of Zn in low-Zn soils due to its essential physiological role in living organisms (Alloway 2008).In human beings, the deficiency of Zn affects epidermal, gastrointestinal, central nervous, immune, skeletal and reproductive systems (Cakmak and Kutman 2018). Various measures have been reported by the scientific community to improve Zn levels in crops. Soil/foliar Zn fertilization has been advocated to alleviate Zn deficiency up to a certain extent; however, fertilizer application may not prove effective due to the low nutrient utilization efficiency of a crop controlled by its genetic characters (Sciacca et al. 2018). Moreover, these measures may not be feasible due to the relatively high economic and labor costs.

The preliminary studies are necessary for the identification of Zn efficient and responsive crop genotypes under low-Zn conditions to obtain optimum yield and Zn concentration. Zinc efficient genotypes refer to the genotypes that possess efficient utilization of Zn, whereas responsive genotypes are those which show a significant response to exogenous applied Zn (Singh et al. 2019). The screening may prove a cost-effective, eco-friendly and sustainable approach due to lesser use of fertilizers. Various reports on the screening of Zn efficient wheat genotypes under different agroclimatic zones have been documented on a limited number of genotypes (Jhanji et al. 2013; Singh et al. 2019). In this paper, an attempt has been made to screen the latest developed Zn efficient wheat genotypes along with some genotypes registered earlier and are still performing well in agriculture production. Keeping this point in view, the present study was conducted to identify Zn efficient BW, DW and TW genotypes on a criterion of higher yield as well as higher Zn accumulation in low-Zn soil. The study would probably assist breeders in incorporating their efficient characters or genes into high yielding wheat cultivars and improve malnutrition.

Materials and methods

Site description

A field experiment was conducted for two years (2018–2019, 2019–2020) at the research farm of the Department of Soil Science, PAU Ludhiana (30° 56′ N, 75° 52′ E and 247 m above mean sea level), to determine the response of foliar application of Zn in 16 wheat genotypes (7-BW, 6-DW and 3 TW). The parental lines, year of notification, duration of days and average yield (t ha^{-1}) at the time of their registration by the state government is given in Table S 1.

Soil sampling and analysis

A composite soil sample was taken from the soil rhizosphere (0–15 cm) of the experimental site, air dried, sieved by a 2 mm sieve and analyzed to study the basic soil properties and Zn content in the experimental soil. The physicochemical properties of the experimental soil were determined using standard methodology. The initial physicochemical properties of soil have been given in Table S 2.

Experimental detail

The experiment was laid out in a randomized block design with a single plot area of 30 m^2 (6 m × 5 m) and the total experimental area was 30*128 m^2 (16 cultivars * 2 treatment * 4 replications). The sowing was done with a drill with row to row spacing of 20 cm. The treatments comprised of two foliar sprays of $ZnSO_4.7H_2O$ @ 0.5% (2.5 kg zinc sulphate in 500 L solution ha^{-1}) at maximum tillering, flag leaf initiation stage and no spray treatment. The recommended dose of N (123.5 kg ha^{-1}), P (61.8 kg ha^{-1}), K (61.8 kg ha^{-1}) were added through urea, diammonium phosphate and muriate of potash, respectively. The whole of diammonium phosphate, muriate of potash and one-third of urea were applied at the time of wheat sowing using seed cum fertilizer drill. However, the remaining urea (two-third part) was applied in two equal splits after first and second irrigation. In all, four channel irrigations were applied throughout the crop season.

Plant sampling and analysis

For plant growth parameters, ten plants samples were tagged randomly from central rows to measure the plant height and spike length in centimeters. The grains of selected spikes were harvested manually to count their respective grain numbers and mean values were expressed as the number of grains per spike. The average weight and number of these grains were computed to express 1000 grain weight in grams. Grain yield was calculated per ha by taking the total plot area 12 square meters (4 m*3 m) by leaving 1 m buffer from all four sides. For Zn content, the grain and straw samples were collected after harvesting of the crop. Grain samples were dried in air, followed by oven drying at 60 °C. For analysis of straw, samples were first washed with tap water and then with 0.01 N HCl and distilled water to remove aerial deposits/contaminants, followed by air drying and oven drying. Regarding the investigation, 0.5 g of dried finely ground, grain and straw samples were weighed and digested with 8 ml di-acid mixture ($HNO_3 + HClO_4$ in ratio 9:4) on an electric hot plate. The digested samples were cooled, diluted with distilled water and filtered. With appropriate dilutions, the concentration of Zn in the digested plant samples was determined through atomic absorption spectrophotometer Model AA 240 FS, Company Varian, Germany.

Zinc accumulation in grain and straw

Zinc accumulation in the grain and straw was calculated by multiplying concentrations with respective yields. The grain yield efficiency index (GYEI) and Zn accumulation efficiency index (ZAEI) were estimated using the following equations (Graham et al. 1992).

$$\text{Znaccumulation}\left(\text{g ha}^{-1}\right) = \text{Yield}\left(\text{tha}^{-1}\right) \times \text{Znconcentration}\left(\text{mg kg}^{-1}\right)$$

$$\text{GYEI} = \frac{\text{Grain yield under control}}{\text{Grain yield under foliar Zn application}} \times 100$$

$$\text{ZAEI} = \frac{\text{Zn accumulation under control}}{\text{Zn accumulation under foliar Zn application}} \times 100.$$

Statistical analysis

The plant attributes, yield, Zn concentration and Zn accumulation data of different wheat genotypes were calculated based on pooled data averaged for two years as the replication effects over the years were found to be non-significant. The data were analyzed using a one-way analysis of variance (ANOVA). Standard error of difference (SED) was worked out from the ANOVA table (Cochran and Cox 1957) by using SAS 9.2 software pack. The least significant difference (LSD) was used for comparison where *F* probabilities were significant ($p < 0.05$).

Results

Plant growth parameters and yield attributes

Significant variations in plant height, spike length, grain number per spike and 1000 grain weight of wheat genotypes were observed with foliar application of Zn (0.5% $ZnSO_4.7H_2O$) as reported in Table S 3. In BW genotypes, plant height values varied from 84.6 (PBW550) to 92.2 cm (PBW677) without Zn application, whereas with foliar application of Zn, it ranged from 90.5 (PBW550U) to 107.1 cm (PBW343U) with the maximum increase in PBW343U (26.0%). In DW genotypes, under control conditions plant height varied from 77.7 (PDW314) to 89.3 (HD2967) cm, whereas with foliar application of Zn the range varied from 89.2 (PDW233) to 102.9 (PDW291, PDW314) cm. PDW314 showed a superior response to Zn application with a 32.4% increase in plant height. Among TW genotypes, the Zn application did not affect the plant height significantly.

In BW genotypes, the spike length varied from 6.3 (PBW677) to 9.9 (PBW343U) cm under control conditions. On the other hand, with foliar application of Zn, it ranged from 7.5 (PBW621) to 10.1 (PBW343U) cm. The superior response of spike length toward Zn application was observed in PBW677 (22.2%), whereas other genotypes did not respond to Zn application. In the case of DW genotypes, spike length varied from 5.8 (PDW291) to 8.1 (PDW274) cm under control conditions. When Zn was applied to these genotypes, it increased the range from 7.9 (PDW314) to 9.8 (PDW233) cm with the maximum increase in PDW291 (56.8%). In TW genotypes, maximum variation in spike length due to Zn foliar application was observed in TL2908 (33.3%).

The grain number per spike in BW genotypes varied from 173.5 (PBW677) to 353.5 (PBWZn1) without Zn application. On the other hand, the Zn application increased the grain number per spike of these genotypes from 262.5 (PBW667) to 463.5 (PBW550) with the maximum increase in PBW621 (71.7%). In DW genotype, grain numbers per spike varied from 215.0 (PDW314) to 385.5 (WHD943) under control conditions, whereas, with Zn application, it varied from 311.5 (PDW291) to 478.5 (PDW233) with superior response in PDW314 (88.1%). Among TW genotypes, TL2942 was found to be most responsive toward foliar Zn application with a 29.0% increase in grain number per spike.

The 1000 grain weight of BW genotypes ranged from 34.9 (PBW550) to 52.4 (PBW550U) in control, whereas, with foliar application of Zn, it ranged from 38.2 (PBW677) to 52.3 (PBW621). PBW621 showed a superior response with the maximum increase of 1000 grain weight (40.5%). In DW genotypes, 1000 grain weight under control conditions varied from 36.1 (PDW274) to 45.4 (PDW291), whereas, foliar application of Zn increased it from 36.9 (WHD943) to 46.3 (PDW314). Maximum increment in 1000 grain weight was observed for PDW233 (28.8%) followed by PDW274 (27.9%). The significant response of TW genotype TL2908 toward 1000 grain weight was observed with a 22.8% increase after Zn spray.

Grain and straw yield

The grain yield of BW genotypes under control conditions ranged from 4.44 (PBW677) to 4.94 (PBW343U) t ha^{-1}, while, with Zn application, it varied from 4.97 (PBWZn1) to

5.88 (PBW550) t ha^{-1} (Table S 4). The maximum increase in grain yield among BW genotypes was observed in PBW550 (26.4%). In the case of DW genotypes, grain yield varied from 4.44 (WHD943) to 5.19 (PDW274) t ha^{-1} without Zn application, whereas, foliar application of Zn resulted in improved grain yield 4.88 (HD2967) to 5.78 (PDW274) t ha^{-1} with a maximum variation in PDW233 (21.7%). Among TW genotypes, TL2942 was found to be most responsive toward Zn application with a maximum increase (24.4%) in grain yield.

The straw yield of BW genotypes under control conditions ranged from 9.11 (PBW550U) to 10.09 (PBW725) t ha^{-1}. Zinc foliar application increased the range of straw yield from 9.75 (PBW550U) to 10.76 (PBW725) t ha^{-1}, with the maximum increase in PBW621 (14.4%). On the other hand, the straw yield of DW varieties ranges from 8.10 (HD2967, PDW233) to 10.18 (PDW291) t ha^{-1} under control conditions and 9.45 (PDW233) to 11.3 (PDW291) t ha^{-1} under Zn application. The maximum response toward Zn application was observed in WHD943 (11.2%). Among TW genotypes, TL2942 was found to be most responsive toward Zn application with a maximum increase (18.8%) in straw yield due to foliar applied Zn.

Zinc concentration in grain and straw

The application of Zn increased the concentration of Zn in both grain as well as straw (Table S 5). The results showed that different wheat genotypes showed differential response toward the absorption of foliar applied Zn in nearly low-Zn soil (Zn 0.62 mg kg^{-1}) having 0.60 mg kg^{-1} as a critical limit of Zn deficiency in the soil. In some genotypes, a considerable difference was observed in Zn concentration of wheat seed before sowing and after harvesting. Among bread wheat (BW) genotypes, the PBWZn1 variety showed significantly lower Zn concentration (16%) in wheat seed before sowing and after harvesting. Among durum wheat (DW) genotypes, HD2967 (24.2%) followed by PDW233 (13.2%) showed a significant decrease in Zn seed concentration.

Under control conditions, the Zn concentration of BW genotypes in grains ranged from 26.1 (PBW621) mg kg^{-1} to 34.3 (PBWZn1) mg kg^{-1}, whereas it ranged from 36.8 (PBW725) to 55.4 (PBWZn1) mg kg^{-1} with the maximum increase in PBWZn1 (61.5%) due to Zn application. Zinc concentration of DW genotypes varied from 30.6 (PDW314) to 41.3 (PDW291) mg kg^{-1}, whereas foliar application of Zn increased it from 35.4 (HD2967) to 57.1 (PDW291). Maximum response of grain Zn concentration to Zn application was observed for HD2967 (68.5%). Among TW genotypes, Zn foliar application enhanced grain Zn concentration maximum in TL2942 (27.7%).

In BW genotypes, Zn concentration in straw varied from 9.2 (PBW343U) to 15.7 (PBWZn1) mg kg^{-1} in the control, whereas with Zn application, it varied from 13.2 (PBW677) to 19.2 (PBW550) mg kg^{-1}. The maximum positive response of straw Zn concentration toward Zn application was observed in PBW343U (68.4%). In the case of DW genotypes, Zn concentration in straw varied from 11.4 (PDW274) to 15.9 (PDW233) mg kg^{-1} without Zn application, whereas, with foliar application of Zn it ranges from 13.9 (PDW274) to 22.0 (PDW233) mg kg^{-1} with maximum variation in PDW233 (38.3%). Among TW genotypes, TL 2969 showed a superior response toward Zn application with a 27.5% increase in straw Zn concentration.

Zinc accumulation in grain and straw

The foliar application of Zn led to increases in Zn accumulation in both wheat grain as well as straw in all the cultivars (Fig. 1). In BW genotypes, under control conditions, grain Zn accumulation ranged from 124.6 g ha^{-1} (PBW621) to 162.9 g ha^{-1} (PBWZn1), whereas with Zn application, the range increased from 207.2 g ha^{-1} (PBW725) to 274.8 g ha^{-1} (PBWZn1). Zinc accumulation in DW genotypes under control conditions varied from 96.0 (HD2967) to 195.6 (PDW291) g ha^{-1}, whereas foliar application of Zn increased it from 172.6 (HD2967) to 299.1 (PDW291) g ha^{-1}. Among TW genotypes, Zn foliar application enhanced grain Zn concentration maximum in TL2942 (228.1–362.7 g ha^{-1}).

Likewise, Zn accumulation in straw was also enhanced in each variety. In the case of BW genotypes, Zn accumulation in straw without Zn application ranged from 89.0 (PBW343U) to 143.6 g ha^{-1} (PBWZn1), whereas with Zn application, the range increased from 138.6 (PBW677) to 191.6 g ha^{-1} (PBWZn1). On the other hand, in DW genotypes, Zn accumulation in straw varied from 99.3 (HD2967) to 136.4 (PDW233) g ha^{-1} without Zn application, whereas foliar application of Zn increased it from 144.8 (PDW274) to 208.0 (PDW233) g ha^{-1}. In the case of TW genotypes, Zn foliar application resulted in a maximum increase in Zn accumulation in the TL2942 genotype (133.4 to 196.4 g ha^{-1}).

GYEI and ZAEI of wheat genotypes

The GYEI and ZAEI of the genotypes were calculated to classify the genotypes based on grain yield and Zn accumulation in low-Zn soil, and their responses to Zn application (Table S 6). Both the indices of the genotypes differed significantly for each genotype. The GYEI of PBW621 (95.0) and PBWZn1 (95.8) among BW genotypes, HD2967 (94.0) and PDW291 (90.5) among DW genotypes and TL2969 (91.6) of TW genotypes were more than the mean value (90.5). The higher and lower values of GYEI indicated the higher and lower grain yield, respectively, in low-Zn soil. The genotypes like PBW677 (83.8) and PBW725 (84.7)

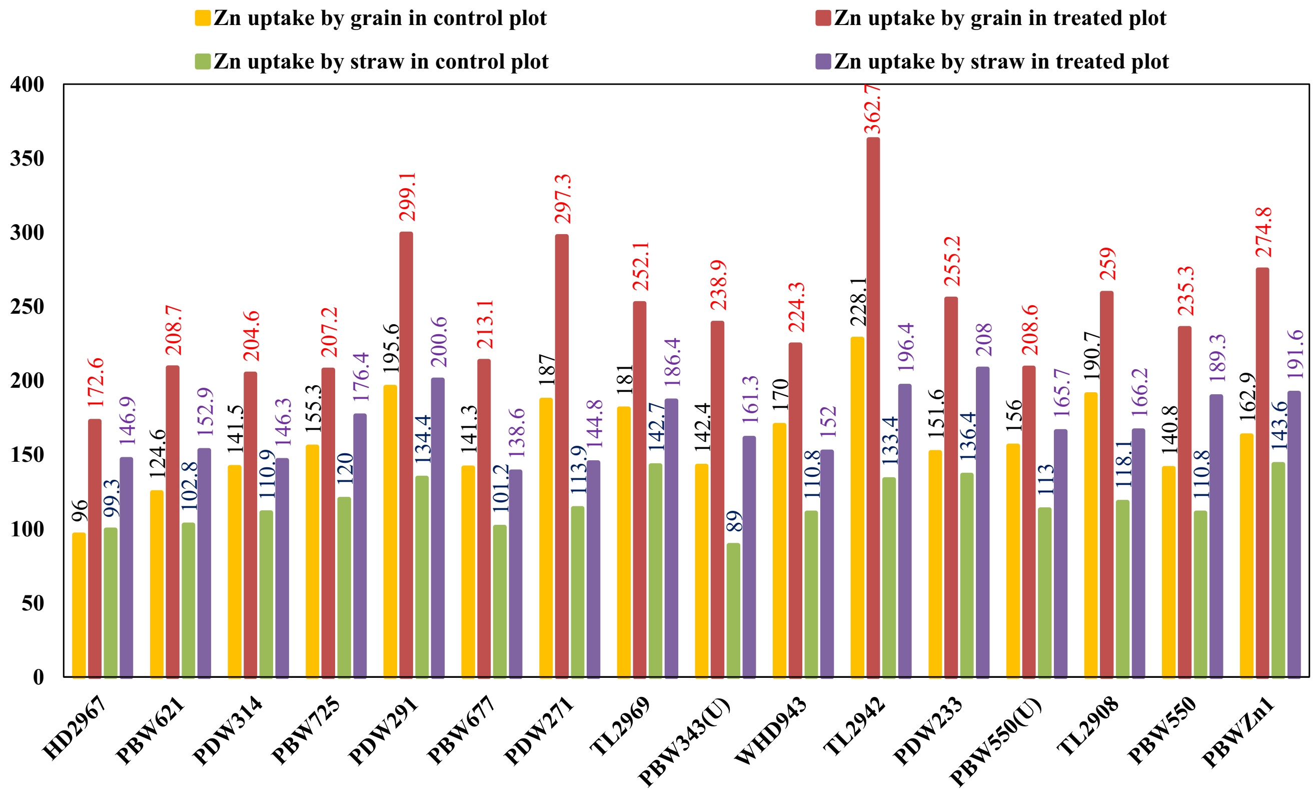

Fig. 1 Zn accumulation by (g ha^{-1}) of wheat genotypes as influenced by the foliar application of Zn

among BW genotypes, PDW233 (122.2), PDW291 (127.9) and WHD943 (86.7) among DW genotypes as well as two TW genotypes TL2908 (84.5) and TL2969 (180.6) had higher ZAEI than the mean value of 77.8.

Based on the GYEI, PBWZn1 (95.8) among BW genotypes, HD2967 (94.0) among DW genotypes and TL 2969 (91.6) among TW genotypes would be considered as the most Zn efficient genotype. However, based on ZAEI PBW725 (84.7) among BW genotypes, PDW291 (127.9) among DW genotypes and TL2969 (180.6) among TW genotypes would be considered as the most Zn efficient genotypes. Thus, to classify genotypes based on either sole GYEI or sole ZAEI as a criterion is not feasible in the present study. However, the above criteria might be applicable for the classification of genotypes possessing identical yield levels under non-limiting nutrient accessibility.

Classification of the wheat genotypes

The genotypes were classified into four classes based on their GYEI and ZAEI and these are shown in Fig. 2 (Singh et al. 2020). Class I included the Zn efficient and responsive (ER) genotypes TL2969 and PDW291 that possessed higher efficiency indices than the mean values of 16 genotypes. Class II comprised of five genotypes which showed Zn efficient and non-responsive (ENR) nature *i.e.*, these genotypes had higher GYEI but lower ZAEI showing their low response toward Zn application. Class III included Zn inefficient and responsive (IER) genotypes with lower GYEI and higher ZAEI and showed a significant positive response toward Zn application. Class IV comprised of Zn inefficient and non-responsive (IENR) genotypes having lower GYEI and ZAEI than the mean values.

Discussion

Growth parameters and yield attributes

The positive impacts of Zn fertilization on wheat crop in low-Zn soil were demonstrated by significant improvement in yield contributing parameters like increased plant height, spike length, grain number per spike and 1000-grain weight over the control. This finding is consistent with results obtained by Singh et al. (2019) on wheat crops. The improvement in growth parameters might be associated with the higher availability of Zn to perform major metabolic activities including carbohydrate metabolism, chlorophyll synthesis, and ribosomal functioning during the reproductive phase of crop growth (Kumar et al. 2019; Zulfidar et al. 2020). Gomez-Coronado et al. (2017) also reported a significant increase of 1000-grain weight along with qualitative

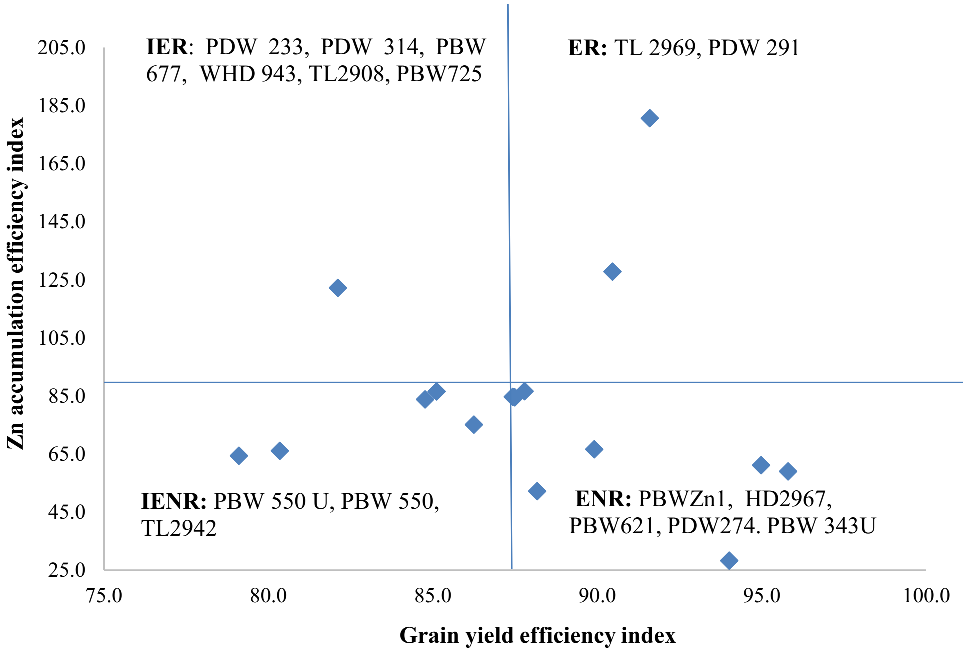

Fig. 2 Classification of wheat genotypes for Zn efficiency (ER- efficient and responsive, IER- inefficient and responsive, IENR inefficient and non-responsive ENR, Efficient and non-responsive

(protein content, phytate–zinc ratio and zinc content) and quantitative parameters on Zn application. The increase in the number of kernels per spike due to Zn application has also been reported (Liu et al. 2016). Seadh et al. (2009) found that Zn treatment resulted in the highest plant height and highest number of spikelets per spike among micronutrient applications in wheat crop.

The results from Table S 5 reflected the importance of Zn application to reduce the gap between the potential and actual yield of wheat particularly in Zn deficient soil. Higher grain and straw yield in response to foliar Zn application might be attributed to the better availability of micronutrients over the control having low Zn level in the soil. Dhaliwal et al. (2009) reported 8.2% and 4.3% higher yields over control with the application of Zn in wheat cultivars for PBW 550 and PBW 343, respectively. The improvement in grain yield due to foliar applied Zn might be associated with its role in chlorophyll (Chl) biosynthesis, maintenance of Chl a/b ratio and plant photosynthetic apparatus along with biosynthesis of auxin, which regulates the re-translocation of carbohydrates to the grains (Liu et al. 2016; Rehman et al. 2012). Moreover, the positive impact of Zn application on yield traits might be due to its structural feature as a metal component or regulatory in numerous key enzymes having a prominent role in plant metabolism, and maintenance of membrane integrity (Rehman et al. 2012).

Zinc concentration and accumulation

In some genotypes, a considerable difference was observed in Zn concentration of wheat seed before sowing and after harvesting. A decrease in Zn content in control plants after harvesting of wheat may be due to the internal genetic potential of wheat cultivars toward Zn accumulation as the basic Zn status of experimental soil was observed close to its critical limit (< 0.62 mg kg^{-1}).

Also, different wheat genotypes showed differential responses toward Zn application for grain and straw Zn concentration. Significant improvement in grain Zn concentration with foliar applied Zn at different plant growth stages might be associated with the Zn mobility in wheat through crease phloem, which has been reported as the key path for transporting Zn to the endosperm (Cakmak et al. 2010). Xue et al. (2012) observed that the application of Zn in wheat crops increased Zn concentration in grain by 8–10% due to its remobilization from leaves to grain (Xue et al. 2012). Ram et al. (2015) also reported that the application of foliar Zn along with propiconazole at earing and milk stages proved beneficial in increasing grain Zn content in both rice and wheat. Foliar Zn fertilization at critical growth stages improved Zn concentration in BW (Abdoli et al. 2014). Zhang et al. (2010) also reported a significant increase in grain Zn concentration in wheat (68%) over the control with foliar Zn application at the grain-development stage.

Literature studies also revealed the existence of significant differences in micronutrient concentrations in different varieties and thus their variable response toward nutrient application (Mathpal et al. 2015). Dhaliwal et al. (2019) also reported that foliar Zn application increased grain Zn concentration in BW, TW and DW genotypes varying from 31.0 to 63.0, 29.3 to 61.8, and 30.2 to 62.4 mg kg^{-1}, respectively. This variation might be related to differences in mechanisms involved in accumulation, translocation of nutrients from the soil and internal utilization of micronutrients due to variable genetic make ups (Fageria and Baligar 2003). Among the tested varieties of wheat, 60–78% higher Zn concentration was found in grain as compared to straw. The higher Zn concentration in wheat grain than straw showed that Zn is more easily mobilized to grain than straw. Similar results were also reported by Dhaliwal et al. (2012). An increase in Zn concentration in different parts of wheat was also reported by Hussain et al. (2013). A similar increase in Zn was also reported by Dhaliwal et al. (2010) in rice grains.

In agreement with the present study, similar results of the increase in Zn accumulation by grain and straw were reported by Dhaliwal et al. (2013). Accumulation of Zn in grain was found to be dependent on the remobilization of Zn from shoot and the continued shoot accumulation of Zn during the grain-filling stage (Impa et al. 2013). In general, variation of Zn accumulation in grains is known to be associated with the root acquisition and internal remobilization of stored Zn within the plants. Zinc deficiency induced ZIP transporters might have contributed to Zn uptake by roots and its transportation across the plasma membrane and cytoplasm (Liu et al. 2019). Apart from the inherent physiological parameters of plants, including root uptake and redistribution of Zn within the plant, environmental factors such as soil chemical and physical properties, climatic conditions and management practices, also play significant roles in variable grain Zn accumulation (Velu et al. 2012). Dhaliwal et al. (2020) reported that the soil and foliar application of Zn at 25 kg ha^{-1} and 0.5% Zn, respectively, at 60 DAS and 90 DAS enhanced the Zn accumulation and quality of fodder oats.

Literature studies demonstrated that the inherent genetic makeup affected Zn accumulation, thus, the selection of wheat genotypes with a higher capacity to accumulate Zn combined with the exogenous supply of Zn is crucial to sustainable crop production in low-Zn soil (Gomez-Coronado et al. 2017; Cakmak et al. 2010). Dhaliwal et al. (2011) concluded that lines with high Zn efficiency had higher Zn accumulation by roots, but not higher Zn concentration in grains because increased Zn accumulation was used to increase dry matter production.

GYEI and ZAEI

The screening of Zn efficient wheat genotypes on the basis of grain yield and Zn accumulation has been reported by Singh et al. (2019) and for Zn and Cu by Dhaliwal et al. (2011). Genetic traits and environmental factors have been reported as key drivers to regulate the nutrient use efficiency of plants (Baligar et al. 2001). Thus, the identification of Zn efficient genotypes having better absorption and utilization capacity is beneficial for the current demand of low input-high output agriculture. Keeping this in view, the genotypes were classified using both GYEI and ZAEI.

Conclusions

The study concluded that the genetically diverse bread, durum and triticale wheat genotypes showed variable responses toward foliar Zn application due to variable inherent genetic characteristics. Plant growth parameters, grain yield, Zn concentration and Zn accumulation were enhanced with the application of Zn on plant foliage. The effective and responsive genotypes (TL2969, PDW291) can produce higher yield in low Zn soils and showed a positive response to Zn fertilizer application, thus could be used for quantitative and qualitative crop production under low Zn soils. Effective and non-responsive (PBWZn1, HD2967, PBW621, PDW274, PBW343U) genotypes showed a significant increase in wheat yield and non-significant changes in Zn accumulation. Ineffective and responsive (PDW 233, PDW 314, PBW 677, WHD 943, TL2908, PBW725) genotypes showed a non-significant increase in wheat yield, however, significant changes were observed in Zn accumulation. Ineffective and non-responsive (PBW 550 U, PBW 550, TL2942) did not show any response on wheat yield as well as in Zn accumulation.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42976-022-00251-8.

Acknowledgments The authors are thankful to the Punjab Agricultural University, Ludhiana, India for providing necessary facilities during the research work.

Funding This work was supported by ICAR Indian Institute of Soil Science Bhopal.

Availability of data and material (data transparency) Data will be available on demand.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Abdoli M, Esfandiari E, Mousavi SB, Sadeghzadeh B (2014) Effects of foliar application of zinc sulphate at different phenological stages on yield formation and grain zinc content of bread wheat (cv. Kohdasht). Azarian J Agric 1(1):11–17

Alloway BJ (2008) Micronutrient deficiencies in global crop production, 1st edn. Springer, New York

Baligar VC, Fageria NK, He ZL (2001) Nutrient use efficiency in plants. Commun Soil Sci Plant Anal 32:921–950

Cakmak I, Kalayci M, Kaya Y, Torun AA, Aydin N, Wang Y, Arisoy Z, Erdem H, Yazici A, Gokmen O, Ozturk L, Horst WJ (2010) Biofortification and localization of zinc in wheat grain. J Agric Food Chem 58:9092–9102

Cakmak I, Kutman UB (2018) Agronomic biofortification of cereals with zinc: a review. Eur J Soil Sci 69:172–180

Cakmak I, McLaughlin MJ, White P (2017) Zinc for better crop production and human health. Plant Soil 411:1–4

Cochran WG, Cox GM (1957) Experimental designs. Wiley, New York

Dhaliwal SS, Ram H, Shukla AK, Mavi GS (2019) Zinc biofortification of bread wheat, triticale, and durum wheat cultivars by foliar zinc fertilization. J Plant Nutr 42:813–822

Dhaliwal SS, Sadana US, Khurana MPS, Dhadli HS, Manchanda JS (2010) Enrichment of rice grains with zinc and iron through ferti-fortification. Indian J Fert 6:28–39

Dhaliwal SS, Sadana US, Khurana MPS, Sidhu SS (2012) Biofortification of wheat grains with zinc through ferti-fortification. Indian J Fert 8:34–45

Dhaliwal SS, Sadana US, Manchanda JS (2011) Relevance and essentiality of ferti-fortification of wheat grains with manganese and copper. Indian J Fert 7:48–55

Dhaliwal SS, Sadana US, Manchanda JS, Dhadli HS (2009) Biofortification of wheat grains with zinc and iron in Typic Ustochrept soils of Punjab. Indian J Fert 5:13–26

Dhaliwal SS, Sandhu AS, Shukla AK, Sharma V, Kumar B, Singh R (2020) Bio-fortification of oats fodder through zinc enrichment to reduce animal malnutrition. J Agric Sci Tech a 10:98–108

Fageria NK, Baligar VC (2003) Methodology for evaluation of lowland rice genotypes for nitrogen use efficiency. J Plant Nutr 26:1315–1333

GOI (2017) Agricultural Statistics at a Glance 2017. URL. http://agricoop.gov.in/sites/default/files/agristatglance2017.pdf

Gomez-Coronado F, Poblaciones MJ, Almeida AS, Cakmak I (2016) Combined zinc and nitrogen fertilization in different bread wheat genotypes grown under mediterranean conditions. Cereal Res Commun 45:154–165

Graham RD, Ascher JS, Hynes SC (1992) Selecting zinc-efficient cereal genotypes for soils of low zinc status. Plant Soil 146:241–250

Hussain S, Maqsood MA, Aziz T, Basra SMA (2013) Zinc bioavailability response curvature in wheat grains under incremental zinc applications. Arch Agron Soil Sci 59:1001–1016

Impa SM, Morete MJ, Ismail AM, Schulin R, JohnsonBeebout SE (2013) Zn uptake, translocation and grain Zn loading in rice (Oryza sativa L.) genotypes selected for Zn deficiency tolerance and high grain Zn. J Exp Bot 64:2739–2751

Jackson ML (1973) Soil chemical analysis. Prentice Hall, England, UK

Jhanji S, Sadana US, Sekhon NK, Khurana MPS, Sharma A, Shukla AK (2013) Screening diverse wheat genotypes for manganese efficiency based on high yield and uptake efficiency. Field Crops Res 154:127–132

Kaur P, Hundal SS (2008) Climatic trends in different agroclimatic zones of Punjab: temperature features and its variability. J Res (PAU) 45:30–40

Kumar D, Dhar S, Kumar S, Meena DC, Meena RB (2019) Effect of zinc application on yield attributes and yield of maize and wheat in maize-wheat cropping system. Int J Curr Microbiol App Sci 8(1):1931–1941

Li M, Tian XH, Li XL, Wang SX (2017) Effect of Zn application methods on Zn distribution and bioavailability in wheat pearling fractions of two wheat genotypes. J Integ Agric 16(7):617–1623

Lindsay WL, Norvell WA (1978) Development of a DTPA soil test for zinc, iron, manganese and copper. Soil Sci Soc Am J 42:421–428

Liu DY, Liu YM, Zhang W, Chen XP, Zou CQ (2019) Zinc accumulation, translocation, and remobilization in winter wheat as affected by soil application of Zn fertilizer. Front Plant Sci 10:426

Liu DY, Zhang W, Yan P, Chen XP, Zhang FS, Zou CQ, Liu D-Y, Zhang W, Yan P, Chen X-P, Zhang F-S, Zou C-Q (2016) Soil application of zinc fertilizer could achieve high yield and high grain zinc concentration in maize. Plant Soil 411(1–2):47–55

Mathpal B, Srivastava PC, Shankhdhar D, Shankhdhar SC (2015) Zinc enrichment in wheat genotypes under various methods of zinc application. Plant Soil Environ 61:171–175

Ram H, Sohu VS, Cakmak I, Singh K, Buttar GS, Sodhi GPS, Gill HS, Bhagat I, Singh P, Dhaliwal SS, Mavi GS (2015) Agronomic fortification of rice and wheat grains with zinc for nutritional security. Curr Sci 109:1171–1176

Merwin HD, Peech M (1950) Exchangeability of soils potassium in the sand, silt and clay fractions as influenced by the nature of the complementary exchangeable cations. Soil Sci Soc America Proc 15:125–128

Olsen SR, Cole CV, Watanabe FS, Dean LA (1954) Estimation of available phosphorus by extraction with sodium bicarbonate. U S Deptt Agric Circ 939:1–19

Rehman H, Aziz T, Farooq M, Wakeel A, Rengel Z (2012) Zinc nutrition in rice production systems: a review. Plant Soil 361:203–226

Sciacca F, Allegra M, Licciardello S, Roccuzzo G, Torrisi B, Virzì N, Brambilla M, Romano E, Palumbo M (2018) Potential use of sicilian landraces in biofortification of modern durum wheat varieties: Evaluation of caryopsis micronutrient concentrations. Cereal Res Commun 46(1):124–134

Seadh SE, El-Abady MI, El-Ghamry AM, Farouk S (2009) Influence of micronutrients foliar application and nitrogen fertilization on wheat yield and quality of grain and seed. J Biol Sci 9(8):851–858. https://doi.org/10.3923/jbs.2009.851.858

Shewry PR (2018) Do ancient types of wheat have health benefits compared with modern bread wheat? J Cereal Sci 79:469–476

Singh MV, Behera SK (2011) All India coordinated research project of micro- and secondary nutrients and pollutant elements in soils and plants – a profile. Research bulletin no. 10. IISS, Bhopal, pp 1–57

Singh P, Shukla AK, Behera SK, Tiwari PK (2019) Zinc application enhances super oxide dismutase and carbonic anhydrase activities in zinc efficient and inefficient wheat genotypes. J Soil Sci Plant Nutr 19(3):477–487

Singh P, Shukla AK, Behera SK, Tiwari PK, Das S, Tripathi A (2020) Categorization of diverse wheat genotypes for zinc efficiency based on higher yield and accumulation efficiency. J Soil Sci Plant Nutr 20:648–656

Tani FH, Barrington S (2005) Zinc and copper uptake by plants under two transpiration rates. Part II. Buckwheat (Fagopyrum esculentum L.). Environ Pollut 138:548–558

Tian SQ, Zhao RY, Chen ZC (2018) Review of the pretreatment and bioconversion of lignocellulosic biomass from wheat straw materials. Renew Sust Energ Rev 91:483–489

Velu G, Singh RP, Huerta-Espino J, Pena RJ, Arun B, Mahendru-Singh A, Mujahid MY, Sohu VS, Mavi GS, Crossa J, Alvarado G, Joshi AK, Pfeiffer WH (2012) Performance of biofortified spring wheat genotypes in target environments for grain zinc and iron concentrations. Field Crops Res 137:261–267

Walkley A, Black CA (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci 37:1367–1378

Xue YF, Yue SC, Zhang YQ, Cui ZL, Chen XP, Yang FC, Cakmak I, McGrath SP, Zhang FS, Zou CQ (2012) Grain and shoot Zn accumulation in winter wheat as affected by nitrogen management. Plant Soil 261:153–163

Zhang Y, Shi R, Rezaul KMD, Zhang F, Zou C (2010) Iron and zinc concentrations in grain and flour of winter wheat as affected by foliar application. J Agric Food Chem 58:12268–12274

Zhu F (2018) Triticale: Nutritional composition and food uses. Food Chem 241:468–479

Zulfidar U, Hussain S, Ishfaq M, Matloob A, Ali N, Ahmad M, Alyemeni MN, Ahmad P (2020) Zinc-induced effects on productivity, zinc use efficiency, and grain biofortification of bread wheat under different tillage permutations. Agronomy 10:1566