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FULL-LENGTH RESEARCH ARTICLE

Zinc Fortification of Oat Grains Through Zinc Fertilisation

Yashbir Singh Shivay · Rajendra Prasad · Madan Pal

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Abstract A two-year study at the Indian Agricultural Research Institute, New Delhi showed that an increase in grain and straw yields and zinc (Zn) fortification of grains of oats is possible by Zn fertilisation. Zn fertilisation is the fastest way to fortify oat grains with Zn, which is wanting in human and animal nutrition, especially in developing countries. Zn fortification of oats deserves special attention, because oat is gaining importance as a healthy cereal for human consumption. Coating oat seeds with Zn sulphate or Zn oxide before sowing was found to be the best method from the viewpoint of grain and straw yields as well as Zn fortification of oat grains. The next best method was deep placement of Zn fertilisers at sowing.

Keywords Biofortification · Coating Zn onto seeds · Deep placement of Zn · Ferti-fortification · Zn nutrition

Introduction

Zinc (Zn) deficiency in humans has received considerable interest in the recent past and as much as one-third of the world's population may be at risk from inadequate Zn intake [3]. Black et al. [4] reported that more than 450,000 children under the age of 5 years died during 2008 due to diarrhoea caused by Zn deficiency. Zn deficiency leads to diarrhoea and pneumonia in children [6]. It also leads to dwarfism in children [5]. Biofortification of cereal grains, which are the staple food in developing countries, has therefore received considerable attention during recent years.

There are three major ways of biofortification of cereal grains. These include food supplements [1, 21], genetic biofortification and agronomic manipulation through micronutrient fertilisers [22]. A number of global projects on genetic biofortification of food crops are underway [9, 20] including 'HarvestPlus, a Global Challenge Program' of the Consultative Group of the International Agricultural Research (CGIAR), which focuses on breeding for higher levels of Fe, Zn and β-carotene in the major staple crops of the developing countries, namely, rice, wheat, maize, cassava, sweet potato and beans; 'The Golden Rice Project', which focuses on genetic engineering approach to biofortify rice with β-carotene, Fe, Zn, vitamin E and protein under the 'Great Challenges in Global Health' scheme funded by Bill & Melinda Gate Foundation and 'African Biofortified Sorghum Project' funded by Bill & Melinda Gates Foundation, which focuses to fortify sorghum with Fe, Zn, vitamin A and vitamin E. Despite the enormous research activities, so far, only two biofortified crop cultivars have been successfully developed. Vitamin A-rich orange-fleshed sweet potato has already been introduced and is being produced in South Africa [14]. Similarly β-carotene-rich golden rice has been allowed to be cultivated in the Philippines [10]. No Zn-rich cultivar has been released in any food crop so far.

Agronomic manipulation (Ferti-fortification) is a quicker and faster approach to increase Zn concentration in cereal grains. Available reports show that Zn fertilisation increased Zn concentration in rice grain from 35 to 141 % in rice [12, 23, 29], from 24 to 48 % in wheat [22, 30] and 72 % in maize [12].

Y. S. Shivay (✉) · R. Prasad · M. Pal
Division of Agronomy, Indian Agricultural Research Institute, New Delhi 110 012, India
e-mail: ysshivay@hotmail.com

Oat is emerging as an important dietary cereal, due to its high β-glucan content, which imparts it human health benefits in terms of lowering cholesterol and blood glucose levels [2, 15]. Oat is being increasingly incorporated in breakfast cereals, beverages and infant foods [7], which make it an important crop that deserves attention for fortification of its grains with Zn. Therefore, the present study was undertaken to study the effect of sources, methods and time of application of Zn on the grain yield and Zn concentration in oat grains.

Materials and Methods

Experimental Site, Soil and Weather Parameters

Field experiments were conducted during winter–spring season (December–May) of 2009–2010 and 2010–2011 at the research farm of Indian Agricultural Research Institute, New Delhi, situated at 228.6 m amsl at 28°40′N latitude and 77°12′E longitude. The mean annual rainfall of Delhi is 650 mm and more than 80 % of it is generally occurs during July–September. The mean annual evaporation is 850 mm. The experimental site used for this experiment was under rice during previous cropping season (*kharif*). Before the start of the experiment in *rabi* season, the soil samples were taken and as regards the initial fertility status of experimental field, it had 216 kg ha^{-1} alkaline permanganate oxidizable N [27], 14.0 kg ha^{-1} 0.5 M $NaHCO_3$ extractable P [18], 233 kg ha^{-1} 1 N ammonium acetate exchangeable K [11] and 0.48 % organic carbon as determined by the procedure described by Walkley and Black [28]. The pH of soil was 7.8 (1:2.5 soil and water ratio) and DTPA-extractable Zn [13] in soil was 0.63 mg kg^{-1} of soil, and the response to Zn was expected. The weather parameters during the growing period of the oat crops in 2009–2010 and 2010–2011 are given in Fig. 1a, b, however, there was no relationship of weather parameters with Zn fortification during 2 years of study.

Experimental Design and Treatments

The experiment was laid out in a randomised block design with three replications. The treatments were 12 combinations of two rates (2 and 5 kg Zn ha^{-1}), 2 sources ($ZnSO_4 \cdot 7H_2O$ abbreviated as ZnSHH in this study and ZnO) and 3 methods of Zn application and a control (no Zn). Two kg Zn ha^{-1} was applied as broadcast or deep placed at 5 cm below the seed (with tyne/plastic tubes attached with a ferti-seed drill) at sowing or coated onto 100 kg oat seeds used for sowing 1 ha of land. ZnSHH or ZnO was coated on oat seeds using neem (*Azadirachta indica* Juss) oil as a binder a day before sowing. Five kg Zn ha^{-1} was applied as broadcast at sowing or banded just before or after first irrigation applied 25 days after sowing (DAS). Commercial grade $ZnSO_4 \cdot 7H_2O$ contained 20 % Zn and thus 10 and 25 kg ha^{-1} was required to supply 2 and 5 kg Zn ha^{-1}, respectively. Commercial grade ZnO contained 80 % Zn and 2.5 and 6.25 kg ha^{-1} was required to supply 2 and 5 kg Zn ha^{-1}, respectively. All plots received 26.2 kg P ha^{-1} as single superphosphate and 33 kg K ha^{-1} as muriate of potash, which was broadcast before final ploughing. Nitrogen @ 90 kg ha^{-1} as prilled urea was applied in all plots in two equal applications; half at the time of sowing and the remaining half after first irrigation at field capacity condition.

Sowing and Raising of Crop

Sowing of the oat variety 'Kent' was done with a seed drill adjusted for an inter-row spacing of 23 cm in the first fortnight of December during both the years. The plot size was 5 m × 4.83 m^2. The seed rate was 100 kg ha^{-1}. The crop received four irrigations, the first being at 25 DAS while the other three were given as per the need of the crop. The crop was harvested in the first week of May during both the years of experimentation.

Grain and Straw Yields

At the time of maturity the net plots (leaving two border rows on each side and 0.5 m area from each side of the length) were harvested and sun-dried for 3 days in the field. The weight of the harvested plants after sun drying and before threshing was recorded. After threshing, cleaning and drying, the grain yield was recorded for each plot and adjusted at 11 % moisture. Straw yield was obtained by deducting the grain weight from the total weight (biological yield). The grain and straw yields were expressed in Mg ha^{-1}.

Sampling of Grains and Straw for Zn Analysis

100 g grain and straw samples were collected from the harvest of each plot and dried in hot air oven at 60 ± 2 °C for 6 h. The oven dried samples were ground in a Wiley Mill and sieved to pass through a 40-mesh sieve. A 0.5 g grain and straw sample was digested in a 3:10 mixture of perchloric and nitric acid and Zn concentration in the digest was determined on an atomic absorption spectrophotometer (Perkin Elmer; Model-A. Analyst 100) [22].

Statistical Analysis

All the data obtained were statistically analysed using the *F* test [8] and least significance difference (LSD) values at $P = 0.05$ were calculated.

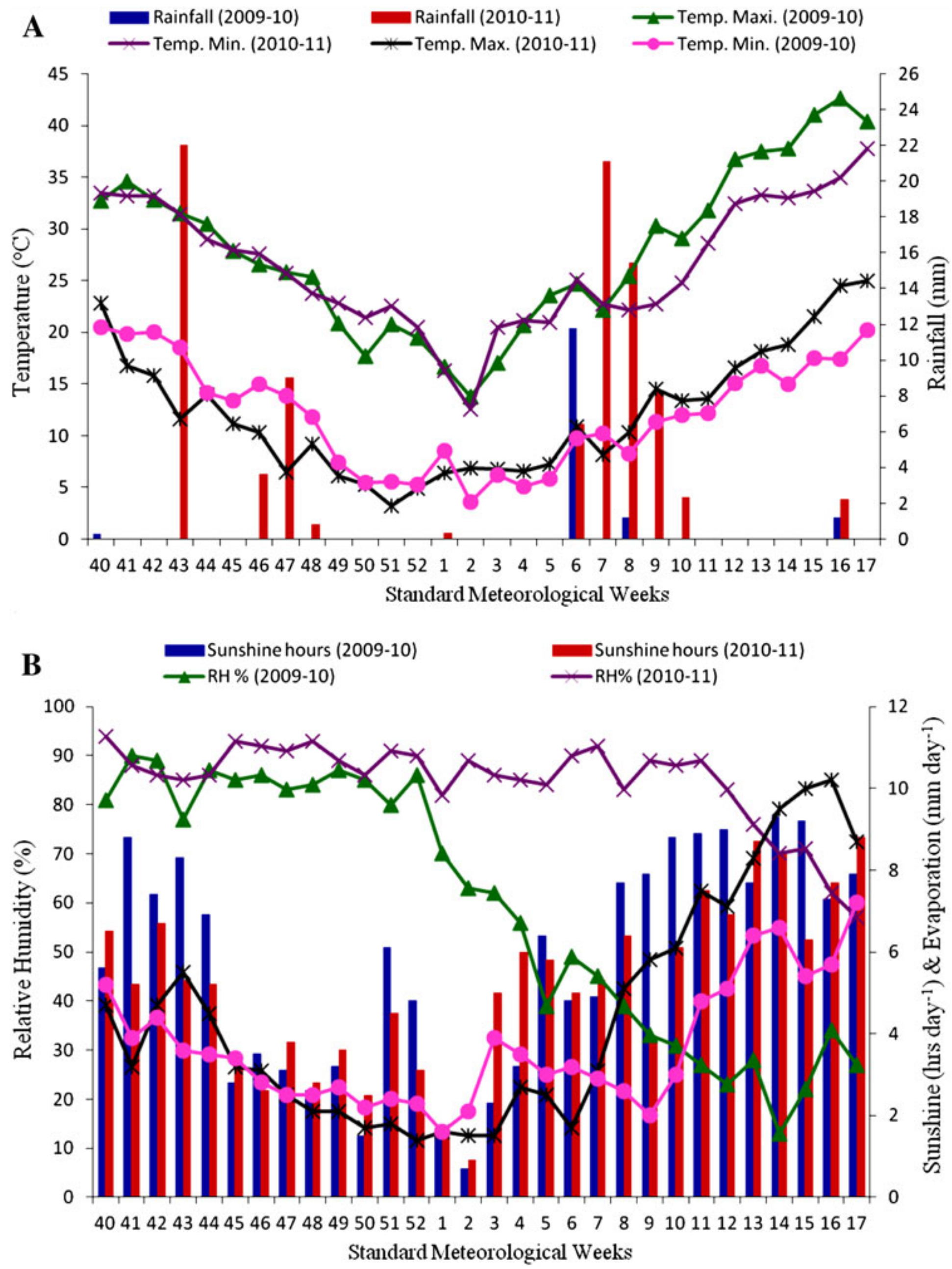

Fig. 1 **a** Weather parameters during the growing period of the oat crops in 2009–2010 and 2010–2011. **b** Weather parameters during the growing period of the oat crops in 2009–2010 and 2010–2011

Results

Grain and Straw Yield of Oats

In both the years of study grain and straw yields of oats were significantly increased due to Zn fertilisation (Tables 1, 2). When broadcast at sowing application of 5 kg Zn ha^{-1} as ZnSHH ($ZnSO_4 \cdot 7H_2O$) or ZnO produced significantly more grain and straw yields than 2 kg Zn ha^{-1}, which in turn produced significantly more than no Zn (control). Deep placement of 2 kg Zn ha^{-1} as ZnSHH produced significantly more grain and straw yields than its broadcast application, but this was not true for ZnO. Also when deep placed at sowing at 2 kg Zn ha^{-1}, ZnSHH produced significantly more grain and straw than ZnO in 2009–2010. When banded @ 5 kg Zn ha^{-1} at first irrigation (25 DAS), ZnSHH and ZnO were equally effective and produced significantly lesser grain and straw than their broadcast application at sowing at the same rate. In both the years of study coating of oat seeds onto with ZnSHH or ZnO (@ 2 kg Zn ha^{-1}) produced the highest grain and straw yield, significantly more than deep placement of Zn at the same rate of application and in the case of ZnSHH it produced significantly more grain and straw than its broadcast application even at 5 kg Zn ha^{-1}. At 5 kg Zn ha^{-1} both the

Table 1 Effect of rate, source and method of Zn application on grain yield of oats

Treatment	Grain yield (Mg ha^{-1})	
	2009–2010	2010–2011
Control (no Zn)	3.15	3.23
2 kg Zn ha^{-1} as ZnSHH[a], deep placed at sowing	3.76	3.83
2 kg Zn ha^{-1} as ZnSHH, broadcast at final ploughing	3.51	3.58
2 kg Zn ha^{-1} as ZnSHH (used for coating onto 100 kg seed required for sowing 1 ha)	4.01	4.08
2 kg Zn ha^{-1} as ZnO deep placed at sowing	3.56	3.64
2 kg Zn ha^{-1} as ZnO broadcast at sowing	3.45	3.53
2 kg Zn ha^{-1} as ZnO (used for coating onto seed required for sowing 1 ha)	3.91	3.98
5 kg Zn ha^{-1} as ZnSHH broadcast at sowing	3.79	3.87
5 kg Zn ha^{-1} as ZnSHH band placed before first irrigation (25 DAS)	3.52	3.60
5 kg Zn ha^{-1} as ZnSHH band placed after first irrigation (25 DAS)	3.51	3.58
5 kg Zn ha^{-1} as ZnO broadcast at sowing	3.77	3.75
5 kg Zn ha^{-1} as ZnO band placed before first irrigation (25 DAS)	3.46	3.54
5 kg Zn ha^{-1} as ZnO band placed after first irrigation (25 DAS)	3.47	3.54
SEM±	0.057	0.077
LSD ($P = 0.05$)	0.167	0.222

[a] $ZnSO_4 \cdot 7H_2O$

Table 2 Effect of rate, source and method of Zn application on straw yield of oats

Treatment	Straw yield (Mg ha^{-1})	
	2009–2010	2010–2011
Control (no Zn)	8.67	8.93
2 kg Zn ha^{-1} as ZnSHH[a], deep placed at sowing	10.80	11.05
2 kg Zn ha^{-1} as ZnSHH, broadcast at final ploughing	10.08	10.33
2 kg Zn ha^{-1} as ZnSHH (used for coating onto 100 kg seed required for sowing 1 ha)	11.60	11.83
2 kg Zn ha^{-1} as ZnO deep placed at sowing	10.18	10.42
2 kg Zn ha^{-1} as ZnO broadcast at sowing	9.98	10.23
2 kg Zn ha^{-1} as ZnO (used for coating onto seed required for sowing one hectare)	11.25	11.53
5 kg Zn ha^{-1} as ZnSHH broadcast at sowing	11.03	11.28
5 kg Zn ha^{-1} as ZnSHH band placed before first irrigation (25 DAS)	10.04	10.28
5 kg Zn ha^{-1} as ZnSHH band placed after first irrigation (25 DAS)	9.94	10.20
5 kg Zn ha^{-1} as ZnO broadcast at sowing	11.03	11.28
5 kg Zn ha^{-1} as ZnO band placed before first irrigation (25 DAS)	9.87	10.14
5 kg Zn ha^{-1} as ZnO band placed after first irrigation (25 DAS)	9.90	10.18
SEM±	0.178	0.151
LSD ($P = 0.05$)	0.519	0.441

[a] $ZnSO_4 \cdot 7H_2O$

sources of Zn were equally effective in increasing grain and straw yield of oats irrespective of the method of application.

Zn Concentration in Oat Grains

Zn concentration in oat grains was 22.2 mg kg^{-1} in control plots and increased from 23.8 to 32.3 mg kg^{-1} due to Zn fertilisation; average increase being about 27 % over control (Table 3). When broadcast at sowing, a significant increase in Zn concentration (29–29.5 % over control) in oat grains was recorded only when 5 kg Zn ha^{-1} applied as ZnSHH or ZnO. The differences between sources and methods of Zn application were not significant. When coated onto oat grains, ZnSHH and ZnO were equally effective and recorded the highest Zn concentration (43.5–45.4 % over control); significantly more than even a 5 kg ha^{-1} broadcast Zn application.

Table 3 Effect of rate, source and method of Zn application on Zn concentration in oat grains

Treatment	Zn concentration in oat grains (mg kg^{-1} grain)	
	2009–2010	2010–2011
Control (no Zn)	22.0	22.5
2 kg Zn ha^{-1} as ZnSHH[a], deep placed at sowing	25.1 (14.1)[b]	25.6 (13.8)[b]
2 kg Zn ha^{-1} as ZnSHH, broadcast at final ploughing	23.8 (8.2)	24.3 (8.0)
2 kg Zn ha^{-1} as ZnSHH (used for coating onto 100 kg seed required for sowing one hectare)	32.0 (45.5)	32.5 (44.4)
2 kg Zn ha^{-1} as ZnO deep placed at sowing	24.7 (12.3)	25.2 (12.0)
2 kg Zn ha^{-1} as ZnO broadcast at sowing	22.1 (0.5)	23.6 (4.9)
2 kg Zn ha^{-1} as ZnO (used for coating onto seed required for sowing 1 ha)	31.6 (43.6)	32.3 (43.5)
5 kg Zn ha^{-1} as ZnSHH broadcast at sowing	29.5 (34.1)	30.3 (34.7)
5 kg Zn ha^{-1} as ZnSHH band placed before first irrigation (25 DAS)	29.0 (31.8)	29.5 (31.1)
5 kg Zn ha^{-1} as ZnSHH band placed after first irrigation (25 DAS)	27.3 (24.1)	27.8 (23.5)
5 kg Zn ha^{-1} as ZnO broadcast at sowing	28.6 (30.0)	29.1 (29.3)
5 kg Zn ha^{-1} as ZnO band placed before first irrigation (25 DAS)	28.0 (27.3)	28.4 (26.2)
5 kg Zn ha^{-1} as ZnO band placed after first irrigation (25 DAS)	26.8 (21.8)	27.3 (21.3)
SEM±	0.65	0.64
LSD ($P = 0.05$)	1.90	1.87

[a] $ZnSO_4 \cdot 7H_2O$

[b] Percentage increase over control (no Zn)

Zn Concentration in Oat Straw

Zn concentration in oat straw was 31.75 mg kg^{-1} in control plots and increased from 37.35 to 48.95 mg kg^{-1} due to Zn fertilisation; average increase being about 33.67 % over control (Table 4). When broadcast at sowing, a significant increase in Zn concentration (35.75–45.95 % over control) in oat straw was recorded only when 5 kg Zn ha^{-1} applied as ZnSHH or ZnO. The differences between sources and methods of Zn application were not significant. When coated onto oat grains, ZnSHH and ZnO were equally effective and recorded the highest Zn concentration (49.75–54.2 % over control); significantly more than even a 5 kg ha^{-1} broadcast Zn application.

Economics

The highest net returns and benefit:cost ratio was obtained when 2 kg ZnSHH or ZnO was coated onto oat seeds followed by deep placed of 2 kg ZnSHH ha^{-1} (Table 5). Deep placement of Zn gave higher net returns and benefit:cost ratio than its broadcast application and deep placed of 2 kg ZnSHH ha^{-1} was at par with broadcast application of 5 kg ZnSHH ha^{-1}. Band placed of Zn either as ZnSHH or ZnO before or after first irrigation gave significantly lower net returns and benefit:cost ratio than its application at sowing, however, it was still better than no Zn check. When coated onto seeds, ZnSHH was significantly superior to ZnO.

Discussion

As regards rate of Zn application, when applied as broadcast at sowing, 5 kg Zn ha^{-1} produced significantly more grain and straw than that of 2 kg Zn ha^{-1}, which in turn produced significantly more than no Zn (control). A significant increase in grain and straw yields of rice, wheat, maize and sorghum up to 5 kg Zn ha^{-1} has been reported in India [19], but no reports are available on oats. In the present study, a significant increase in Zn concentration in oats was recorded only when 5 kg Zn ha^{-1} was applied. A number of researchers have reported an increase in Zn concentration of other cereals [12, 23, 29, 30].

As regards method of Zn application, coating of ZnSHH or ZnO @ 2 kg Zn ha^{-1} onto oat seeds recorded the highest grain yield, Zn concentration in oat grains and straw as well as net profit and B:C ratio, significantly higher than even a broadcast application of 5 kg Zn ha^{-1}. Coating of Zn onto seeds permits better absorption of Zn by plants and therefore gave better results. Seed treatment of rice with Zn was found to be quite effective in AR, USA [26]. Martens et al. [16] reported that band application of Zn fertilisers in contact with maize seeds at rates ranging from 0.34 to 1.34 kg Zn ha^{-1} produced grain yields equal to those achieved when 26.9 kg Zn ha^{-1} as ZnSHH was broadcast on soil surface and incorporated. Patel [19] also observed that seed coating may be a better option for supplying Zn to maize and wheat. Deep placement of ZnSHH or ZnO also gave higher grain and straw yields of

Table 4 Effect of rate, source and method of Zn application on Zn concentration in oat straw

Treatment	Zn concentration in oat straw (mg kg^{-1} dry oat straw)	
	2009–2010	2010–2011
Control (no Zn)	31.3	32.2
2 kg Zn ha^{-1} as ZnSHH[a], deep placed at sowing	40.4 (29.1)[b]	41.2 (27.9)[b]
2 kg Zn ha^{-1} as ZnSHH, broadcast at final ploughing	38.5 (23.0)	39.3 (22.0)
2 kg Zn ha^{-1} as ZnSHH (used for coating onto 100 kg seed required for sowing 1 ha)	48.6 (55.3)	49.3 (53.1)
2 kg Zn ha^{-1} as ZnO deep placed at sowing	39.6 (26.5)	40.3 (25.2)
2 kg Zn ha^{-1} as ZnO broadcast at sowing	36.9 (17.9)	37.8 (17.4)
2 kg Zn ha^{-1} as ZnO (used for coating onto seed required for sowing 1 ha)	47.5 (51.8)	48.2 (47.7)
5 kg Zn ha^{-1} as ZnSHH broadcast at sowing	45.9 (46.6)	46.8 (45.3)
5 kg Zn ha^{-1} as ZnSHH band placed before first irrigation (25 DAS)	42.5 (35.8)	42.5 (32.0)
5 kg Zn ha^{-1} as ZnSHH band placed after first irrigation (25 DAS)	40.4 (29.1)	41.3 (28.3)
5 kg Zn ha^{-1} as ZnO broadcast at sowing	42.7 (36.4)	43.5 (35.1)
5 kg Zn ha^{-1} as ZnO band placed before first irrigation (25 DAS)	41.8 (33.5)	42.3 (31.4)
5 kg Zn ha^{-1} as ZnO band placed after first irrigation (25 DAS)	40.6 (29.7)	41.2 (28.0)
SEM±	0.55	0.50
LSD ($P = 0.05$)	1.61	1.47

[a] $ZnSO_4.7H_2O$

[b] Percentage increase over control (no Zn)

Table 5 Effect of rate, source and method of Zn application on gross returns, net returns and net benefit:cost ratio of oats (mean of 2 years)

Treatment	Gross returns (₹ ha^{-1})	Net returns (₹ ha^{-1})	Net benefit: cost ratio
Control (no Zn)	58,300	41,338	2.44
2 kg Zn ha^{-1} as ZnSHH[a], deep placed at sowing	70,660	53,441	3.10
2 kg Zn ha^{-1} as ZnSHH, broadcast at final ploughing	66,000	48,781	2.83
2 kg Zn ha^{-1} as ZnSHH (used for coating onto 100 kg seed required for sowing one hectare)	75,630	58,411	3.39
2 kg Zn ha^{-1} as ZnO deep placed at sowing	66,900	49,613	2.87
2 kg Zn ha^{-1} as ZnO broadcast at sowing	65,200	47,913	2.77
2 kg Zn ha^{-1} as ZnO (used for coating onto seed required for sowing 1 ha)	73570	56,283	3.25
5 kg Zn ha^{-1} as ZnSHH broadcast at sowing	71,750	54,145	3.07
5 kg Zn ha^{-1} as ZnSHH band placed before first irrigation (25 DAS)	66,080	48,475	2.75
5 kg Zn ha^{-1} as ZnSHH band placed after first irrigation (25 DAS)	65,610	48,005	2.73
5 kg Zn ha^{-1} as ZnO broadcast at sowing	71,050	53,275	3.00
5 kg Zn ha^{-1} as ZnO band placed before first irrigation (25 DAS)	65,000	47,225	2.66
5 kg Zn ha^{-1} as ZnO band placed after first irrigation (25 DAS)	65,120	47,345	2.66
SEM±	599.1	599.1	0.033
LSD ($P = 0.05$)	1,748.6	1,748.6	0.097

[a] $ZnSO_4·7H_2O$

oats than their broadcast application, but was not as good as coating Zn onto oat seeds.

As regards timing of Zn application, it was better at seeding than at first irrigation (25 DAS) and while applying at this stage, it was better to apply it before than after irrigation. Late application of Zn is therefore not as good as its application at sowing from the view point it gives yield (grain and straw) as well as Zn concentration in oat grains and straw. Applying Zn before irrigation permitted it better to reach the active root zone, which is important for Zn uptake by plants [24]. Nayyar et al. [17] reported that rice yield was reduced from 4.3 to 4.0 Mg ha^{-1}, when Zn application was delayed by 15 days after transplanting.

As regards the source of Zn, in general ZnSHH produced more oat grains and straw and recorded higher Zn concentration in grain and straw than ZnO, although differences between the two sources were not significant in general. Slaton et al. [25] have reported that for rice Zn fertilisers containing more water soluble Zn performed better.

Conclusion

The present study brings out that for higher yield of oat grains and straw and fortification with Zn; ZnSHH or ZnO should be coated onto seeds before seeding.

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