An overview of zinc use and its management in oilseed crops

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Introduction

Agricultural soils with low zinc (Zn) availability are widespread worldwide. There are estimates that more than 30% of agricultural soils globally are low in available Zn leading to deficiency in crops cultivated on these soils (Alloway 2008). Therefore Zn malnutrition has become a major health concern among the resource-poor people (Singh 2011). In India, Zn is one of the multi-nutrient deficiencies that are causing poor crop yields. Zinc deficiency in Indian soils is expected to increase from 42% in 1970 to 63% by 2025 due to continuous depletion of soil fertility (Singh 2011). A direct yield loss of US$ 1.5 billion yr^{-1} is estimated due to low crop yields besides huge loss due to disease concerns arising out of Zn malnutrition in the country (Singh 2010).

The oilseeds sector has been one of the most dynamic components of world agriculture in the past three decades growing at 4.1% production per annum; and thus surpassing the growth rate recorded in agriculture and livestock products. Oilseed crops account for nearly 3% of the gross domestic product and 5.98% of the value of all agricultural products in India (Varaprasad et al. 2011). India occupies a premier position in global oilseeds scenario with 12–15% of oilseeds area, 6–7% of vegetable oil production, 9–10% of the total edible oils consumption and 13.6% of vegetable oil imports (Varaprasad et al. 2011). In the agricultural economy of India, oilseeds are important next only to food grains in terms of area, production and value. The diverse agroecological conditions in the country are favorable for growing nine oilseed crops which include seven edible oilseed crops, viz, groundnut (*Arachis hypogaea*), mustard (*Brassica juncea*), soybean (*Glycine*), sunflower (*Helianthus annuus*), safflower (*Carthamus tinctorius*), sesame (*Sesamum indicum*) and niger (*Guizotia abyssinica*) and two non-edible oilseed crops, viz, castor (*Ricinus communis*) and linseed (*Linum usitatissimum*). In India oilseed crops are cultivated on 26.77 million ha, with productivity of 1087 kg ha^{-1} for the triennium ending 2012/13. However, this production is not enough to meet the ever-growing vegetable oil demand and so the country is a net importer at a huge cost to the exchequer. The average productivity of oilseeds in India is far below that of developed countries (2.5–3.0 t ha^{-1}) and world average (1.9 t ha^{-1}). Low productivity of oilseeds is mainly due to their cultivation under rainfed conditions and on marginal soils. Apart from water shortage, the productivity in rainfed systems of semi-arid India is low due to poor fertility status of the soils (Sahrawat et al. 2010). The soils are devoid of not only macro and secondary nutrients but also of micronutrients. Most of such lands are inhabited by resource-poor farmers who can rarely afford to use minimum nutrients required in a balanced nutrient approach. So, oilseed crops are in general more hungry than thirsty and there is wide gap in fertilizer requirement and additions, thus causing huge mining of soil fertility leading to complex nutrient imbalances and deficiencies. In India only about one-third of the fertilizer requirements of oilseed crops are actually applied leading to continuous mining of nutrients from the soil by oilseeds (Sudhakara Babu and Hegde 2011). Thus there is urgent need for stepping up use of deficient major, secondary and micronutrients (Hegde and Sudhakara Babu 2009).

Slow pace in productivity growth in oilseeds has thus been often linked to imbalanced and inadequate application of major, secondary and micronutrients. Among the micronutrients, Zn has gained macro importance to meet soil fertility needs to enhance productivity. For an optimum plant growth and seed yield, adequate supply of Zn is essential. Therefore, this e-paper discusses about widespread Zn deficiency in major oilseed growing states, effects of Zn use and soil–crop–zinc fertilization management for increasing productivity of oilseed crops.

Role of Zn in crop production

Zinc is an essential micronutrient and plays a key role as a structural constituent or regulatory cofactor of a wide range of different enzymes and proteins in many important biochemical pathways like carbohydrate metabolism, photosynthesis, conversion of sugars to starch, protein metabolism, auxin (growth regulator) metabolism, pollen formation, integrity of biological membranes and resistance to infection by certain pathogens (Alloway 2008). Zinc is needed in small, but critical concentrations and if the amount available is not adequate, plants will suffer from physiological stress. Under Zn-deficient conditions, flowering and fruit development is reduced, and growth period is prolonged resulting in delayed maturity, leading to lower yield, poor quality and suboptimal nutrient use efficiency.

Zn deficiency symptoms in oilseed crops

Zinc deficiency in plants causes typical symptoms; however, up to 50% reduction in crop growth can result due to Zn deficiency without the appearance of visual symptoms. Zinc deficiency symptoms common to many crops normally appear in four-week-old plants on older and emerging leaves. These are light green yellow or bleached spots in interveinal areas of older leaves. The emerging leaves become smaller in size and often termed as “little leaf”. During severe deficiency, internodal distance becomes too short so that all leaves appear to come out from the same point, and is termed as “rosetting”. Oilseed crops like soybean and groundnut show similar symptoms at early stages of growth. The general deficiency symptoms of Zn on various oilseed crops were reviewed by Murthy (2011). In Indian mustard the interveinal areas of the subterminal leaves develop light brown necrotic patches whereas in sunflower and sesame the deficiency symptoms first appear on middle leaves as loss of green color, followed by development of brown spots, which grow between the veins. Zinc-deficient plants are stunted and produce small, thin grains. Adverse soil conditions, such as increasing occurrence of drought spells or salinity aggravate Zn deficiency problem in crop plants (Bagci et al. 2007). These abiotic stresses/adverse soil conditions lead to impeded growth of plants and slow root activity, resulting in an inhibited spatial availability of Zn.

Major factors responsible for increase in incidences of Zn deficiency include large Zn removal due to high crop yields and intensive cropping system, lesser application of organic manures, use of high analysis fertilizers, increased use of phosphatic fertilizers resulting in phosphorus (P)-induced Zn deficiency and the use of

Table 1. Districts of major oilseed growing states of India affected by zinc deficiency in soils[1].

State[2]	% soils deficient in Zn	Total oilseed area (’000 ha) during 2010/11	Districts deficient in Zn
Andhra Pradesh (9)	46.8	2316	Anantapur, Guntur, Krishna, Kurnool, Nizamabad, Nalgonda, Nellore, Prakasam, Mahabubnagar
Gujarat (7)	23.9	2853	Ahmadabad, Banaskantha, Bharuch, Jamnagar, Kachchh, Narmada, Panchmahal
Karnataka (5)	72.8	850	Dharward, Haveri, Kolar, Tumkur, Chitradurga
Maharashtra (24)	86.0	3527	Ahmednagar, Aurangabad, Amravati, Akola, Bhandara, Buldhana, Washim, Chandrapur, Dhule, Gadchiroli, Gondia, Hingoli, Jalna, Jalgaon, Latur, Yaotmal, Nashik, Nagpur, Nanded, Osmanabad, Pune, Parbhani, Solapur, Wardha
Madhya Pradesh (26)	44.2	7029	Bhind, Balaghat, Bhopal, Chhatarpur, Chindwada, Dewas, Dhar, Guna, Indore, Jabalpur, Jhabua, Mandla, Panna, Rajgarh, Raisen, Rewa, Sagar, Sahdol, Satna, Seoni, Sehore, Shivpur, Shajapur, Sidhi, Tikamgarh, Vidisha
Uttar Pradesh (40)	45.7	1073	Saharanpur, Rampur, Mathura, Bareily, Badaun, Mainpuri, Hardoi, Sitapur, Bahraich, Barabanki, Lucknow, Unnao, Kanpur (dehat), Balrampur, Siddharthnagar, Jalaun, Allahabad, Hamirpur, Mahoba, Banda, Fatehpur, Mirzapur, Raibareili, Basti, Ambedkarnagar, Sultanpur, Sonbhadra, Chandauli, Maharajganj, Azamgarh, Santkabirnagar, Gorakhpur, Deoria, Ballia, Jaunpur, Ravidasnagar, Varanasi, Chitrakut, Pratapgarh, Kausambi

1. Source: Rego et al. (2007).
2. Figures in parentheses indicate the number of districts.

poor quality irrigation without adequate drainage (Prasad 2006).

Zn deficiency in major oilseed growing states in India

The major oilseed growing states in India are Madhya Pradesh, Rajasthan, Maharashtra, Gujarat, Andhra Pradesh, Karnataka and Uttar Pradesh. Across different states in India, Zn deficiency is widespread in most of the districts (Table 1). In general, nearly 50% of the soil samples analyzed were found to be deficient in Zn. Incidentally these are the states that contribute >82% of the total oilseed production from 80% of total oilseed cultivated area. Such an alarming signal of Zn deficiency has made its application equally important as that of application of major nutrients.

Soil maps as tools to delineate and manage deficient regions. Soil testing can be used to diagnose and manage nutrient problems in farmers' fields and develop nutrient maps using the geographic information system (GIS) and delineate deficient regions from sufficient ones for use by farmers and other stakeholders.

The results of analysis of selected soil samples collected from farmers' fields of semi-arid regions (Karnataka, Andhra Pradesh, Rajasthan, Madhya Pradesh, Tamil Nadu and Gujarat states) of India demonstrated that low soil test values for Zn were widespread in all states, except in Rajasthan. The percentage of farmers' fields testing low in Zn ranged from 46% in Rajasthan to 85% in Gujarat (Table 2). Soil maps were prepared showing soil nutrients status including Zn for 15 dryland districts of Karnataka (Sahrawat et al. 2011). A large contiguous tract of land deficient in Zn was identified across Bagepalli and Gundibanda blocks in Chikballapur district of Karnataka state (Fig. 1). Thus, soil test results can be used for preparing nutrient maps for informed decisions about balanced nutrient management in farmers' fields and there is a need to up-scale such activity across the country.

Critical Zn nutrient levels

In India, oilseeds are cultivated on almost all types of soils and the critical nutrient levels (CNLs) of deficiency vary accordingly. It has been shown that for a given soil–crop situation, more than one extractant can be suitable but the CNLs used for categorizing soils into deficient, marginal and sufficient categories vary with the method. Available Zn content in most of the Indian soils is estimated by DTPA extractant. For DTPA extractable-Zn, 0.6 mg kg^{-1} was taken as the CNL of deficiency in

Figure 1. Zinc map for Chikballapur district of Karnataka state, India (Source: Sahrawat et al. 2011).

general (Murthy 2011). The critical Zn level of deficiency is 0.5 mg kg^{-1} for Vertisols of Gujarat, 0.7 mg kg^{-1} for Alfisols and Vertisols of Andhra Pradesh, 0.6 mg kg^{-1} for Vertisols of Madhya Pradesh and 1.2 mg kg^{-1} for Alfisols and Vertisols of Tamil Nadu. To delineate the Zn responsive soils for oilseed crops, 0.75 mg kg^{-1} was considered critical DTPA-Zn level for the semi-arid tropical soils (Rego et al. 2007). Similarly, crop age, sampled part of the plant and genotypic differences play a significant role in establishing the CNLs of the crop. The sufficiency levels of Zn in oilseed crops, viz, groundnut, mustard and soybean were found to be >22 mg kg^{-1}, 34–200 mg kg^{-1} and 21–50 mg kg^{-1} respectively.

Establishment of CNLs for soil and plant will help in delineating responsive to non-responsive soil types as well as for the different genotypes used. Currently available information and recent advances made in the establishment of critical level for Zn in soils and oilseed crops are discussed by Murthy (2011).

Table 2. Soil test results of farmers' fields in different states of India[1].

State	No. of districts	No. of farmers' fields	% classed as low[2] OC	Av. Zn
Karnataka	16	33200	66	57
Andhra Pradesh	11	3650	76	69
Rajasthan	9	421	38	46
Madhya Pradesh	12	341	22	66
Tamil Nadu	5	119	57	61
Gujarat	1	82	12	85

1. Source:. Sahrawat et al. (2011).
2. OC = Organic carbon; and Av. Zn = Available zinc.

Table 3. Average zinc (Zn) uptake by oilseed crops[1].

Crop[2]	Average Zn uptake (g per ton of economic produce)
Soybean (25)	77
Groundnut (20)	120
Mustard (12)	95
Sunflower (15)	50
Sesame (10)	150
Linseed (8)	45

1. Source: Shukla and Behera (2011).
2. Figures in parentheses indicate the number of experiments.

Table 4. Response of oilseeds to zinc fertilization in India[1].

Crop	No. of experiments	Response (kg ha^{-1}) Range	Average
Groundnut	83	210–470	320
Soybean	12	160–390	360
Mustard	11	140–260	270
Linseed	5	150–200	160
Sunflower	8	150–200	240
Sesame	6	80–150	110

1. Source: Shukla and Behera (2011).

Zn uptake by oilseed crops

Zinc is absorbed as Zn^{+2} from soil solution through roots. The amount of Zn absorbed depends on soil condition, crop, variety and yield level. On an average, one ton of oilseed yield leads to 45–150 g uptake of Zn (Table 3). Its distribution pattern among seed and stem parts varies widely across the oilseed crops. Zinc percent uptake by the seed portion in various oilseeds follows the order linseed > soybean > mustard > sunflower > groundnut. In linseed, maximum amount of Zn is transferred to the seed than to straw.

Intensive cropping systems deplete soil Zn more due to higher production. The amount of Zn absorbed varies with the oilseed-based cropping systems and ranges from 242 to 504 g ha^{-1} yr^{-1} (Sakal et al. 1996). The use efficiency of applied Zn was found to be low in general. In oilseed crops, the utilization of applied Zn by the crops was found to be <0.5% (Prasad 2006).

Genotypes of oilseed crops tolerant and sensitive to Zn stress

Genotypes vary in their magnitude of response to Zn. This variability among genotypes for Zn can be explored for optimizing crop production under fertilizer/resource constraint. A particular genotype may grow well while another genotype may produce much lower yields in the same soil. Growing Zn-efficient plants on Zn-deficient soils represents the strategy of 'tailoring the plants to fit the soil' in contrast to the difficult strategy of 'tailoring the soil to fit the plant'. Tolerance to Zn-deficient soils, as a genetic trait, is usually called Zn efficiency and defined as the ability of a genotype (or plant species) to grow and yield well in soils deficient in Zn for a standard genotype. Grewal et al. (1997) in Australia conducted pot experiments to determine the genotypic variation in rape (*Brassica napus*) and mustard (*B. juncea*) to tolerate Zn deficiency and to identify the efficient genotypes. The studies revealed that considerable genotypic variation exists in oilseed rape for Zn efficiency, and therefore, to tolerance in Zn-deficient soils. Root dry matter accumulation and retranslocation from root to shoot were higher in efficient genotypes which may be either the cause or the result of Zn-efficiency. There seems a genetic control over Zn concentration in tissue: efficient genotypes had lower Zn concentration in roots but higher Zn concentration in youngest fully opened leaf blade; Zn uptake by shoots was also higher in efficient genotypes and this also appears to be related to expression of the Zn efficiency trait (Grewal et al. 1997). Similarly, promising and recommended genotypes of groundnut, soybean and brown mustard were screened in pots for their relative tolerance to Zn stress (Tandon 1995) and most Zn efficient and susceptible genotypes were identified. The susceptibility or tolerance of a genotype may be related to the exploring capacity of roots for nutrients. The tolerant cultivar of groundnut MH-2 had higher Zn content than susceptible cultivars (Tandon 1995). Thus, genetic potential of crop varieties to withstand Zn stress can be used for breeding crop cultivars, which may perform well without Zn application.

Effects of Zn application on crop yield, quality and economic benefits

Critical analysis of the results of experiments conducted in farmers' fields (Table 4) revealed that average response of oilseed crops to Zn was 110–360 kg ha^{-1}. This signifies the necessity of Zn application for obtaining higher crop yield in Zn-deficient areas.

Some of the advances made with reference to effects on Zn application on productivity and quality of oilseeds (crop-wise) are discussed below.

Groundnut. In Zn-deficient soils, application of Zn increased the nodulation, chlorophyll content and pod yield of groundnut. Application of $ZnSO_4$ at 5 kg ha^{-1} + $FeSO_4$ at 10 kg ha^{-1} + boron (B) at 1 kg ha^{-1} with the recommended dose of NPK (nitrogen, phosphorus, potassium) showed significantly highest pod yield, oil content and seed quality (Janakiraman et al. 2005). Soil application of 25 kg $ZnSO_4$ ha^{-1} was the most effective method for correcting Zn deficiency, and for obtaining high pod yield (3888 kg ha^{-1}) of groundnut grown in Zn-deficient coarse-textured soils. Foliar spray (0.5% $ZnSO_4$) or seed coating (24 g and 31.2 g $ZnSO_4$) was not as effective as soil application of Zn in significantly improving the yield. Zinc application also increased protein content of groundnut besides significant increase in pod yield (Table 5). Application of Zn and B through foliar application recorded higher pod and haulm yield, seed weight and shelling percentage compared to soil application. Among the levels through soil, the application of $ZnSO_4$ at 20 kg ha^{-1} + borax at 0.5 kg ha^{-1} was the best and recorded 28% increased yield over NPK alone (Shankar et al. 2003). Farmers' field trials conducted in two agroclimatic zones of Orissa showed that application of secondary and micronutrients to soil and seed dressing increased the pod yield, shelling outturn and oil content over control in both the zones (Nayak et al. 2009). Application of iron (Fe) and Zn micronutrients to groundnut crop revealed that with the recommended dose of fertilizer (RDF) at 25:50 kg N and P ha^{-1} significantly higher dry pod yield (1992 kg ha^{-1}), seed yield (1418 kg ha^{-1}), haulm yield (4765 kg ha^{-1}) and maximum oil yield (663 kg ha^{-1}) were obtained (Thakur et al. 2010). Mean responses to Zn application varied from 210 to 470 kg ha^{-1} for groundnut in different agroecological regions of the country. So, to enhance the productivity of groundnut crop in Zn-deficient soils, optimum rate of Zn application in conjunction with other nutrients is necessary.

Mustard. Mustard, in general is very sensitive to micronutrient deficiency, specially Zn and B. As discussed earlier, Zn efficiency of mustard genotypes varied considerably. The response of Indian mustard varieties, viz, Pusa Bold and Vardan to applied Zn was higher (AICRP-RM 2000) as compared to Varuna, RH-30 and Aravali. When low Zn seed types and high Zn seed types were sown in Zn-deficient soil, the high types had better vigor, increased root and shoot growth, more leaf area and chlorophyll concentration in fresh leaf, and higher Zn uptake in shoot compared to those of low Zn seed types in rape genotypes (Grewal et al. 1997). The

Table 5. Effect of zinc (Zn) on pod yield and quality of groundnut[1].

Treatment	Pod yield (kg ha^{-1})	Oil content (%)	Protein content (%)
Control (NPK)	3990	41.2	20.26
Zn 5.6 kg ha^{-1} (Soil)	4740	41.5	24.19
Zn 11.2 kg ha^{-1} (Soil)	4880	40.9	22.49
Zn 1 g kg^{-1} seed (ZnO)	4510	40.9	22.49
Zn 2 g kg^{-1} seed (ZnO)	4630	41.5	25.81
CD (*P* = 0.05)	190	Not significant	0.89

1. Source: Gopala Gowda et al. (1995).

concentration of Zn at flowering and pod formation stage and concentration and uptake of Zn in straw and grain at maturity of Indian mustard increased significantly with increase in Zn levels (Gupta and Kaushik 2006). The increase in seed yield was 8.5% at 12.5 kg $ZnSO_4$ ha^{-1}. The harvest index was significantly affected by Zn application, although seed yield showed diminishing returns with additional $ZnSO_4$ doses.

With application of Zn at 5 and 10 kg ha^{-1}, seed yield response of Varuna was 300 to 500 kg ha^{-1} and 450 to 700 kg ha^{-1}, respectively. Zinc uptake also increased in soils. The increase in average Zn uptake over no Zn treatment at 5 and 10 kg Zn ha^{-1} was observed to be 63% and 103%, respectively (Sakal et al. 1996). On sandy loam soils of Gujarat, the application of multi-micronutrient mixture showed a significant improvement in mustard yield attributes, micronutrient uptake and seed yield (1982 kg ha^{-1}) with soil application of 1.5 kg $FeSO_4$ + 8 kg $ZnSO_4$ as per the soil test value. The yield increase because of soil application as per the soil test value was 16.2% over control (Patel et al. 2010).

Soybean. In highly Zn-deficient soils of Pantnagar, application of 10 kg Zn ha^{-1} increased soybean yield by more than 50% (Saxena and Chandel 1997). Soybean (JS-335) seed yield was significantly high (2.59 t ha^{-1}) at high levels of Zn while it was lower (2.1 t ha^{-1}) in control. Further, significantly higher oil content (20.1%) and test weight (11.3 g) was recorded at high levels of Zn application. Application of Zn (ZnO) and sulfur (S) as gypsum at increased levels on soybean (PKV-1) significantly increased the protein and oil content of grain over control. High protein (37.25%) and oil (20.42%) contents were noted with application of 3 kg Zn ha^{-1}, while 40 kg S ha^{-1} gave the highest protein (37.25%) and oil (21.29%) contents in soybean seed (Sonune et al. 2001). The effect of P, phosphate solubilizing microbes (PSM) and Zn on yield of soybean in Vertisols of Chhattisgarh revealed application of $ZnSO_4$ improved the grain yield up to low P level (30 kg P_2O_5 ha^{-1}) over no P but grain yield was decreased with 60 kg P_2O_5 ha^{-1} and PSM. Maximum percent increase in grain yield of soybean over control was recorded under 60 kg P_2O_5 ha^{-1} + PSM (47.8%) followed by 30 kg P_2O_5 ha^{-1} + PSM + 25 kg $ZnSO_4$ ha^{-1}. Maximum impact of PSM and $ZnSO_4$ (22.9%) was observed with no P and it decreased with increasing levels of P. Higher levels of Zn application were not much effective at the lower levels either through $ZnSO_4$ or ZnO. Decreased uptake of Fe by soybean could be ascribed to the antagonistic relation of Zn with Fe. On-station experiments were conducted to evaluate the application strategy of Zn at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru; maximum productivity increase and net benefit were realized with 50% Zn plus B and S applied every year for soybean which was a more effective fertilizer management strategy than application of full dose once in 2 or 3 years (Chander et al. 2011).

Sunflower. Zinc spray at 0.25% at button stage of sunflower had a significant influence on plant height, 100-seed weight and oil content while 0.75% dose caused reduction in seed yield and oil content. Interaction (stages × levels) effect was significant on plant height, 100-seed weight (4.3 g) and oil content (29.1%) (Murthy 2011). Zinc and other micronutrient accumulation, uptake ratio and nutrient use efficiency showed that sunflower hybrids AS-471 and PAC-6753 were rather more efficient in using bio-available micronutrients than the other hybrids and checks (KBSH-1, MSFH-17) (Murthy 2001). Zinc sulfate (Zn-130%, Teprosyn F-2498/Zn) application showed higher root length (22.5 cm) and vigor index (3263). Phosphorus is essential for root development and F-3090 (Zn-P) formulation enhances root growth (Sankaran et al. 2002) resulting in better utilization of applied Zn. Combination of $ZnSO_4$ at 25 kg ha^{-1} and borax at 60 kg ha^{-1} was found to improve the growth characters and yield (34.4 g $plant^{-1}$) of sunflower cv Morden showing the advantage of combined application of Zn and B. Sunflower hybrid MSFH-8 was found to be the most Zn efficient cultivar. The P-Zn uptake efficiency of the crop was positively related to the nutrient influxes. Despite the low root and shoot ratio a higher uptake efficiency of sunflower was due to its higher Zn influx, compared to maize (*Zea mays*) and potato (*Solanum tuberosum*) crops (Trehan and Sharma 2000). Sunflower crop showed Zn deficiency symptoms, viz, decreased seed size, seed weight and concentration of chlorophyll a and b under Zn stress conditions. When sufficient Zn supply was made, the plants showed a significant increase in seed size, seed weight and chlorophyll a and b concentrations as a result of increased carbonic anhydrase and reduced acid phosphatase activities in sunflower leaves (Murthy 2011).

Safflower. Safflower seed yield was significantly high (2.37 t ha^{-1}) with application of Zn (15 kg ha^{-1}). With the application of 30 kg Zn ha^{-1}, straw yield (7.62 t ha^{-1}) and nutrient concentration in the seed and dry matter were significantly high. Increase in levels of S and Zn significantly increased the oil and protein content in seed. The interaction of S and Zn was significant, and the highest seed (2.93 t ha^{-1}) and straw (9.42 t ha^{-1}) yields were obtained with the combined application of 45 kg S and 15 kg Zn ha^{-1} (Babhulkar et al. 2000). Application of 45 kg elemental S and 30 kg Zn ha^{-1} increased safflower seed yield (29.34 kg ha^{-1}), giving 92.1% increase over control. Further S × Zn interaction was synergistic and better in improving oil and protein contents and nutrient uptake by safflower (Dinesh Kar and Babhulkar 1998). In Zn-deficient Vertisols, an economical dose of 5 kg Zn ha^{-1} is enough to achieve higher safflower seed yield (2366 kg ha^{-1}). Further, Zn application showed a synergistic influence on uptake of other micronutrient cations at flowering stage of the crop. An antagonistic effect of copper and Fe uptake by seed with increasing levels of Zn application suggests that lower level of Zn is enough to meet crop Zn need to realize optimum seed yield. Zinc use efficiency by the seed decreased with increasing levels of Zn application (Murthy and Padmavathi 2008). Application of farmyard manure (FYM) at 2.5 t ha^{-1} with RDF (NPK 50:25:0 kg ha^{-1}), soil application of elemental S at 5.1 kg ha^{-1} and $ZnSO_4$ at 30 kg ha^{-1} resulted in significantly higher seed yield and better economic returns of safflower under dryland condition of Maharashtra (Khadtare et al. 2009). Available Zn status improved from initial 0.49 to 0.68 mg kg^{-1} because of the continuous application of $ZnSO_4$ at 30 kg ha^{-1} for a period of 7 years in black soils at Parbhani. Seven years pooled data showed a significant influence of Zn application at 30 kg $ZnSO_4$ ha^{-1} in increasing the seed yield of safflower (2108 kg ha^{-1}). In the black soils of Indore too an improvement in safflower seed yield was observed because of the application of Zn (AICRP-Safflower 2011).

Castor. Zinc application at 5 kg ha^{-1} was found adequate for Zn-deficient red soil for castor hybrids DCH-32 and GCH-4 and varieties Kranti and 48-1 (Murthy and Muralidharudu 2003). A significant increase in seed yield of the hybrid GCH-6 was due to Zn fertilization. Zinc fertilization at 10 kg ha^{-1} and 5 kg ha^{-1} increased seed yield by 12.8 and 11.5%, respectively over control (Mathukia and Khanpara 2008). Application of 5 kg Zn ha^{-1} significantly increased the dry matter yield of the hybrid DCS-9 and was rated as the most optimum and economical level. Dry matter yield of 90-day-old crops in different red soils ranged between 6.9 and 13.4 g $plant^{-1}$ in control plots whereas in Zn treated plots, it varied from 8.5 to 18.8 g $plant^{-1}$.

In Alfisols with low Zn status (0.46 mg kg^{-1}) the growth and yield of castor hybrid GCH-4 was superior, and Zn at 5 kg ha^{-1} was the optimum dose (Murthy and Muralidharudu 2003). On-farm trials conducted during three seasons (2002–04) in the semi-arid zone of India showed significant yield responses of castor and groundnut, to the applications of S, B and Zn (Rego et al. 2007). The yield responses were larger when S, Zn and B were applied with N and P. Applications of S, B and Zn also signiûcantly increased the uptake of Zn and other nutrients in the crop biomass (Table 6). Zinc use efficiency in castor at optimum Zn (5 kg ha^{-1}) dose decreased with an increase in DTPA-Zn (Murthy et al. 2009). Field studies on the effects of integrated nutrient management practices on yield characters, economic yield, economics and nutrient uptake of castor under irrigated conditions revealed that the maximum length of primary spike, more number of spikes $plant^{-1}$, capsules $spike^{-1}$, seed and oil yield and nutrient uptake of castor were recorded with application of 75% RDF (NPK) + $ZnSO_4$ at 12.5 kg ha^{-1} as basal and 0.25% $ZnSO_4$ foliar spray twice at 30 and 45 days after sowing compared to other inorganic nutrients. Performance of castor to

Table 6. Yield and nutrient uptake of castor and groundnut in response to fertilization in Andhra Pradesh, India, 2002–04[1].

	Seed yield (kg ha^{-1})			Total dry matter (kg ha^{-1})			Zn uptake (g ha^{-1})		
Treatment[2]	2002	2003	2004	2002	2003	2004	2002	2003	2004
Castor									
Farmers' input (FI)	590	690	990	1400	1610	2220	40.0	47.8	41.0
FI + SBZn	890	1000	1240	2070	2270	2710	62.2	70.4	73.0
FI + SBZn + NP	–	1190	1370	–	2770	3350	–	79.4	86.6
LSD (0.05)	143	186	285	360	403	484	14.2	13.7	18.2
Groundnut									
Farmers' input (FI)	700	560	920	2690	2920	4080	50.2	59.0	87.3
FI + SBZn	940	810	1190	3420	4150	4930	80.9	151.5	141.5
FI + SBZn+NP	–	980	1280	–	4740	5060	–	116.8	129.6
LSD (0.05)	103	59	96	145	183	262	5.1	13.2	52.0

1. Source: Rego et al. (2007).
2. SBZn: A mixture of 200 kg gypsum (30 kg S ha^{-1}), 5 kg borax (0.5 kg B ha^{-1}) and 50 kg zinc sulfate (10 kg Zn ha^{-1}); the mixture was surface broadcasted prior to the final land preparation.
   NP for castor: 60 kg N ha^{-1} in 20 and 40 split doses and 30 kg P_2O_5 ha^{-1}.
   NP for groundnut: 20 kg N ha^{-1} + 30 kg P_2O_5 ha^{-1}.

application of Zn differed across irrigated/rainfed locations. Soil application of $ZnSO_4$ at 15 kg ha^{-1} resulted in higher seed yield and economic returns under irrigated conditions of Mandor (Rajasthan) whereas foliar application of $ZnSO_4$ at 0.5% twice was found to be better than soil application of $ZnSO_4$ at 15 or 25 kg ha^{-1} at Palem and Hiriyur under rainfed conditions (AICRP-Castor 2013).

Sesame. Micronutrient content in sesame seeds in general followed the order Fe>Cu>Zn>Mn. The sesame varieties Gowri and Madhavi have high requirements of macro and micronutrients. Seed inoculation with *Azospirillum* and foliar Zn spray (0.5% $ZnSO_4$), and soil application of $ZnSO_4$ (5 kg ha^{-1}) and foliar application of planofix (30 mg kg^{-1}) were found useful in increasing growth characters, yield attributes and seed yield (1163 kg ha^{-1}) in sesame over control (Murthy 2011). Application of 100% RDF (60:30:30 NPK kg ha^{-1}) + 2.5 t FYM ha^{-1} + 20 kg $ZnSO_4$ ha^{-1} recorded higher seed yield (840 kg ha^{-1}) and was found more remunerative (net returns ` 15,774 ha^{-1}). Effects of S and Zn on nutrient uptake and quality of sesame grown under semi-arid conditions showed that maximum uptake of S (9.68 kg ha^{-1}) and Zn (39.94 g ha^{-1}) was recorded with recommended dose of NPK + 20 kg S ha^{-1} + 5 kg $ZnSO_4$ ha^{-1} + 1 t FYM ha^{-1} which was significantly more than all other treatments.

Zinc management in oilseed-based cropping systems

For maximizing the efficiency of applied Zn, efforts are being made to develop Zn fertilization schedule for the cropping system rather than the individual crops. Since use efficiency of fertilizer Zn by crops seldom exceeds 2–5%, most of the added Zn remains unutilized in the soils and has, thus, potential of meeting external Zn requirement of the crops grown in succession. Otherwise, continuous Zn application may turn the deficient soil toxic and/or induce the deficiency of other nutrients consequently. However, no Zn toxicity is reported in India. Crops in the system utilize fertilizer or soil Zn differently. For example, on a Zn-deficient sandy loam soil of Punjab initially fertilized with 11.2 kg Zn ha^{-1}, the reduction in DTPA-Zn to the critical level of Zn deficiency on time scale was variable in wheat (*Triticum aestivum*)–groundnut, mustard–mungbean (*Vigna radiata*) cropping system; in another experiment, 11.2 kg Zn ha^{-1} applied to the first groundnut crop of groundnut–wheat sufficed the external Zn requirement of the 10 crops grown in succession (Nayyar et al. 1990). Zinc application could be withdrawn to the succeeding crops if 20 kg $ZnSO_4$ ha^{-1} yr^{-1} was applied continuously up to four to five years. Further applications become necessary when the soils retested deficient in available Zn (Shukla and Behera 2011). Field studies conducted for four years revealed that the grain yield of soybean was significantly higher at 10 kg Zn ha^{-1} level for two years. Zinc concentration was significantly higher at the same level in leaf at anthesis in all the years over control. In soybean–wheat cropping system grain yields increased significantly with 10 kg $ZnSO_4$ ha^{-1} during the 3rd and 4th year of the experiment. In a nutshell, in soybean–wheat and fallow–wheat cropping systems an application of 10 kg Zn ha^{-1} is enough for four years or eight crops in Vertisols.

Direct and residual effects of Zn enriched organic manures in maize–sunflower cropping showed that irrespective of the manure sources, the seed and stalk yields of sunflower were significantly influenced by the residual effect of Zn enriched manure application. Seed yield of sunflower significantly increased by 15% over control for residual effect of $ZnSO_4$ application at 25 kg ha^{-1} while that for manures increased by 12% over control. Among the manures, poultry manure was superior and recorded the highest uptake of Zn by sunflower seed for the residual effect followed by biogas slurry. Persisting residual effect confirmed that Zn application to each crop is not necessary in case of Zn enriched manure application (Latha et al. 2002).

A long-term field experiment was initiated during *kharif* (rainy season) 1999 in a fixed plot at the Directorate of Oilseeds Research (DOR), Hyderabad to assess the need and response of major, secondary and micronutrients on a long-term basis for sustainable sunflower production in sorghum (*Sorghum bicolor*) (*kharif*)–sunflower (*rabi* or postrainy season) cropping system in Alfisols. Soil fertility in general is declining over the years except for increase noticed in organic carbon in treatment receiving FYM or crop residue along with NPK. The build-up of P was significant over the years in all treatments receiving regular P application compared to those that received only N or no manure application. During 2012–13, Zn application along with RDF to preceding sunflower caused reduction in seed yield of sorghum grown with application of its RDF. This may be because of possible antagonistic effect of P and Zn wherein it was found that a very high P build-up over 13 years in all treatments with P application to both crops and with this specific Zn application treatment to preceding sunflower, the antagonism effect was evident on sorghum seed yield (DOR 2013).

Application of $ZnSO_4$ at 25 kg ha^{-1} in *rabi* linseed and FYM at 5 t ha^{-1} for *kharif* black gram (*Vigna mungo*) was found superior in increasing seed yield of linseed (1464 kg ha^{-1}). The black gram–linseed crop sequence fetched the highest monetary gain (` 24,503 ha$^{-1}$) for the same treatment. Application of $ZnSO_4$ at 25 kg ha$^{-1}$ with FYM at 5 t ha$^{-1}$ to both rice (*Oryza sativa*) and linseed showed significant and highest linseed equivalent yield (2350 kg ha$^{-1}$) and maximum net monetary return (` 11,330 ha^{-1}) from rice–linseed crop sequence at Faizabad. Thus, in field studies, the application rate ranged from 10 to 25 kg $ZnSO_4$ ha^{-1} for oilseed crops as well as oilseed-based cropping systems. The responses were of higher magnitude under irrigated conditions than in rainfed conditions.

New fertilizer products containing Zn

Customized fertilizers. Recent developments in crop-specific customized fertilizers (CFs) are drawing attention to improve the fertilizer recommendations for sustainable crop production. Customized fertilizers are multi-nutrient carriers designed to contain macro, secondary and/or micronutrients, manufactured through a systematic process of granulation, satisfying the crop's nutritional needs specific to the site, soil and stage, validated by a scientific crop model and capability developed by an accredited fertilizer manufacturing or marketing company. Farmers will have a choice of CFs on account of crop and area specificity and the advantage of ready-to-use fertilizer material available to them.

Response of castor–sorghum cropping sequence in rainfed Alfisols of Andhra Pradesh was assessed to CFs. Application of CFs (NPKSZn 10:20:15:7:2%) with 2% Zn or fertilizers based on soil test crop response (STCR) resulted in 16–17% improvement in system productivity and economic returns compared to RDF (Ramesh et al. 2013). On an average, CFs recorded 18.8% higher seed yield (1.224 t ha^{-1}) followed by fertilizers based on STCR with 18.3% higher seed yield (1.22 t ha^{-1}) compared to RDF (1.03 t ha^{-1}).

SBZn fertilizer. The new combined source of S, B and Zn was evaluated on sunflower during *kharif* 2012 on Alfisols. The new SBZ-source recorded higher crop yield response over NPK due to the combined application of S and Zn. The higher response observed only in combined application of S or Zn along with NPK indicates the criticality of S and Zn for soil application to sunflower in the site along with NPK (DOR 2013).

Conclusions

Zinc is one of the 17 essential nutrients required for plant growth. It acts as an activator of several enzymes in plants; and is directly involved in the biosynthesis of growth substances such as auxin which is involved in plant growth and cell division. Zinc deficiency in soils and oilseed crops is one of the emerging constraints in improving the productivity of oilseed crops. The critical concentration of Zn in various plant parts of oilseed crops varies from 15 to 46 mg kg^{-1}. Soils having <0.6 mg kg^{-1} DTPA-Zn are usually considered as deficient and they respond to Zn fertilization. The extent of Zn deficiency in various states varies from 21 to 86% with an average of 49%. Wide differences in the oilseed cultivars to Zn stress have been observed. Zinc uptake by different cropping systems varies from 242 to 504 g ha^{-1} yr^{-1}. In soils low in total Zn, regular Zn fertilization is needed to avoid further Zn depletion in the top soil and thus to guarantee high crop productivity in the future. Among Zn sources, $ZnSO_4$ is the most effective, cheapest and readily available. Application of 25 kg $ZnSO_4$ ha^{-1} (5 kg Zn) was found to be ideal for most of the oilseed crops. In several cropping system studies succeeding oilseed crops benefited from the residual effect of Zn. Foliar spray of $ZnSO_4$ (range 0.2 to 0.5%) is recommended when the standing crop shows Zn deficiency as a contingency measure. Application of new fertilizer products containing Zn such as CFs and SBZn sources to oilseeds showed promise. Adopting suitable integrated nutrient management practices with balanced application of all the necessary nutrients including Zn resulted in higher oilseed productivity.

Issues of concern and way forward

Zinc supplying capacity of well-defined soil types in intensively and traditionally growing areas of oilseed crops need to be strengthened. Data should be generated by constantly monitoring the Zn status in oilseed-based cropping systems. Soil test results can be used for preparing Zn nutrient maps for informed decisions about balanced nutrient management in farmers' fields and there is a need to up-scale such activity across the country. Screening of oilseed crop cultivars for Zn deficiency tolerance should be intensified and the morphological, physiological and biochemical traits of varieties and hybrids associated with mining power of Zn need to be determined. There is a need to investigate the suitability of field-based biochemical test kits for assessing the Zn status of crops without relying on analytical laboratories for rapid estimation. In cereal crops the beneficial role of Zn fertilization in alleviating the adverse effects of stress conditions such as impeded root growth during drought is clearly established. There is an urgent need to verify the agronomic advantage of Zn fertilization/stress-mitigating role of Zn in rainfed oilseed crops. Systematic long-term studies on the residual influence of Zn in oilseed crop production are important. Interactions of Zn with other essential nutrients in oilseed crops need further impetus. Studies on response of coated, fortified fertilizers with micronutrients as well as customized Zn fertilizers in oilseed crops need to be intensified. The future Zn management strategy should be able to meet 25% of the crop requirements through renewable organic sources, 5–10% through mobilization by crop varieties and the rest through the application of Zn containing fertilizers.

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