REVIEW

ROLE OF ZINC IN CROP PRODUCTION- A REVIEW

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ABSTRACT

Zinc is plant micronutrient which is involved in many physiological functions its inadequate supply will reduce crop yields. Zinc deficiency is the most wide spread micronutrient deficiency problem, almost all crops and soils are affected. Calcareous soils, sandy soils, peat soils, and soils with high phosphorus and silicon are expected to be deficient. Zinc deficiencies can affect by stunting plant growth, decreasing number of tillers, increasing crop maturity period and spikelet sterility in rice. Beside its role in crop production Zn plays a part in the basic roles of cellular functions in all living organisms and is involved in improving the human immune system, due to its insufficient intake, human body will suffer from hair and memory loss, skin problems and weakness in body muscles.

Key words; Zinc Efficiency, Soil Zinc Deficiency, Zinc Rice

INTRODUCTION

Zinc is essential for the growth in animals, human beings, and plants it is vital to the crop nutrition as required in various enzymatic reactions, metabolic processes, and oxidation-reduction reactions. In addition, Zn is also essential for many enzymes which are needed for nitrogen metabolism, energy transfer and protein synthesis. Zinc deficiency not only retards growth and yield of plants, but it also has effects on human beings. More than 3 billion people worldwide are suffering from Fe and Zn deficiencies, and this condition is particularly widespread in areas where population is heavily dependent on an unvaried diet of cereal-based foods, in which Fe and Zn are stored almost exclusively in the husk, and are therefore lost during milling and polishing (Cakmak, 2002; Graham *et a*l*.,* 2001).

1. Importance of Zn in Humans

Zinc deficiency is common in humans, animals and plants. More than 30% world's population suffers from Zn deficiency (Welch *et al*., 2002). Zinc plays a part in the basic roles of cellular functions in all living organisms and is also involved in improving the human immune system. The optimum dietary intake for human adults is 15 mg Zn per day. Zinc acts as a catalytic or structural component in various body enzymes.
Unsatisfactory intake and improper absorption of Zn in the body may cause deficiency of Zn. Due to Zn deficiency; the human body will suffer from hair and memory loss, skin problems and weakness in body muscles. Further insufficient intake of Zn during pregnancy also causes stunted brain development of the fetus. Infertility has also been observed in Zn deficient men. Zinc deficiency may cause congenital diseases like Acrodermatitis enteropathica (Lukaski, 2004; Morley, 2004 and Zimmermann, 2001).
As per recommendations of the FAO/WHO (2002) and Hotz and Brown (2004) an average male need 11 mg of Zn daily while an average female needs 9 mg of Zn. During pregnancy and lactation, the female needs 13 mg to 14 mg of Zn daily. Infants from 7 months to 3 years

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need 3 mg, 4 to 8 years need 5 mg and children from 9 to 13 years need 8 mg of Zn daily. The foods rich in Zn are beef, pork, chicken, and breakfast cereals, nuts like roasted peanuts, almonds, walnuts, oats and dairy products like yogurt, cheese and milk.

2. Zinc Effects on Plant Growth

Studies on seeds containing low Zn carried out in the International Rice Research Institute (IRRI) indicated that under severe Zn deficiencies, tillering was decreased or could stop completely, and time of crop maturity increased. Zn deficiencies could also increase spikelet sterility in rice. Zinc removal by rice ranged from 0.04 to 0.06 kg Zn per ton of grain yield, with an average of 0.05. A rice crop yielding 6 tons ha^{-1} takes up about 0.3 kg Zn ha^{-1}, of which 60% remains in the straw at maturity (IRRI, 2000). Similarly, Nand and Ram (1996), Rajan (1993) and Maharana *et al*. (1993) reported increases in the uptake of Zn by rice plants with Zn application.

3. Zinc Deficiency in Soil

Zinc deficiency was first diagnosed in rice (Oryza *sativa*) on the calcareous soils of northern India (Yoshida and Tanaka, 1969; Nene, 1966). Zinc deficiency is now considered as the most widespread nutrient disorder in lowland rice after nitrogen, phosphorus and potassium (Quijano-Guerta *et al.,* 2002; Neue and Lantin, 1994). Generally, Zn deficiency is expected in calcareous soils, sandy soils, peat soils, and soils with high phosphorus and silicon (Alloway, 2008, 2004). For that reason, more attention has been given to research work on calcareous soil. The submerged soils are well recognized for the lack of Zn availability to the plants; particularly due to the reaction of Zn with free sulphide (Mikkelsen and Shiou, 1977). Flooding and submergence bring about a decline in available Zn because of the changes in pH value and the formation of insoluble Zn compounds. Meanwhile, the insoluble Zn compounds formed are likely to be with Mn and Fe hydroxides from the breakdown of oxides and adsorption on carbonates, specifically magnesium carbonate. Under the submerged conditions for rice cultivation, Zn is transformed into amorphous sesquioxide precipitates or franklinite; $ZnFe_2O_4$ (Sajwan and Lindsay, 1988). Zinc deficiency causes multiple symptoms which usually appear 2 to 3 weeks after transplanting of rice seedlings, with leaves developing brown blotches and streaks that may fuse to entirely cover older leaves, and plants remain stunted, whereas in severe cases, the plants may die, while those which recover will show substantial delay in maturity and reduction in yield (Yoshida and Tanka, 1969; Van Breemen and Castro, 1980 and Neue and Lantin, 1994).

Zinc deficiency can be found in every part of the world and almost all crops respond positively to application of Zn (Alloway, 2008). Normal soils inherit their trace elements which include Zn primarily from the rocks through geochemical and pedochemical weathering processes. Besides mineralogical composition of the parent material, the total amount of Zn present in the soil is also dependent on the type, intensity of weathering, climate and numerous other predominating factors during the process of soil formation (Saeed and Fox, 1977). Meanwhile, high pH and high contents of $CaCO_3$, organic matter, clay and phosphate can fix Zn in the soil and give rise to the reduction of available Zn (Imtiaz, 1999). Soils derived from granite and gneiss can be low in total Zn (Krauskopf, 1972). Similarly, total Zn is low in highly leached, acid, sandy soils such as the ones found in many coastal areas. Quartz in the soil dilutes Zn from it because the reported concentrations of Zn in quartz are very low, which ranged from 1.0 µg g^{-1} to < 5 to 8 µg g^{-1} (Helmke *et al*., 1977 and Brehler and Wedepohl, 1978). According to the Food and Agriculture Organization (FAO), about 30% of the cultivable soils of the world contain low levels of plant available Zn (Sillanpaa, 1990). The lowest Zn concentrations were always found in Spodosols (28 µg g^{-1}) and luvisols (35 µg g^{-1}), while higher levels were found in fluvisols (60 µg g^{-1}) and Histosols (58µg g^{-1}) (Kiekens, 1995).

4. Zinc under Submerged Soil Conditions

Zn deficiency is very common under flooded soil conditions. In acidic soils, Zn is precipitated as Zn $(OH)_2$ and as ZnS in sulfur-rich and alkaline soils. The availability and solubility of Zn decreases while pH increases. The oxides of Mn and Zn along with $CaCO_3$ or $MgCO_3$ are

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strongly absorbed by Zn under submerged condition. Whereas in calcareous soils, HCO_3^- is the predominant anion, which mainly reduces Zn transport from root to shoot, but not so much the Zn uptake by roots. Under anaerobic condition Zn forms an insoluble Zn-phosphate. Under this condition plant roots will not take up the soluble Zn from the Zn solution as required by the plant. Under submerged conditions, when organic acid concentration increased, the Zn uptake is reduced and this effects the plant growth. The Zn uptake is also reduced under acidic rhizosphere condition due to the release of H^+ from the roots and the surplus intake of cat ions over anions. Under acidic rhizosphere conditions, Zn is released from acid-soluble fractions (e.g., absorbed Zn, organic matter or Fe $(OH)_3$) and is available for plant uptake. Generally, rice plants absorb most Zn from solubilization in the rhizosphere because the available Zn in soil is very low in flooding condition (Dobermann and Fairhurst 2000).

5. Soil Factors Associated with Zn Deficiency

All types of soil may be affected by Zn including: loams, sands, clays (with all classification), loess, alluvium, and soils formed from basalt, sandstone, granite, volcanic ash and many other rocks. In general, soils of arid and semi arid regions and the slightly acidic, leached soils of warm and tropical climates are most inclined to Zn deficiency, however, crops are not equally susceptible to Zn deficiency and at the same soil some crops may suffer from Zn deficiency while others are not affected (Takkar and Randhawa, 1978). Lindsay (1972); Pendias and Pendias (1992) and Alloway (2008) reported that major Zn deficiency causes include: (i) Soils of low Zn content (Parent material), (ii) soils with Restricted Zones, (iii) pH, (iv) soils low in organic matter, (v) Microbially inactivated Zn, (vi) Cool soil temperature, (vii) Plant species and genotypes
(viii) High level of available phosphorus and (ix) Effects of nitrogen.

Zn deficiency problems may occurs in soils with the subsequent characters; (a) neutral to alkaline in reaction (b) high phosphorus status (c) sandy soils (d) acid soils of low total Zn status developed on highly weathered parent material (e) calcareous soil (f) peat and muck soils (g) permanently wet (water logged) and (h) high bicarbonate and magnesium in soils or irrigated water (Alloway, 2004).

5.1 Parent Material of Soils and Zn Content

The major factors affecting the concentration of Zn in soils is the concentration of Zn in soil parent material. The soils derived from gneisses and granites can be low in total Zn and also those originating from sandstone and limestone had lower Zn contents (Barak and Helmke, 1993 and Pendias and Pendias, 1992). Quartz (sand) in the soils also dilutes soil Zn as concentrations of Zn in quartz are very low which range between 1 - 8 $\mu g\ g^{-1}$ (Brehler and Wedepohl, 1978). Also total Zn is low (< 30 $\mu g\ g^{-1}$) in highly leached acid sands. Zinc deficiency may occur in such soils which are inherently low in Zn. The total Zn concentrations in soils vary between 10 to 300 $\mu g\ g^{-1}$ with an average of 50 $\mu g\ g^{-1}$ (Lindsay, 1972). But the average available Zn varied from 1 to 3 $\mu g\ g^{-1}$ (extracted by dithizone). The problem is that only a small amount of soil Zn is available to the crop because of one or more adverse factors. The remainder of the total Zn is fixed in the soil in an insoluble or unexchangeable form and difficult to make available to crop (Stahl and James, 1991).

5.2 Soil pH

Zinc availability is highly dependent on pH. When the pH is above 6, the availability of Zn is usually very low. The availability of Zn in alkaline soils is reduced due to lower solubility of the soil Zn. The concentration of Zn in the soil solution decreases from 10^{-4} (6.5 $\mu g\ g^{-1}$) to 10^{-10} M (0.007 $\mu g\ L^{-1}$) with an increase from pH 5 to pH 8 (Kiekens, 1995). Thus it is more probable that Zn deficiency will occur in alkaline rather than acidic soils. The solubility constant values of $ZnCO_3$ and hydroxides suggest that a soil having high pH would usually contain a small amount of available Zn. In the case of soils characterized by high contents of hydroxyl (OH^-) ions, it is difficult to get a crop response even to applied Zn. The lower availability of Zn under alkaline conditions is attributed to the precipitation of Zn as Zn $(OH)_2$ (Shukla and Mittal, 1979) or $ZnCO_3$ (Saeed and Fox, 1977). The higher carbonate contents

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in alkaline soils also absorb Zn and hold it in an unexchangeable form (Udo *et al.,* 1970). All these factors contribute to the low availability of Zn at higher pH values. Liming of acidic soils increases pH and also the Zn fixing capacity, particularly in soils with high P levels (Alloway, 2004). The movement of Zn in limed soils is considerably lower than in acidic soils (Mortvedt and Giordano, 1967) so that absorption of Zn by the crop may be low. Liming can thus reduce the Zn uptake (Shukla and Moris, 1967) and induce Zn deficiency (Viets, 1966).

5.3 Soil Organic Matter

Low organic matter contents in soils give rise to Zn deficiency as it is observed that available Zn increases with increase in organic matter in soil. Soil organic matter is an important soil constituent which originates from decomposition of animal and plant products. The most stable organic compounds in soil are humic substances such as humic and fulvic acids. Both of these substances contain a relatively large number of functional groups (OH, COOH, SH) which have a great affinity for metal ions such as Zn^{2+}. Fulvic acids mainly form chelates with Zn over a wide pH range and increases the solubility and mobility of Zn (Kiekens, 1995). Simple organic compounds such as amino acids, hydroxy acids and also phosphoric acids are effective in complexing Zn, thus increasing its mobility and solubility in soils (Pendias and Pendias, 1992). An increase in the organic matter contents of a soil will increase its Zn availability; however, if the organic matter content in soil is too high, like in peat and muck soils, this can also contribute to Zn deficiency due to the binding of Zn on solid state humic substances (Katyal and Randhawa, 1983).

5.4 Soil Texture

Lighter textured soils (sands) contain low levels of Zn. Finer texture soils like clay have higher CEC values and therefore have highly reactive sites and can retain more Zn than lighter textured soils (Shukla and Mittal, 1979). Therefore heavier textured soils with larger CEC have higher capacities for Zn adsorption than light textured soils (Stahl and James, 1991). Consequently, Zn deficiency is more likely to occur in sandy than clayey soils. Clay soils adsorb Zn and this adsorption is controlled by CEC and pH (Ellis and Knezek, 1972). Nelson *et al.*, (1953) showed that a certain portion of the Zn adsorbed on the clay was not exchangeable but was acid soluble. This portion of Zn was not available to the plants. Reddy and Perkin (1974) found that kaolonite fixes less Zn than bentonite or illite. Thus clays such as bentonite and illite with higher CECs contribute to the fixing of Zn more strongly, thus making it unavailable to plants.

5.5 Phosphate Fertilizers

Soils with higher phosphate levels, either from native P or due to application of phosphate fertilizers, can cause Zn deficiency stress in crops (Alloway, 2008). Heavy application or prolonged use of phosphatic fertilizers reduces Zn uptake by plants. This effect may be due to the physiological imbalances within the plant (Olsen, 1972). Zinc deficiency due to phosphorus application is termed “P-induced Zn deficiency” (Singh *et al*., 1986).

5.6 Soil Flooding

Zinc deficiency is more often associated with flooded soil than dry soils. For example, rice plants under submerged conditions suffer from Zn deficiency in calcareous soils. But wheat grown in the same soil following rice grows normally (Kausar *et a*l., 1976). Zinc deficiency due to flooding was a result of Zn reaction with free sulphide (Mikkelsen and Shiou, 1977). Under the submerged conditions of rice cultivation, Zn is changed into amorphous sesquioxide precipitates or franklinite; $ZnFe_2O_4$ (Sajwan and Lindsay, 1988 and Singh and Abrol, 1986). Thus a delay in Zn application until after flooding for rice minimizes Zn fixation by sesquioxides (Mandal and Mandal, 1986).

5.7 Soil Temperature

In warm and moist soils, Zn uptake was higher in rice than in maize (*Zea mays* L.) (Bauer and Lindsay, 1965). Temperatures below 16°C during growth caused decreased Zn uptake in maize tops (Ellis *et al*., 1965). It appears that Zn deficiency was associated with cool and wet seasons. Soil temperature effects appear to be due to the rate of Zn mineralization (Takkar and Walker, 1993). Other factors which can cause Zn deficiency in plants are high

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light intensity and long day-lengths (Marschner and Cakmak, 1989). Besides the natural soil and environmental factors, soil management practices carried out by man often causes Zn deficiency beside this plants can also suffer from Zn deficiency under adverse climatic conditions such as drought or compaction (Alloway, 2008).

6 Zinc Interaction with Other Nutrients

Interactions occur between the micronutrients and some macronutrients. 'Interaction' may be defined as "an influence, a mutual or reciprocal action of one element upon another in relation to plant growth" (Olsen, 1972). Another factor is the differential response of plants to one element in combination with varying levels of a second element applied simultaneously i.e. the two elements combine to produce an added effect not due to each of them acting alone (Olsen, 1972). Such interactions may take place in the soil and within the plant. These interactions should be taken into account when providing adequate micronutrient supply to plants. Other nutrients may interact with Zn by affecting its availability from soils and its status in the plant throughout the growth process, especially Zn absorption, distribution or utilization. These interactions may enhance or reduce plant growth as a response to Zn. Where an interaction does occur, it is necessary for the diagnosis and treatment of Zn deficiency to identify the factors and its sites and modes of action (Loneragan and Webb, 1993). Some important interactions of Zn with other nutrients will be discussed below.

6.1 Phosphorus-Zn Interactions

The study of the interaction between P and Zn started in1936 (Barnette *et a*l., 1936) and till now, this important plant growth disorder is still under investigation. The interaction is usually termed 'P-induced-Zn deficiency'. This disorder in plant growth is associated with high levels of available P or with application of P to soil. The Zn deficiency symptoms can be prevented by the application of Zn fertilizers. The actual causal relationship and mechanisms are still not fully understood. In general, four possible causes have been considered responsible for P-induced-Zn deficiency. These include (i) a P-Zn interaction in soil; (ii) a slower rate of translocation of Zn from the roots to shoot; (iii) a simple dilution effect on Zn concentration in plant tops due to growth responses to P; (iv) a metabolic disorder within plant cells related to an imbalance between P and Zn (Olsen, 1972).

It was suspected that formation of an insoluble $Zn_3\ (PO_4)_2$ in the soil reduced the Zn concentration in soil to deficient levels. But these suspicions were disproved by Brown *et al* (1970) who observed that $Zn_3\ (PO_4)_2$ was a good source of fertilizer for sorghum. The investigation of this precipitation as a mechanism that causes Zn deficiency continued till 1970. Carrol and Loneragan (1968) reported that maximal or near maximal yields were found with legumes at 0.05 µM Zn in flowing culture and with cereals at 0.01 µM. This evidence indicates that precipitation of $Zn_3(PO_4)_2$ is not involved in P-induced -Zn deficiency. Many researchers have reported that applied P accentuated Zn deficiency symptoms in plants (Loneragan *et al*., 1979; Sharma *et al*., 1968). The higher P levels in soil reduced the Zn concentrations in the plant tops and also reduced total Zn contents (Singh *et al*., 1986; Clark, 1978). These scientists suggested that P-Zn antagonism existed in the roots of the plants. Other studies suggested that although P decreased the Zn concentrations in the tops, the total Zn contents either increased or remained the same (Boawn and Brown, 1968; Boawn and Leggett, 1968). The cause of this P-induced-Zn deficiency has been suggested to be due to interference by P with the uptake, translocation, or utilization of Zn (Adriano *et al*., 1971).

6.2 Nitrogen-Zn Interactions

Zinc deficiency can be increased or ameliorated in plants with the application of nitrogen fertilizers. The interactions resulting from the effects of N application helps to promote plant growth and, to a lesser extent, in changing the pH of the root environment since application of N promotes the growth of plants, it is possible to find positive interactions between increasing levels of Zn and N fertilizers (Alloway, 2004). Chaudhry and Loneragan (1970) reported that wheat grown on N deficient soil with adequate levels of all nutrients except N

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and Zn, did not respond to Zn application in the absence of NH_4NO_3 fertilizer, however, a strong response to Zn application was observed in the presence of N fertilizer.

On the other hand, in soils low in Zn and high in fertility, N fertilizers have ameliorated (or intensified) Zn deficiency by affecting Zn absorption through changing pH (Viets *et al*., 1957). As ammonium ions have an acidifying effect, $ZnSO_4$ application with concurrent dressings of N were very effective in controlling Zn deficiency where $ZnSO_4$ alone had no effect (Viets *et al*., 1957). It was also observed that NH_4^+ salts inhibited Zn absorption from low Zn $^{2+}$ concentration, in a short term study with wheat (Chaudhry and Loneragan, 1972b). Ammonium ions inhibited Zn^{2+} absorption more strongly than alkali and alkaline earth anions, but were competitive with alkali and alkaline earth cat ions. So NH_4^+ effect would be diminished by relatively high concentrations of competing ions in soil. Thus any direct effect of NH_4^+ on Zn absorption would disappear.

6.3 Macronutrient Cations-Zn Interaction

Macronutrient cations such as Ca, Mg and K inhibit the absorption of Zn by plants from solution. They need to be considered when interpreting the results of solution culture experiments involving Zn nutrition, however, in soil they seem to be less effective in the inhibition of Zn absorption compared to the effects of their salts on soil pH. Zinc concentrations were highest in legumes grown in solution culture at constant pH with the lowest Ca level at which the plants were not Ca deficient. Zinc concentrations progressively decreased with increasing Ca concentrations in solutions (Bell *et al*., 1990). This finding that Ca inhibits Zn absorption was in accord with a short term study conducted by Chaudhry and Loneragan (1972). They found that increasing concentrations of Ca $(NO_3)_2$ from 0 mM to 40 mM inhibited the rate of Zn absorption by wheat seedlings in a non-competitive manner, however, higher Ca concentrations (100mM) had no additional effect on Zn absorption. This inhibition was attributed to Ca as varying the anions and had little effect on Zn absorption, whereas substituting other cat ions for Ca had similarly negative effect.

In soils, the effects of Ca compounds on Zn nutrition are variable, due to the effects of its salts on soil pH. Zinc concentrations in plants growing in soil treated with $CaSO_4$ (which decreased the soil pH from 5.6 to 4.8) increased slightly but decreased strongly when an equivalent amount of $CaCO_3$ was applied (which increases the soil pH from 5.7 to 6.6) (Wear and Evan, 1968).The macronutrient cat ions K, NH_4 and Mg all inhibited the rate of Zn absorption strongly from solutions of low Ca concentrations; with increasing Ca concentrations, the inhibitory effects weakened and in the case of two ions (K, Mg) tested at sufficiently high Ca concentration (2.5-10 mM) eventually disappeared, suggesting that they operate through the same mechanism as Ca (Chaudhry and Loneragan, 1972).

6.4 Copper-Zn Interactions

Loneragan and Webb (1993) reported that Cu and Zn may interact in several ways: Zn strongly depresses Cu absorption, Cu competitively inhibits Zn absorption and Cu nutrition affects the redistribution of Zn within plants.

A very strong Cu-Zn antagonism has been observed in wheat growing on soils deficient in Cu and Zn (Kausar *et al*., 1976). In N-Cu-Zn experiment, Chaudhry and Loneragan, (1970) found that N fertilizer increased grain yield in the absence of Zn and diluted Cu concentrations to deficiency levels in plant. Addition to that, Zn along with N fertilizer intensified the Cu deficiency so severely that grain yield was lower than in the control plants (without NH_4NO_3). In this case, Zn intensified Cu deficiency in plants by depressing Cu uptake. This may be a result from competitive inhibition of Zn on Cu absorption (Bowen, 1987). The competitive inhibition of Cu $^{2+}$ ion on Zn^{2+} absorption has been established in short term studies (Giordano *et al*., 1974). While Zn severely depressed Cu uptake by wheat, Cu did not depress Zn absorption in the same experiment. The reason for the difference in soil and solution culture results may be the form of these ions present in the soil and solution. In solution studies, the Cu and Zn were present as divalent ions whereas in most of the soils they are predominantly present as complex forms and a much higher proportion of Cu is complexed compared to Zn (Geering and Hodson, 1969). So Zn $^{2+}$

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activity would be much higher than Cu^{2+} activity at the absorbing sites making it an effective competitor in Cu absorption and making its absorption less sensitive to competition from Cu (Loneragan and Webb, 1993).

6.5 Iron-Zn Interaction

The interaction between Zn and Fe is also complex like P-Zn interaction. The increased application of Zn had little effect (Norvell and Welch, 1993) or decreased (Safaya, 1976) Fe concentrations in the shoot. In the same way, higher levels of Fe generally have only a depressive effect on Zn concentration in plant tissues (Zhang *et al*., 1991b), although it has been shown to increase have no effect on or to decrease the rate of Zn absorption by plant roots (Giordano *et al*., 1974). These conflicting reports are probably due to differences in experimental details, especially in plant species and the concentration, ionic state and complexation of Fe.

Iron (Fe^{2+}) at low concentrations (10 µM) had no effect on the rate of Zn absorption by wheat seedlings from solutions containing 1 or 10 µM Zn and 50 mM $Ca(NO_3)_2$ (Chaudhry and Loneragan, 1972b). But at higher concentrations (100 µM Fe^{2+}), and at concentrations likely to occur in flooded rice soils, Fe completely suppressed the Zn absorption by rice seedlings from a solution of 0.05 µM $ZnCl_2$ with no Ca (Giordano *et al*., 1974). Iron deficiency increased Zn concentrations in shoots of plants (Agarwala *et al*., 1979) and also the rate of Zn absorption in both dicotyledonous plants (Romheld *et al*., 1982) and grasses (Zhang *et al*., 1991b). In dicotyledonous plants, the mechanism for increasing Zn absorption is probably the acidification of the rhizosphere resulting from Fe deficiency (Marschner and Cakmak, 1989). For grasses, the release of phytosiderophores under Zn deficiency is responsible for the higher Zn absorption rate as phytosiderophores have enhanced the mobilization of Zn from calcareous soils (Zhang *et al*., 1991b and Treeby *et al*., 1989). In a similar way, under Zn deficient conditions, Fe accumulated in the shoots of Zn deficient navy beans and corn plants are possibly due to the acidification of the rhizosphere and the release of reductants and phytosiderophores ((Ambler and Brown, 1969 and Jackson *et al*., 1962).

7. **Dilution Effect**

When the rate of plant growth is faster than the rate of uptake of a particular nutrient, the concentration of the nutrient is "diluted" in the plant (Singh *et al.,* 1986; Olsen, 1972). These researchers also showed that in wheat and bean the yield and total Zn content increased with P application while the Zn concentrations in plants decreased. A response in yield was found for applied P, so a dilution effect on Zn is largely accountable for this effect. In general, this interaction occurs when the soil is deficient in P and/or slightly deficient in available Zn. The growth rate increases due to applied P but the rate of Zn uptake does not increase fast enough to maintain Zn concentration in plants. In some cases of P-induced-Zn deficiency the dilution effect only partially explains the data (Singh *et al*., 1986).The applied P reduces the Zn concentration in the tops of the plant while the yield response to P is minimal (Singh *et al.,* 1986).

8. Distribution of Zn in Plant Roots and Tops

The plant part (roots) close to the source of Zn supply meets its nutritional requirement first before significant translocation to the top occurs (Olsen, 1972). Legume plants had 35 % of the total Zn contents in the roots during growth reduction by Zn deficiency compared to the 18 % under optimum Zn supply (Carrol and Loneragan, 1968). Due to this difference, a greater reduction in shoot yield was observed compared with roots. Stuckenholtz *et al.* (1966) found that Zn concentration and uptake by the corn roots increased with applied P in a silt loam soil at pH 7.9, whereas the Zn concentration and uptake decreased in leaves, nodes and inter-nodes. Burleson *et al*. (1967) suggested the possibility of P-Zn antagonism within the roots.

A small increment in fertilizer P produced a great effect on the increment of Zn concentration in plant tops (Stuckenholtz *et al*., 1966). This effect of added P on Zn concentrations may be designated as a "physiological effect" (Olsen, 1972), but the simple explanation appears to

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be related to the distribution of Zn between the roots and tops. The low mobility of Zn within the plant means that it maintains its localized distribution with plant growth. Analyses of the tops of plants growing under these conditions could possibly indicate the interference of P with the translocation of Zn to the tops (Olsen, 1972).

9. Zinc Efficiency

Zn efficiency can be defined as "the ability of plants to maintain high yields in soils with low Zn availability". Many mechanisms are perhaps involved in Zn efficiency (Rengel, 2001). Depending on the nature of experiments and plant species, the most significant mechanisms may be Zn utilization in tissues (Hacisalihoglu and Kochian, 2003) and Zn uptake (Genc *et al*., 2006). Under Zn deficiency, Zn-efficient genotypes have a high activity of Cu/Zn anhydrase (Hacisalihoglu *et al*., 2003a; Yu *et al*., 1999; Cakmak *et al*., 1997) and carbonic anhydrase (Hacisalihoglu *et al*., 2004; Rengel, 1995). Zn efficiency and Zn uptake are very susceptible for plant growth and its total content in soil is influenced by several soil properties like pH, $CaCO_3$, organic matter content, crop, as well as cultivars and nutrient interactions in soil environment. There is no precise mechanism used in determining Zn efficiency is available so far; however, several crops have been evaluated for their Zn efficiency like: beans (Ambler and Brown, 1969; Hacisalihoglu *et al*., 2001; Hacisalihoglu *et al*., 2003b), wheat (Graham and Raangel 1993; Cakmak *et al*., 1997a) and rice (Brown *et a.l*, 1993; Clark, 1990; De Datta and Neue, 1993; Nand, 2002; Geo, 2007).

9.1 Zinc Deficiency in Plants

Zinc is an essential micronutrient for plant growth and plays an important role in the catalytic part of several enzymes (Fageria, 2002). Many researchers observed that Zn is closely related to the nitrogen metabolism pathway of plants, thus causing a reduction in protein synthesis for Zn deficient plants. Zinc deficiency significantly affects the root system including root development (Fageria, 2004). Zinc deficiency affects the absorption of water and nutrients from soil and thus resulting in growth and yield reduction in the plant. Epstein and Bloom (2005) indicated that the flowering and fruiting process were greatly reduced under severe Zn deficiency.

9.2 Zinc deficiency Symptoms in plants

Visual symptoms of Zn deficiency in plants are fairly characteristic and are relatively easy to identify. These distinctive symptoms are useful for recognizing acute Zn deficiency and for indicating Zn responsive soils, but not the hidden or marginal deficiencies. The most common symptoms of Zn deficiency include: stunted growth, shortened internodes and petioles, and small malformed leaves (little leaf) which results in the "rosette" symptom in the early growth stages of dicotyledons and "fan shaped" stems in monocotyledons (Snowball and Robson, 1986). The deficiency symptoms first appear on young leaves as Zn is immobile under conditions of deficiency. These leaves remain small, cup upward and develop interveinal chlorosis and necrotic spots on the upper leaf surfaces which later join to each other to form brown necrotic and brittle patches. The necrosis is often more noticeable on middle aged leaves which eventually wilt, bend and collapse (Brennan *et a*l., 1993). Zinc deficiency is typically patchy, even within a single field and symptoms develop rapidly but depend greatly on the degree of stress (Kubota and Allaway, 1972). Enzyme activity, like ribonuclease activity or carbonic anhydrse activity can be used as an index for precise information. This is particularly important in the initial stages of growth when micronutrient requirements of plants are very low and the total contents of Zn fail to provide precise information about the hidden deficiency.

9.3 Zn Deficiency Symptoms and Tolerance in Rice

The visible symptoms in rice are: wilting due to loss of turgidity in the leaves, basal chlorosis of the leaves, delayed development of the plants, " bronzing" of the leaves and in some cases death of the rice seedling (Neue *et al*., 1998). Neue *et al* (1998) stated that the common symptoms of Zn deficiency in rice are: chlorosis in the mid rib at the base of the youngest leaf within 2-4 weeks after sowing or transplanting and the appearance of brown spots on the older leaves. The spots enlarge, coalesce and give the leaves a brown color.

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Zinc deficient plants show stunted growth and reduced tillering. If the deficiency is not too severe the plant may recover after 4-6 weeks but maturity is delayed and yields of susceptible cultivars are reduced. The most noticeable symptom is the plant's loss of turgidity, where plants fall over and float on the surface of the water. The basal leaves become pale green and after 3-7 days the leaves become chlorotic. It is important to note that visual symptoms of Zn deficiency in rice vary, to a certain extent, with soil type, cultivar and growth stages. Symptoms can be mistaken for those of of N, Mg, Mn or Fe deficiencies which are often combined with Zn deficiency, making it difficult to distinguish between the symptoms of the two. Therefore, plant analysis is required for confirmation (Dobermann and Fairhurst, 2000; Alloway, 2004, 2008).

The different toleration systems to Zn in rice have been recognized by various researchers (Neue *et al*., 1994). Generally, early maturing genotypes are disposed to Zn deficiency due to high requirement of Zn in the initial stages of its development. Rice cultivars vary in their Zn requirements. The International Rice Research Institute (IRRI), at Los Banos in the Philippines screened more than 23,000 rice cultivars for Zn deficiency tolerance. All cultivars were found to differ in their Zn efficiency (Alloway, 2004). Kirk and Bajita (1995) indicated that the uptake of Zn increased with root-induced changes in the rhizosphere.It may be due the solubilisation of root-induced acidification from the H^+ generated and oxidation of Fe^+ or intake of cations, such as NH^+_4, relative to anions and the associated release of H^+ from the root. Most of the Zn in flooded soils is expected to be acidic-solubilized from the previously mentioned ions and absorbed by ferrous carbonates and hydroxides. The concentration of plant available Zn is very low and the plants generally depend on plant-induced solubilisaton for the bulk of their supplies of Zn.

10. Zinc Critical Levels in Plants

It was reported by Katyal and Randhawa (1983) that there is a strong relationship between Zn concentration in tissues with the growth and yield of crops. The critical limits of Zn in plants indicates deficiency as suggested by Dobermann and Fairhurst (2000) are :< 10 mg kg^{-1} definite Zn deficiency, 10–15 mg kg^{-1} very likely,15–20 mg kg^{-1} likely and >20 mg kg^{-1} unlikely (sufficient). Zinc deficiency is one of the major constraints in world food production. It is therefore essential to identify the Zn-deficient areas, and the different causes of deficiency. It would help in planning the appropriate strategies to correct these Zn deficiencies. Although Zn is being used as a fertilizer, an understanding of efficient and economical methods to correct Zn deficiency on a long term basis and in a specific cropping system is desirable. Zinc deficiency can be corrected through the application of Zn fertilizers, recycling crop residues, natural organic manures and cultivation of Zn efficient genotypes (Singh, 2008).

11. Zinc Toxicity

High Zn concentrations in plants can cause phytotoxicity. The yield may be reduced when plant leaf Zn concentrations reaches about 300 - 1000 µg Zn g^{-1}. A typical phytotoxicity critical concentration is about 500 µg Zn g^{-1} (Chaney, 1993). The best way to identify Zn deficiency in crops is the determination of Zn concentrations in tissues, however, the results should be interpreted in full recognition of the interaction of Zn with other nutrients because the deficiency of one nutrient may result in excess accumulation of other nutrients by a plant (Katyal and Rawdhawa, 1983).

12. Effect of Zn on Microbial Activity

Microorganism requires various nutrients for their growth and metabolism. Among the nutrients, Zn is an element present in the enzyme system as co-factor and mental activator of many enzymes (Vankatakrishnan *et al*., 2003). According to Vankatakrishnan *et al*. (2003); Baath (1992) and Doelman and Haanstra (1984), the solubilization of Zn might limit the growth of bacteria at higher levels (>13.60 mg kg^{-1}). Furthermore, cell growth as well as microbial populations and their activity in soil were badly affected under high levels of Zn.

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