

ZINC NUTRITION IN RICE BASED CROPPING SYSTEMS:A COMPREHENSIVE REVIEW

Abstract:

Rice based cropping systems being the most practiced cropping system in India, it suffers zinc deficiency as majority of the Indian soils are deficient in the Zn micronutrient. Zn is considered as the fourth most important yield limiting nutrient of Agricultural crops. Apart from the plant nutrition Zn also plays crucial role in human nutrition. Zn plays vital role in the physiological function of plants and is associated with the phytohormone activity, protein synthesis, carbohydrate metabolism. To understand better about the zinc nutrition and its associated benefits from optimum nutrition and ways to manage Zn in rice based cropping systems, the present review critically examines nutrient mobilization and transformation of Zn in rice based cropping systems of India.

Keywords: Rice based cropping systems, phytohormone, protein synthesis, carbohydrate metabolism, optimum nutrition.

Introduction :

Zinc is considered as the key element effecting growth, development and life of the living organisms along with playing essential role in physiological activities (Fageria *et al.*, 2002; Stanton *et al.*, 2022; Wu *et al.*, 2022). Zn deficiency in people results in symptoms such as , loss of appetite, anorexia, loss of taste and smell, and other symptoms. It can also have an impact on the immune system, leading to arteriosclerosis and anemia (Gondal *et al.*, 2021). Growth retardation, congenital fetal abnormalities, and pregnancy and birthing problems have all been linked to zinc deficiency (Black, 2001).

Micronutrient deficits, particularly those of Zn, are one of the main causes of economic loss in developing nations (Stein, 2014). According to recommendations, an average individual needs 11 mg of zinc per day for males and 8 mg of zinc per day for females (NIH, 2021).

Comment [Mu1]: Link with hyphen

Comment [Mu2]: Link with hyphen

Comment [Mu3]: Link with hyphen

Comment [Mu4]: Link with hyphen

Comment [Mu5]: Affecting

Comment [Mu6]: Add "an" before it

Comment [Mu7]: Reduce the space

Zinc is a crucial element needed to improve crop growth and output; of all micronutrients, Zn is regarded as the most important nutrient (Samreen *et al.*, 2017). More than 300 enzymes, including carbonic anhydrase, alcoholic dehydrogenase, alkaline phosphatase, carboxy peptidase, phospholipase, superoxide dismutase (SOD), and RNA polymerase, depend on zinc for their structural and functional integrity. These enzymes regulate a variety of biochemical and physiological processes, including cell division, protein synthesis, photosynthesis, gene transcription, nucleic acid metabolism, and pollen (Hacisalihoglu, 2020).

Rice is a considerable staple food cereal on which half the world population is dependent for energy and 20% protein requirements (Rehman *et al.*, 2012). Around 50% of Asia's population, or roughly 2 billion people, are at danger of Zn insufficiency, despite the fact that Asia covers about 87% of the world's rice-growing area and consumes 90% of all rice produced (Chen *et al.*, 2017, FAO, 2018). Agronomic biofortification of Zn could be a potential option to address the problem of Zn deficiency (Zulfiqar *et al.*, 2021).

The primary cropping system used in India is the rice-based cropping system (RBCS), which rotates crops with vegetables, fodder crops, pulses, and oilseeds. The productivity of a system is significantly influenced by how nutrients are managed during different seasons. Any farming system can be made more productive by using micronutrients (Tutiet *al.*, 2018). Zn is thought to be the micronutrient that is needed the most.

Rice based cropping systems (RBCS)

Rice is the predominant crop in the world meeting 20% of the human food calories and India is considered as the largest producer occupying ~ 45 million ha under cultivation (Tuti *et al.*, 2018). Due to varying climatic situations during the crop year the annual crops are grown in progression. The crops may either be grown along with rice as a inter crop or in sequence

Comment [Mu8]: World's

Comment [Mu9]: in

Comment [Mu10]: even though

Comment [Mu11]: link with hyphen

Comment [Mu12]: link with hyphen

according to the climatic conditions and feasibility in order to maximize the resource utilization (Sarwar *et al.*, 2022).

Rice based cropping system can be described as, in a farming practice considering rice as the major crop is succeeded by other adaptable crops. In India major cropping system followed is the Rice based cropping system where, the major crop rice is followed by either pulses, cereals, oilseeds etc. (Tuti *et al.*, 2018).

Comment [Mu13]: link with hyphen to all in this work

Comment [Mu14]: add "of" before it

The central principle in considering a crop in cropping system lies with a. the biological traits of the crop and how they interact with and are influenced by its physical, chemical, and ecological environment, b. the crop to be grown in sequence after the major crop, c. the management practices to be followed for the cropping system (Jensen *et al.*, 2010). The major crop in cropping systems was rice, which was chosen based on the agro-climatic and socio-economic circumstances of the area. In India, rice-rice, rice-wheat, rice-pulse, and rice-potato are the most common rice-based cropping systems (Sravan and Murthy, 2018).

Table 1: Rice cropping systems occurring in Indian states (Tuti *et al.*, 2018)

Agro-climatic region	Cropping system followed
Western himalayan	Rice-wheat, rice-potato-potato
Eastern himalayan	Rice fallow, rice-rice, rice-pulses/oilseeds
Lower gangetic plain	Rice-rice, rice-wheat, rice-potato-jute/vegetables
Middle gangetic plain	Rice-wheat, rice-maize, rice-potato-sunflower
Upper gangetic plain	Rice-wheat, sugarcane-ratoon-wheat
Trans gangetic plain	Rice-wheat
Eastern plateau and hills	Rice-blackgram, rice-niger/linseed, rice-vegetables
East coast plain and hills	Rice-groundnut-greengram, Rice-greengram/blackgram, rice-rice
West coast plains and hills	Rice-rice
Andaman and Nicobar	Rice- fallow

Nutrient mobilization of zinc in RBCS

Movement of the nutrient Zn in crop sequence of the cropping system can be understood as ~~the~~ nutrient mobilization. Cropping systems following the integrated mode of nutrient management **was** found to have **significant** effect on soil fertility. Including pulse crops like green gram and vegetable crops in the rice based cropping system along with supplementing nutrients through different sources of biofertilizers and organic manures significantly improves crop nutrient absorption by increasing the availability of soil nutrients, the total zinc nutrient uptake by the rice and wheat (Verma *et al.*, 2020).

Comment [Mu15]: were

Comment [Mu16]: add "a" before it

The organic sources of nutrients and biofertilizers **supplies** considerable amounts of the major and micronutrients continuously throughout the crop growth period unlike, ~~in~~ the inorganic sources the nutrients are available to the plants in the earlier and the later stages of ~~the~~ growth, organic sources provide long-term availability of nutrients (Singh *et al.* (2010); Garai *et al.* (2013) and Verma *et al.* (2017)).

Comment [Mu17]: supply

Change from the current, conventional cropping system to an enhanced cropping system including potato and cucumber between two seasons of rice has **resulted** 49% higher rice equivalent yield due to the more profits gained under higher yield of cucumber and potato (Alam *et al.*, 2021). Rice-non rice **crop based** cropping systems were more profitable compared to rice-rice cropping system (Nagoli *et al.*, 2017).

Comment [Mu18]: resulted in

Comment [Mu19]: link with hyphen

In a rice-based cropping system, crop intensification results in a rice equivalent yield that is two to four times greater (Samant, *et al.*, 2015, Jat *et al.*, 2012). The rate of increase of REY depends on **type** of crop, number of crops involved and the ecosystem in which the crop is grown (Alam *et al.*, 2021). In an improved cropping system consisting of transplanted Aman rice followed by potato, cucumber and transplanted Aus rice has received 49% higher rice equivalent yield compared to the existing cropping system consisting of transplanted Aman rice followed by potato and transplanted Boro rice (Alam *et al.*, 2021).

Comment [Mu20]: add "the" before it

The Nutrient Index (N.I) gauges how well a soil can supply nutrients to plants (Singh *et al.*, 2016). Cropping systems with pulse as a component will have higher nutrient index than the vegetables as a component (Singh *et al.*, 2020). Supply of recommended dose of fertilizers along with inclusion of pulse crops as a component/sequence in a cropping system will results in the improved nutrient response of the crop to Zn (Shankar *et al.*, 2021). In order to gain higher productivity and profitability from a cropping system need based application of Zn is essential along with the application of inorganic sources of fertilizers as the nutrients will be present in the available forms plants gets maximum benefited (Xu *et al.*, 2014).

Comment [Mu21]: add "the" before it

Comment [Mu22]: add "the" before it

Comment [Mu23]: application

Comment [Mu24]: benefit

Comment [Mu25]: add "the" before it

Thus application of both organic and inorganic sources of nutrients will make the nutrients more available as is the case with DTPA-extractable Zn content in post-harvest soil of both rice and wheat, Customized fertilizer application had shown increased Zn content by 95% and 158% over 100% RDF in soils of wheat and rice, respectively (Kumar *et al.*, 2021).

Status of Zn in Indian soils

Fertility of Indian soils is generally poor with progressively emerging micronutrient deficiencies due to their catalyzed removal under agricultural intensification. According to latest estimates, out of about 188.4 thousand tonnes (Tt) of micronutrients removed by 263 Mt of food grains produced, nutrient removal by Zn is 23.9 Tt and in Indian soils, total Zn content ranges from 7-2960 mg/kg and available Zn content ranges from 0.01-52.9 mg/kg. Currently, 36.5% of soil samples nationwide have deficiencies in available Zn, with acute, latent, and total deficiencies occurring in 8, 29, and 15% of the country, respectively (Shukla *et al.*, 2019). Zn is currently regarded as the fourth-most significant nutrient for agricultural crops in India that limits productivity. By 2025, zinc deficiency in Indian soils is predicted to rise from 42 to 63% (Sharma *et al.*, 2021). According to a study of Indian soils, out of 2.52 lakh soil samples examined, 49% were found to be low in the available Zn spread throughout 20 states. There is

widespread zinc deficiency throughout all agro-ecological zones (AEZ). Maximum Zn deficit extended, up to 60%, in AEZ 6 and 10 soils. Agro-ecological zones 3, 4, 7, 8, 13, and 14 had soils that were 50–60% zinc deficient. In states like Punjab, Haryana, Uttar Pradesh, Andhra Pradesh, Bihar, and Madhya Pradesh, the severity of Zn deficiency is decreasing.

The extent of zinc deficiency was found to be 55, 47, and 36% in Trans-northern, Central, and Eastern sections of IGP alluvial plains, according to analysis of 90419 surface soil samples from AEZ 4, 9, 13, and 16 of the Indo-Gangatic alluvial plains(IISS, 2021).

Map 1 : Map showing area having Zinc deficient soils

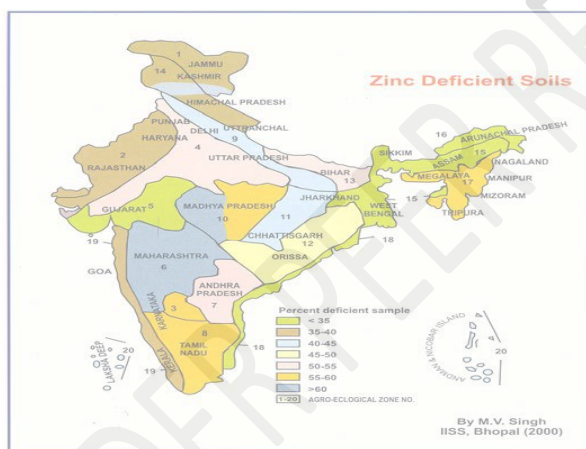


Table 2: Critical limits of available Zn for agricultural soils of India.

	Available Zn (mg kg^{-1})
Acute deficient	≤ 0.30
Deficient	$> 0.30 - \leq 0.60$
Latent deficient	$> 0.60 - \leq 0.90$
Marginal sufficient	$> 0.90 - \leq 1.20$
Adequate	$> 1.20 - \leq 1.80$
High	> 1.80

UNDER PEER REVIEW

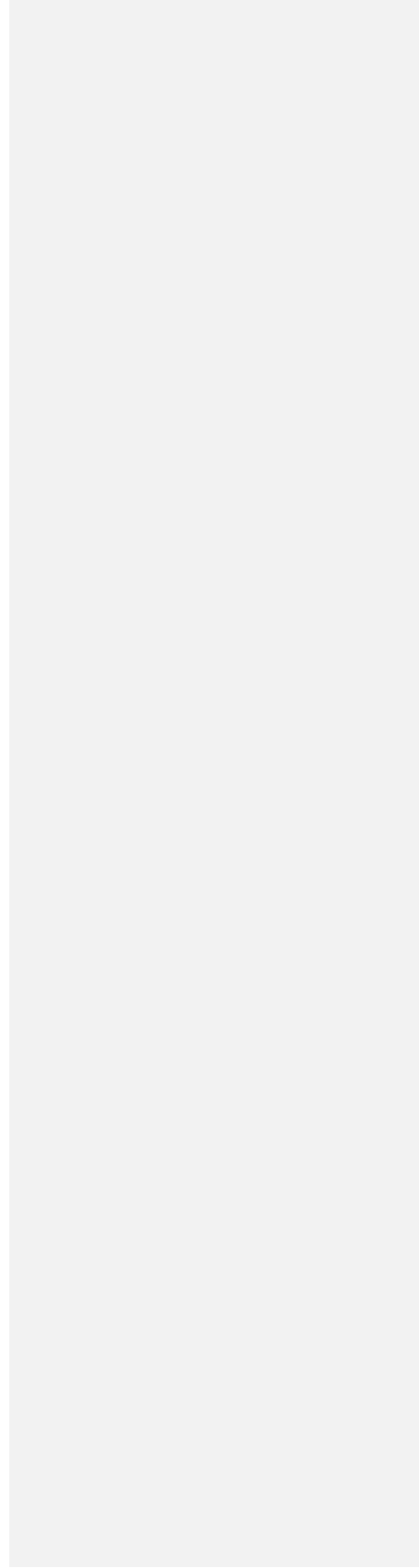
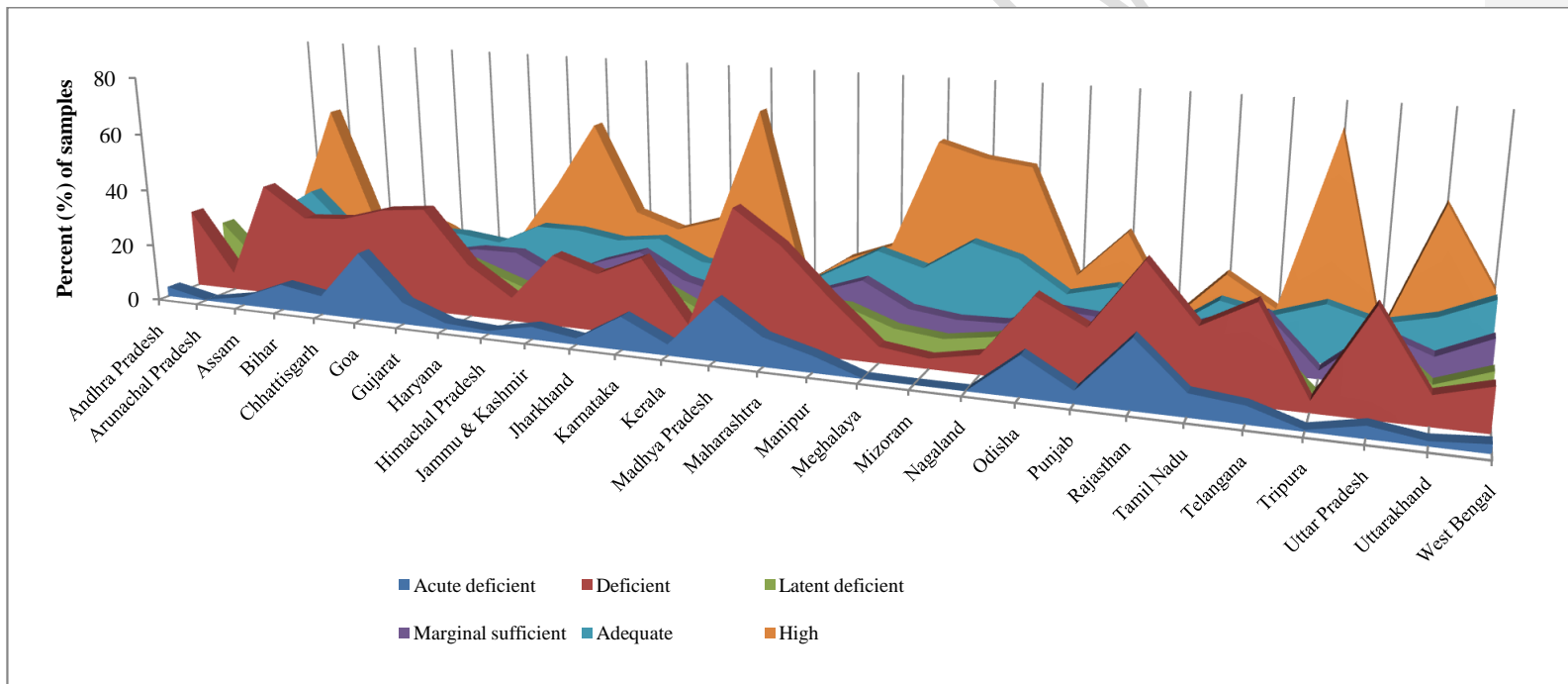


Fig 1: Deficit by state (% of soil samples) available Zn. (Shukla *et al.*, 2021)



Physiological functions of Zn in plants

Zinc is the vital nutrient having its role in normal growth and productivity of the plants (Suganya A. *et al.*, 2020). The nutrient was also found to have its role in structurally and functionally maintaining the cell membranes (Hafeez, B., *et al.* 2012). Optimum Zn nutrition helps in the improvement of the photosynthetic activity by 50%-70% and thus increases the chlorophyll content, net photosynthetic rate, transpirational rate and stomatal conductance (Liu *et al.*, 2016, Rudani *et al.*, 2018). Zn application improves the plant activity under drought conditions by enhancing the photosynthetic process (Hassan, M.U., *et al.* 2020). Deficiency of zinc in plants results in the decreased content of the chlorophyll content and also affects the ratio of chl a: chl b. Reduced photosynthetic activity leads to reduced growth, leaf area (up to 72%) and reduced number of leaves (Hajiboland R. *et al.*, 2010). Zinc plays role in phytohormone activity, enzyme activation, protein synthesis, carbohydrate metabolism and noticeable role in defending phytopathogens (Grungreiff *et al.*, 2020, Suganya A. *et al.*, 2020). Zinc is identified as the primary requisite of enzyme classes such as transferases, ligases, oxidoreductases, isomerases, lyases, hydrolases and is also a constituent of ribulose 1,5-biphosphate carboxylase (RuBpc) involved in photosynthesis. As the element is involved in different categories of enzymes the functions indirectly involved in the metabolism of carbohydrates, proteins, auxins will get affected, meanwhile the productivity of the plants gets hindered under the deficient conditions (Romheld and Marschner 1991, Singh *et al.*, 2005). The enzyme carbonic anhydrase which governs the fixation of carbohydrates by conversion of carbon dioxide to bicarbonates is managed by zinc (Kandil *et al.*, 2022). The most rudimentary effect of zinc in protein metabolism is its activity in maintaining the stability and functioning of genetic material (Rudani *et al.*, 2018). Living membranes are maintained by zinc, cell membrane integrity is often regulated by the availability of zinc which drives the detoxification of membrane damaging ROS and thus

Comment [Mu26]: add "A" before it

Comment [Mu27]: affects

Comment [Mu28]: add "against" before it

Comment [Mu29]: change to "be"

Comment [Mu30]: link with hyphen

involved in the plant water relations (Ghazi *et al.*, 2022). So, in the absence of the Zn sulphhydryl groups and lipids in the membrane undergoes injury and organic compounds leaks through the cells, especially root cells exposed to certain situations leads to root diseases in Zn deficient plants (Mousavi, S. R. *et al.*, 2013, Sadeghzadeh, B. 2013. The defence mechanism of plants against the diseases is often correlated to the Zn nutrition through which the plants attains resistance by modifying the physiology and morphology of the plants (Kandil *et al.*, 2022).

Comment [Mu31]: defense

Comment [Mu32]: diseases

Factors affecting availability of zinc:

Parent material from which the soils are derived has significant effect on availability of Zn. The soils those originating from gneisses, granite, sandstone and lime stone are found to be lower in the available Zn contents (Barak and Helmke 1993). The major concern in availability of Zn lies in its fixed/ insoluble/ unexchangeable forms (Suganya *et al.*, 2020).

Comment [Mu33]: limestone

Availability of Zn is highly reliant on pH, with increase in pH above 6, Zn availability decreases with increase in pH. Precipitation of Zn into insoluble forms of soil Zn, $ZnSiO_4$ or $ZnFe_2O_4$ will takes place leading to reduced solution Zn / available Zn.

Comment [Mu34]: take

Zn deficiency is more likely to be noticed in the alkaline soils than acid soils. Soils with high hydroxyl (OH^-) ions, response of the plants to external application of the Zn is negligible. Under alkaline situations Zn is precipitated as $Zn(OH)_2$ or $ZnCO_3$ (Barak and Helmke 1993, Suganya and saravanan 2015). Soils with higher carbonate contents will relatively exhibit unavailability of the Zn due to absorption of Zn on to soil particles and turned to unexchangeable forms (Alloway 2004).

Comment [Mu35]: negligible

Comment [Mu36]: onto

Zn deficiency is more prevalent in the soils with low organic matter. In high organic matter containing soils available Zn is accordingly high (Hafeez *et al.*, 2013).

Comment [Mu37]: link them with hyphen

Humic acid and fulvic acids are the identified stable organic compounds with comparably contains more functional group ions like (OH, COOH, SH) which shows affinity

Comment [Mu38]: show

to Zn^{2+} (Suganya *et al.*, 2020). Fulvic acids generally forms chelates with Zn increasing mobility and solubility of Zn. In case of the high organic soils like peat and muck binding of zinc to humic substances takes place and make Zn unavailable (Katyal and Randhawa 1983).

Soil texture also ~~has effect on~~ the effect on the Zn availability, sandy soils with lighter texture exhibits more deficiency in available Zn compared to the heavier textured clay soils. Clay soils with high CEC values certainly have more affinity to retain Zn (Hafeez *et al.*, 2013, Suganya *et al.*, 2020).

Comment [Mu39]: affect

Soil moisture significantly affects the availability of nutrients to the plants as the diffusion of nutrients to roots is affected by soil moisture. Zn nutrition is considered to be at stake in arid and semi arid regions due to the coincidence of prolonged water deficit periods during the growing season. Whereas, in water logged situations Zn co-precipitates with iron and aluminium makes Zn unavailable to the plants (Hafeez *et al.*, 2013, Suganya *et al.*, 2020). Compared to dry soils, flooded soils are more prone to Zn deficiency because in the prior case Zn reacts with free sulphide. In case of rice delayed application of the Zn until after flooding rice decreases fixing of zinc with sesquioxides (Suganya and Saravanan 2014, 2015)

Comment [Mu40]: link them up

Comment [Mu41]: link them up

Comment [Mu42]: making

Fluctuations in temperature towards the colder side below 16 °C during growing period will hinder the zinc availability to the plants due to change in the rate of Zn mineralization. Besides plants suffer Zn deficiency as a result of unfavourable climatic situations (Alloway, 2008).

Comment [Mu43]: add "the" before it

Available sources of Zn

The following order describes the reduction in solubility of several zinc minerals: Zn (OH)₂ (amorphous) > Zn(OH)₂ > ZnCO₃ (smithsonite) > ZnO (zincite) > Zn (PO₄)₂·4H₂O (willemite) > soil Zn > Zn Fe₂O₄ (franklinite). Zinc forms soluble complexes with chloride, phosphate, nitrate, and sulphate ions however, the neutral sulphate (ZnSO₄) and phosphate

(ZnHPO₄) species are the most significant and contribute to the overall concentration of zinc in solution. When acidifying fertilizers like ammonium sulphate [(NH₄ (SO₄)₂)] are employed, the ZnSO₄ complex accounts for the enhanced availability of zinc and may increase the solubility of Zn²⁺ in soils (Arunachalam *et al.*, 2013). Most commonly available forms of zinc sulphate are (ZnSo₄.H₂O)-33% Zn - Zinc sulphate monohydrate, (ZnSo₄.7H₂O)-21% Zn- Zinc sulphate heptahydrate and chelated form as (Zn EDTA)-9% Zn(Gite *et al.*, 2021).

Nano Zn- ZnO-Zinc oxide nanoparticles in a colloidal solution are utilized as fertilizer. A plant nutrient known as nano fertilizer is more than just a fertilizer because it not only gives plants the nutrients they need, but also restores the soil to its organic state without the negative effects of chemical fertilizers. Nano fertilizers have the benefit of being able to be applied in extremely small quantities (Sabir *et al.*, 2014).ZnO as fertilizer source will aid in improved growth and yield resulting in enhanced qualitative and quantitative value of the crop (Azam *et al* 2022).

Zinc deficiency symptoms in plants:

In **general** the deficiency symptoms of Zn includes: shortening of internodes leading to stunted growth, malformation of leaves which will be visible as little leaf and rosette leaf formation. **Usually** the deficient symptoms tend to be visible in younger leaves because under deficient conditions Zn gets immobile in plants. Necrosis symptom is often seen in **the middle aged** leaves, interveinal chlorosis is another predominant symptom visible under Zn deficient situations.

Comment [Mu44]: general,

Comment [Mu45]: usually,

Comment [Mu46]: link them up

In rice:

Chlorosis of the basal leaves, loss of turgidity in leaves leading to wilting, bronzing of the leaves, death of the young seedlings is seen. In younger seedlings of age 2-4 weeks after transplanting or sowing, chlorosis of the youngest leaves in the midrib at base is seen.

Appearance of brown spots on the older leaves, which eventually enlarge and coalesce to form brown colored leaves (Hafeez *et al.*, 2013). Other predominant symptoms includes reduced tillering, stunted growth, loss of turgidity and plants fall down on the surface of the water and float.

Comment [Mu47]: "The" before it

Comment [Mu48]: link them up

Comment [Mu49]: floating

In many cases the zn deficiency can be mistaken for the deficiency of N, Mg, Mn or Fe. So, plant analysis is often recommended before drawing conclusions.

Comment [Mu50]: concluding

Effective Zinc management methods in Rice Based Cropping Systems

Comment [Mu51]: capitalized each word

Soil conditions and rice production systems play a crucial role in deciding the method of application of zinc to the plants in order to maximize benefits. Most promising methods followed in rice based cropping systems are soil application, seed priming, zinc encapsulated fertilizers, foliar application, seed coating, seedling root dip method, bio-fertilizer based application.

Comment [Mu52]: "The" before it

Soil application of Zn fertilizers are found to be effective in promoting growth, yield and biofortification of the grains. Basal application of zinc has improved the yield by 18% compared to control (Zulfiqar *et al.*, 2020). Plants are capable of absorbing soluble compounds and gases through leaves. Application of foliar sprays make the leaves absorb them and export to the growing tissues. Jose (2019) reported that higher grain and straw yield of rice were recorded with foliar spray of $ZnSO_4$ at 0.1% at different growth stages. Combined soil + foliar applied Zn resulted in maximum kernel yield and kernel Zn concentration in fine rice (Ali *et al.*, 2021). Improved yield components and nutrient recovery through Zn foliar nutrition is observed by (El-Sobky *et al.*, 2022).

Seed coating with nutrients like zinc using plant based substances as adhesives is also a possible method to maximize the benefits, 13 % increase in yield was noticed with this practice in rice by (Zulfiqar *et al.*, 2020).

By partially hydrating seeds, a practice known as "seed priming," germination-related metabolic processes can start to take place but radicle emergence is prevented. This is a feasible method to raise the Zn content in seeds to improve yield-attributing characteristics and yields because of the tiny amounts of Zn required for seed priming and the simplicity of the procedure. (Sharma *et al.*, 2021). Seed priming has significant effect on yield and grain Zn contents in the rice under different production systems and zinc application methods (Ali *et al.*, 2021).

The growth, Zn nutrient content, and Zn nutrient uptake of rice were all found to be improved by inoculating it with arbuscular mycorrhizal fungus (Purakayastha and Chhonkar, 2001). Replacing 25% of inorganic nutrients with bio-fertilizers has shown promising nutrient uptake and performance of zinc in rice (El-Sobky *et al.*, 2022).

CONCLUSION

Through the review it is understood that India is highly under risk of zinc malnutrition as the soils are deficient in the nutrient at first place and the zinc nutrition is often neglected in agriculture. Correcting the zinc deficiency in rice-based cropping systems will be a significant endeavor to achieve the benefits of biofortification through fertilization because rice-based cropping systems are widely used in India and rice is the main diet for the majority of Indians. As availability of the Zn to plants is dependable on various factors related to the soil like pH, organic matter, moisture availability etc. considering the factors responsible for unavailability, with available sources of Zn, effective zinc management methods like seed priming, foliar application etc. has to be adopted to deal with zinc deficiency.

Comment [Mu53]: at

Comment [Mu54]: in

REFERENCES

- Alam, M.J., Al-Mahmud, A., Islam, M.A., Hossain, M.F., Ali, M.A., Dessoky, E.S., El-Hallous, E.I., Hassan, M.M., Begum, N., and Hossain, A. 2021. Crop diversification in rice-based cropping systems improves the system productivity, profitability and sustainability. *Sustainability*. 13: 6288.
- Ali, M.F., Adnan, M., Khan, Asif, M., Perveen, S., Ammar, A., Ali, A., Hanif, M.S., Ali, U., Rehman, F.U., Ilahi, H., and Raza, A. 2021. Agronomic zinc bio-fortification in rice production systems. *Plant Cell Biotechnol. Mol. Biol.* 22(25&26): 103-113.
- Alloway, B. J. 2008. Micronutrients and crop production. In *Micronutrient deficiencies in global crop production*, 1–39.
- Arunachalam, P., Kannan, P., Prabhukumar, G., and Govindaraj, M. 2013. Zinc deficiency in Indian soils with special focus to enrich zinc in peanut. *African J. Agric. Res.* 8(50): 6681-6688.
- Azam, M., Bhatti, H.N., Khan, A., Zafar, L., and Iqbal, M. 2022. Zinc oxide nano-fertilizer application (foliar and soil) effect on the growth, photosynthetic pigments and antioxidant system of maize cultivar. *Biocatal. Agric. Biotechnol.* 42: 102343.
- Barak, P., and P. A. Helmke. 1993. The chemistry of Zinc. In *Zinc in soils and plants*, ed. A.D. Robin, pp. 90-106. Dordrecht: Kluwer Academic Publishers.
- Black, R.E. 2001. Micronutrients in pregnancy. *Br. J. Nutr.* 85:193-197.
- Chen, X.P., Zhang, Y.Q., Tong, Y.P., Xue, Y.F., Liu, D.Y., Zhang, W., and Cui, Z.L. 2017. Harvesting more grain zinc of wheat for human health. *Sci. Rep.* 7(1): 7016
- El-Sobky, EEA., Taha, AE, El-Sharnouby, M., Sayed, S.M., and Elrys, A.S. 2022. Zinc-biochemical co-fertilization improves rice performance and reduces nutrient surplus under semi-arid environmental conditions. *Saudi J Biol Sci.* 29(3):1653-1667.
- Fageria, N.K., Baligar, V.C., and Clark, R.B. 2002. Micronutrients in crop production. *Adv. Agron.* 77: 189–272.
- FAO [Food and Agriculture Organization]. 2018. <https://www.fao.org/food-systems/en/>.

- Garai, T.K., Datta, J.K., and Mondal, N.K. 2013. Evaluation of integrated nutrient management on boro rice in alluvial soil and its impacts upon growth, yield attributes, yield and soil nutrient status. *Arch. Agron. Soil Sci.* 60(1): 1–14.
- Ghazi, S., Diab, A.M., Khalafalla, M.M., and Mohamed, R.A. 2022. Synergistic effects of selenium and zinc oxide nanoparticles on growth performance, hemato-biochemical profile, immune and oxidative stress responses, and intestinal morphometry of Nile tilapia (*Oreochromis niloticus*). *Biol. Trace Elem. Res.* 200: 364–374.
- Gite, D., Gite, H., Darvhankar, M., and Gite, P. 2021. Zinc sulphate a potential micronutrient for wheat growth: A review. *Pharma Innovation.* 10 (5): 473-475.
- Gondal, A.H., Zafar, A., Dua-e-Zainab., Toor, M.D., Sohail, S., Ameen, S., Ijaz, A.B., Imran, C.B., Hussain, I., Haider, S., Ahmad, I.A., Rehman, B., and Younas, N. 2021. A detailed review study of zinc involvement in animal, plant and human nutrition. *Ind. J. Pure App. Biosci.* 9(2): 262-271.
- Grungreiff, K., Gottstein, T., and Reinhold, D. 2020. Zinc deficiency-An independent risk factor in the pathogenesis of haemorrhagic stroke?. *Nutrients.* 12: 3548.
- Hacisalihoglu, G. 2020. Zinc (Zn): The last nutrient in the alphabet and shedding light on Zn efficiency for the future of crop production under suboptimal Zn. *Plants.* 9: 1471.
- Hafeez, B., Khanif, Y.M., and Saleem, M. 2013. Role of zinc in plant nutrition – a review. *Am. J. Exp. Agric.* 3(2): 374-91.
- Hafeez-ur Rehman., Aziz, T., Farooq, M., Wakeel, A., and Rengel, Z. 2012. Zinc nutrition in rice production systems: a review. *Plant Soil.* 361: 203–226.
- Hajiboland, R., and Amirzad, F.2010. Drought tolerance in Zn-deficient red cabbage (*Brassica oleracea L. var. capitata f. rubra*) plants. *Hortic. Sci.* 37: 88-98.
- Hassan, M.U., Aamer, M., Chattha, M.U., Haiying, T., Shahzad, B., Barbanti, L., Nawaz, M., Rasheed, A., Afzal, A., Liu, Y., and Guoqin, H. 2020. The critical role of zinc in plants facing the drought stress. *Agric.* 10(9): 396.
- IISS [Indian Institute of Soil Science]. 2021. *Extent of micro- and secondary nutrient deficiencies in Indian soils and their correction.* Available:<https://iiss.icar.gov.in/#modal-one>. [11 November 2021].
- Jat, R.A., Dungrani, R.A., Arvadia, M.K., and Sahrawat, K.L. 2012. Diversification of rice (*Oryza sativa L.*)-based cropping systems for higher productivity, resource-use efficiency and economic returns in south Gujarat. *India. Arch. Agron. Soil Sci.* 58: 561-572.

- Jensen, E.S., Peoples, M.B., and Nielsen, H.H. 2010. Faba bean in cropping systems. *Field Crops Res.* 115:203-216.
- Jose, A. 2019. Agronomic biofortification of zinc in rice (*Oryza sativa* L.). M.Sc. (Ag) thesis, Kerala Agricultural University, Thrissur, 119p.
- Kandil, E.E, El-Banna, A.A.A., Tabl, D.M.M., Mackled, M.I., Ghareeb, R.Y., Al-Huqail, A.A., Ali, H.M., Jebril, J., and Abdelsalam, N.R. 2022. Zinc Nutrition Responses to Agronomic and Yield Traits, Kernel Quality, and Pollen Viability in Rice (*Oryza sativa* L.). *Front. Plant Sci.* 13:791066.
- Katyal, J.C., and Randhawa, N.S. 1983. *Micronutrients FAO Fertilizer and Plant Nutrition Bulletin* in 7. Rome: Food and Agriculture Organization of the United Nations.
- Kumar, M., Singh, S.K., and Patra, A. 2021. Effect of different nutrient sources on yield and biochemical properties of soil under rice–wheat cropping sequence in middle Gangetic alluvial plain, *J. Plant Nutr.* 44(15): 2310-2330.
- Liu, J., Zhu, R., Xu, T., Xu, Y., Ge, F., Xi, Y., Zhu, J., and He, H., 2016. Co-adsorption of phosphate and zinc (II) on the surface of ferrihydrite. *Chemosphere.* 144:1148–1155.
- Mousavi, S.R., Galavi, M., and Rezaei, M. 2013. Zinc importance for crop production - a review. *Int. J. Agron. Plant Prod.* 4:64-68.
- Nagoli, S.B., Basavanneppa, M.A., Sawargaonkar, G.L., Biradar, D.P., Biradar, S.A., and Tevari, P. 2017. Diversification of Rice-rice (*Oryza sativa* L.) cropping systems for productivity, profitability and resource use efficiency in Tunga Bhadra Project Command Area. *BEPLS.* 6, 108–114.
- NIH [National Institutes of Health]. 2021. *Zinc fact sheet for health professionals.* Available: <https://ods.od.nih.gov/factsheets/Zinc-HealthProfessional/>. [10 November 2021]
- Purakayastha, T.J. and Chhonkar, P.K. 2001. Influence of vesicular-arbuscular mycorrhizal fungi (*Glomus etunicatum* L.) on mobilization of zinc in wetland rice (*Oryza sativa* L.). *Biol Fertil Soils.* 33: 323-327.
- Rehman, H., Aziz, T., Farooq, M., Wakeel, A., and Rengel, Z. 2012. Zinc nutrition in rice production systems: A review. *Plant Soil.* 361: 203-226.
- Romheld, V., and H. Marschner. 1991. Function of micronutrients in plants. In *Micronutrients in agriculture*, ed. J. J. Mortvedt, F. R. Cox, L. M. Shuman, and R. M. Welch, 297–328. Madison, USA: Soil Science Society of America, Book Series No. 4.

- Rudani, L., Vishal, P., and Kalavati, P. 2018. The importance of zinc in plant growth-A review. *Int. Res. J. Nat. Appl. Sci.* 5, 38–48.
- Sabir, S., Arshad, M., and Chaudhari, S.K. 2014. Zinc oxide nanoparticles for revolutionizing agriculture: synthesis and applications. *Sci. World J.* 1-8.
- Sadeghzadeh, B. 2013. A review of zinc nutrition and plant breeding. *J. Soil Sci. Plant Nutri.* 13:905–27.
- Samant, T.K. 2015. System productivity, profitability, sustainability and soil health as influenced by rice based cropping systems under mid central table land zone of Odisha. *Int. J. Agric. Sci.* 7, 746–749.
- Samreen, T., Humaira H.U.S., Ullah, S., and Javid, M. 2017. Zinc effect on growth rate, chlorophyll, protein and mineral contents of hydroponically grown mung beans plant (*Vigna radiata*). *Arab. J. Chem.* 10(1): 1802–1807.
- Sarwar, N., Atique-ur-Rehman, Ahmad, S., Hasanuzzaman, M. (2022). Rice-Based Cropping Systems. (eds) Modern Techniques of Rice Crop Production . Springer, Singapore.
- Sharma, M., Parmar, D.K., Kumar, P., Sankhyan, N.K., Kumar, P., and Butail, N.P. 2021. Efficacy of zinc nutrition for improving zinc content at different growth stages of rainfed pea-maize sequence in North Western Himalaya. *J. Plant Nutr.* 44(20): 1-11.
- Shankar, T., Banerjee, M., Malik, G.C., Dutta, S., Maiti, D., Maitra, S., Alharby, H., Bamagoos, A., Hossain, A., and Ismail, I.A. 2021. The Productivity and Nutrient Use Efficiency of Rice–Rice–Black Gram Cropping Sequence Are Influenced by Location Specific Nutrient Management. *Sustainability.* 13: 3222.
- Shukla, A.K., Behera, S.K., Pakhre, A., and Chaudhari, S.K. 2019. Micronutrients in soils, plants, animals and Humans. *Indian J. Fertilizers.* 14(4): 30-54.
- Shukla, A.K., Behera, S.K., Prakash, C., Tripathi, A., Patra, A.K., Dwivedi, B.S., Trivedi, V., Rao, C.S., Chaudhari, S.K., Das, S., and Singh, A.K. 2021. Deficiency of phyto-available sulphur, zinc, boron, iron, copper and manganese in soils of India. *Sci. rep.* 11: 19760.
- Singh, K.K., Singh, Y. V., and Sharma, S.K. 2010. Influence of biofertilizers and urea application on grain yield and quality attributes in rice (*Oryza sativa* L.) cultivars. *J Soil Water Conserv.* 9(4): 271–76.
- Singh, B., S. Kumar, A. Natesan, B. K. Singh, and K. Usha. 2005. Improving Zinc deficiency of cereals under zinc deficiency. *Current Science.* 88:36–44.

- Singh, G., Sharma, M., Manan, J., and Singh, G. 2016. Assessment of soil fertility status under different cropping sequences in District Kapurthala. *J Krishi vigyan*. 5(1): 1-9.
- Singh, S.R., Yadav, P., Singh, D., Bahadur, L., Singh, S.P., Yadav, A.K., Mishra, A., Yadav, P.P.S., and Kumar, S. 2020. Impact of different crop grown systems on land nutrient index, microbial diversity and soil quality. *Land Degrad Dev*. 32(14): 3973-3991.
- Stanton, C., Sanders, D., Krämer, U., and Podar, D. 2022. Zinc in plants: integrating homeostasis and biofortification. *Mol. Plant*. 15, 65–85.
- Stein, A.J. 2014. Rethinking the measurement of under nutrition in a broader health context: Should we look at possible causes or actual effects?. *Glob. Food. Secur.* 3(3&4): 193-199.
- Pravan, U.S. and Murthy, K.V.R. 2018. Enhancing productivity in rice-based cropping systems. *IntechOpen*. 59-75.
- Suganya, A., Saravanan, A., and Manivannan, N. 2020. Role of Zinc Nutrition for Increasing Zinc Availability, Uptake, Yield, and Quality of Maize (*Zea Mays* L.) Grains: An Overview. *Commun Soil Sci Plant Anal*. 51:15.
- Suganya, A., and Saravanan, A. 2014. DTPA – Zn in soil under simulated moisture conditions as influenced by graded levels of Zn in combination with zinc solubilizing bacteria. *Biosci. Trends*.7:3968–71.
- Suganya, A., and Saravanan, A. 2015. DTPA – Zn in pH varied soils under simulated moisture conditions as influenced by graded levels of Zn in combination with zinc solubilizing bacteria. *Biosci. Trends*. 8:812–15.
- Tuti, D.M., Kumar, M., Saha, S., and Singh, A. 2018. Rice-based cropping systems for enhancing productivity of food grains in India: decadal experience of AICRP. *Indian Farming*. 68(01): 27–30.
- Verma, R.K., Shivay, Y.S., and Ghasal, P.C. 2017. Effect of different cropping systems and nutrient sources on growth, productivity and economics of direct seeded basmati rice (*Oryza sativa*). *Indian J. Agric. Sci*. 87(10): 1377–83.
- Verma, R.K., Shivay, Y.S., Choudhary, M., Ghasal, P.C., and Madar, R. 2020. Nutrient mobilization and crop assimilation as influenced by nutrient management strategies under direct seeded basmati rice (*Oryza sativa*)-based cropping systems. *Indian J. Agric. Sci*. 90(10): 1894-1901.

- Wu, Q., Liu, C., Wang, Z., Gao, T., Liu, Y., and Xia, Y. 2022. Zinc regulation of iron uptake and translocation in rice (*Oryza sativa* L.): Implication from stable iron isotopes and transporter genes. *Environ. Pollut.* 297:118818.
- Xu, X., He, P., Pampolino, M.F., Johnston, A.M., Qiu, S., Zhao, S., Chuan, L., and Zhou, W. 2014. Fertilizer recommendation for maize in China based on yield response and agronomic efficiency. *Field Crop. Res.* 157: 27–34.
- Zulfiqar, U., Hussain, S., Maqsood, M., Ishfaq, M., and Ali, N. 2021. Zinc nutrition in puddle transplanted and direct seeded production systems to enhance productivity, zinc use efficiency and grain biofortification of fine aromatic rice. *J. Plant Growth Regul.* 40: 1539-1556.
- Zulfiqar, U., Hussain, S., Maqsood, M., and Ishfaq, M. 2020. Zinc nutrition to enhance rice productivity, zinc use efficiency and grain biofortification under different production systems. *Crop Ecol. Manag. Quality.* 10: 1-11.

UNDER PEER REVIEW