PHOSPHORUS-ZINC INTERACTIONS IN THE SOIL ENVIRONMENT AND THEIR EFFECTS ON THE SUSTAINABILITY OF AGRICULTURAL SOILS

ABSTRACT

Phosphorus (P) and zinc (Zn) are essential nutrients required for plant growth and productivity. Phosphorus plays a pivotal role in energy transfer (ATP), nucleic acid synthesis, root development, and grain formation, while zinc is involved in enzyme activation, hormone synthesis, photosynthesis, and seed development. Calcareous soils, which dominate large areas of Iraq and the Middle East, pose significant challenges due to their high calcium carbonate content and alkaline pH. These conditions lead to phosphorus precipitation as insoluble calcium phosphates and zinc immobilization through adsorption or precipitation as carbonates and hydroxides, thereby reducing their availability and causing deficiency symptoms such as slow growth and purpling of leaves in P deficiency, or stunted plants and interveinal chlorosis in Zn deficiency. Nutrient interactions between P and Zn represent an additional challenge; excessive P fertilization often suppresses Zn uptake, while balanced fertilization enhances the utilization of both nutrients. The major processes governing phosphorus include mineralization, immobilization, adsorption–precipitation, and desorption, whereas zinc undergoes mineral weathering, adsorption onto soil minerals, precipitation, organic complexation, and redox reactions, all of which restrict their bioavailability, particularly in calcareous soils.

Recent studies from Iraq, the broader Middle East, and global field trials have demonstrated that integrating nanofertilizers, foliar applications, and organic amendments (such as compost and vermicompost) within integrated nutrient management (INM) systems significantly improves the availability of phosphorus and zinc. These practices enhance the productivity of strategic crops such as wheat, barley, and maize. Linking these nutrient management strategies with the United Nations Sustainable Development Goals (SDGs)—particularly SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being) through zinc biofortification, and SDG 12 (Responsible Consumption and Production)—highlights the strategic importance of sustainable phosphorus and zinc management in calcareous soils.

Keywords :Phosphorus, Zinc**,** Calcareous soils**,** Sustainable agriculture**.**

INTRODUCTION

Phosphorus (P) and Zinc (Zn) are among the most essential nutrients required for plant growth and sustainable crop production. Phosphorus is a key component of nucleic acids, phospholipids, and ATP, playing a critical role in energy transfer, root development, and grain formation (Alikhani et al., 2024). Zinc, on the other hand, functions as a cofactor for over 300 enzymes, influences protein synthesis, hormonal balance, membrane integrity, and resistance to environmental stresses (Zhao et al .,2023 ;Ali et al., 2025). In calcareous soils, which dominate large areas of Iraq and the Middle East, the availability of both nutrients is severely restricted. High levels of calcium carbonate and alkaline pH lead to phosphorus precipitation as insoluble calcium phosphates and zinc immobilization through adsorption or precipitation as carbonates and hydroxides. These processes reduce the bioavailability of P and Zn below critical thresholds, resulting in nutrient deficiencies and yield losses (Adnan et al., 2025; Ahmed et al., 2024). The interaction between P and Zn further complicates nutrient management. Excessive phosphorus application frequently induces zinc deficiency, while balanced fertilization enhances the efficiency of both nutrients (Bashir et al., 2024; Ding et al., 2023). Therefore, understanding the dynamics of phosphorus and zinc in soils and plants is crucial for improving nutrient management practices and ensuring sustainable agricultural production (Gerenfes&Negasa 2021; He et al., 2021).

Zinc deficiency in cereals also represents a global human health issue, particularly in developing countries where cereal-based diets predominate. Optimizing phosphorus and zinc fertilization improves not only crop yield but also grain nutritional quality, contributing to biofortification strategies that address micronutrient malnutrition (Desta et al., 2023; Chahal et al., 2023; Alikhani et al., 2023). Recent advances have emphasized the role of nanofertilizers, biofertilizers, and organic amendments in overcoming P and Zn fixation in calcareous soils. These integrated strategies improve nutrient cycling, enhance soil fertility, and contribute to achieving the United Nations Sustainable Development Goals (SDGs), especially Zero Hunger (SDG 2) and Good Health and Well-being (SDG 3) (Ding et al., 2021 ; Gerenfes et al.,2021 ; Hui et al.,2025).

1. Importance of Phosphorus in Plant Nutrition:

Phosphorus (P) is one of the most essential macronutrients required for plant growth and productivity. It plays a direct role in energy production and transfer through adenosine triphosphate (ATP) and adenosine diphosphate (ADP), which are central to almost all biochemical reactions in plant cells (Adnan et al., 2020 ; El-Damarawy et al.,2025). Moreover, phosphorus is a key component of nucleic acids (DNA and RNA), making it crucial for cell division, protein synthesis, and the development of new tissues, thereby influencing both vegetative and root growth (Bibi et al., 2024). In addition, phosphorus is vital for root development and branching, as its availability stimulates lateral root formation and root hair elongation, leading to improved uptake of water and other essential nutrients such as nitrogen and zinc (Duan et al., 2024). Recent findings have shown that combining phosphorus with organic amendments such as biochar significantly enhances soil fertility, microbial activity, and root mycorrhizal colonization, ultimately improving plant health and productivity (Ei-Damarawy et al., 2025). Field experiments on soybean have further demonstrated that the application of calcined low-grade phosphate rock improved biological nitrogen fixation, increased grain yield, and enhanced nutritional quality, highlighting the broader role of phosphorus in supporting both growth and nutrient efficiency (Ghosh et al., 2021). On a global scale, it has been estimated that nearly 50% of agricultural soil phosphorus fertility originates from anthropogenic sources such as chemical fertilizers, emphasizing the risks of over-reliance on non-renewable inputs and the urgent need for sustainable phosphorus management strategies to secure long-term agricultural productivity (Mousavi et al., 2023).

2. Forms of Phosphorus in Soil :

Phosphorus exists in soils in both organic and inorganic forms, but only a small fraction is directly available to plants. The major forms include:

2-1.1 Inorganic Phosphorus

Found mainly as calcium phosphates in calcareous soils.

At high pH (>7.5), soluble phosphate ions ($H_2PO_4^-$ and HPO_4^{2-}) precipitate with calcium to form dicalcium phosphate, octacalcium phosphate, and hydroxyapatite, which are poorly soluble (Hou et al., 2024; Islam et al., 2022).

2-2 Organic Phosphorus

Comprises 20–80% of total P in soils, depending on management and organic matter levels. Includes inositol phosphates (phytate), phospholipids, and nucleic acids. Organic P becomes available through mineralization by soil microorganisms, especially under warm and moist conditions (Mayadunne et al., 2024; Yang et al., 2025).

2-3 Available Phosphorus

The fraction that can be absorbed by plants is usually <0.1% of total soil P.
It exists as orthophosphate ions in soil solution.
Continuous fixation and immobilization make this pool very dynamic (Vahedi et al., 2022).

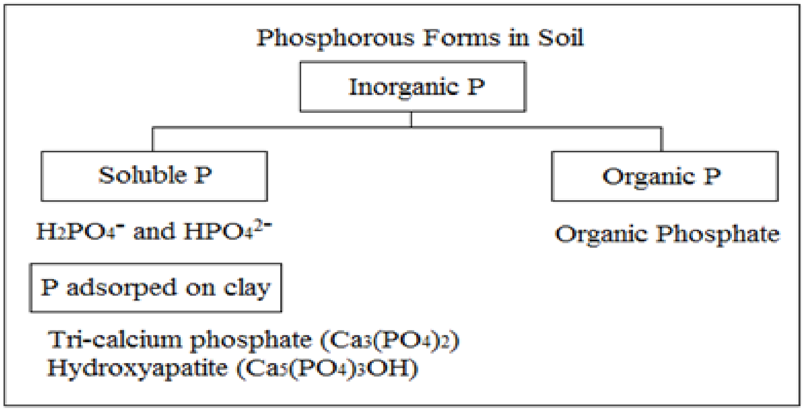

Figure (1) : Phosphorus forms in soil

3. Major Processes of Phosphorus Transformations in Soil and Plants

3-1 Mineralization

Organic compounds such as phytate are decomposed by phosphatase and phytase enzymes secreted by soil microorganisms, converting organic phosphorus into inorganic phosphate that can be absorbed by plants (Stamm et al., 2022).

C6H18O24P6+6H2O→Phytase6H3PO4C_6H_{18}O_{24}P_6 + 6H_2O \xrightarrow{Phytase} 6H_3PO_4C6H18O24P6+6H2OPhytase6H3PO4

3-2 Solubilization

Insoluble phosphate minerals such as $Ca_3(PO_4)_2$ are solubilized through the secretion of organic acids (e.g., citric and gluconic acids) by phosphate-solubilizing microorganisms. These acids lower soil pH and form complexes with calcium, releasing available phosphate into the soil solution (Xie et al., 2021).

Ca3(PO4)2+2H2(C6H6O7)→3Ca2++2HPO42−Ca_3(PO_4)_2 + 2H_2(C_6H_6O_7) \rightarrow 3Ca^{2+} + 2HPO_4^{2-}Ca3(PO4)2+2H2(C6H6O7)→3Ca2++2HPO42−

3-3 Adsorption–Desorption

Phosphate ions can bind strongly to the surfaces of iron and aluminum oxides or clay minerals, reducing their availability in the soil solution. However, this phosphorus can be released again when soil conditions change, such as variations in pH or the presence of competing ions (Desta et al.; Hou et al., 2025).

≡FeOH+H2PO4−→≡FeH2PO4+OH−\equiv FeOH + H_2PO_4^- \rightarrow \equiv FeH_2PO_4 + OH^-≡FeOH+H2PO4−→≡FeH2PO4+OH−

3-4 Biological Recycling

Plants recycle phosphorus internally by remobilizing it from older tissues such as senescent leaves to actively growing organs like young leaves and seeds. This process involves specific phosphorus transporter proteins, while soil microorganisms also contribute by releasing phosphorus after their death and decomposition (Nadeem et al.,2024).

Organic Pold tissues→PhosphatasesH2PO4−→TransportersNew tissuesOrganic\;P_{\text{old tissues}} \xrightarrow{Phosphatases} H_2PO_4^- \xrightarrow{Transporters} New\;tissuesOrganicPold tissuesPhosphatasesH2PO4−TransportersNewtissues

3-5 Precipitation/Fixation

In acidic soils, phosphate reacts with aluminum or iron ions to form insoluble compounds such as $AlPO_4$, whereas in alkaline soils it precipitates with calcium as $Ca_3(PO_4)_2$, limiting its availability for plants (Rafiullah et al., 2021).

Al3^{+}+H2PO4−→AlPO4↓Al^{3+} + H_2PO_4^- \rightarrow AlPO_4 \downarrowAl3++H2PO4−→AlPO4↓ 3Ca2++2HPO42−→Ca3(PO4)2↓3Ca^{2+} + 2HPO_4^{2-} \rightarrow Ca_3(PO_4)_2 \downarrow3Ca2++2HPO42−→Ca3(PO4)2↓

4.The Importance of Zinc in Plant Nutrition

Zinc (Zn) is a vital micronutrient for plant physiological processes, acting as a cofactor for over 300 enzymes involved in protein synthesis, gene regulation, and membrane stability (Ali et al., 2025). In addition, Zn plays a critical role in photosynthesis by contributing to chlorophyll production and activating enzymes such as carbonic anhydrase, which is essential for efficient energy fixation in plants (Hui et al., 2025). Under saline or drought stress, zinc helps to protect the photosynthetic apparatus and sustain physiological functions by mitigating negative impacts on photosynthesis and preserving plasma membrane integrity (Lakshmi et al., 2021). Furthermore, Zn enhances plant tolerance to salinity stress through improved antioxidant enzyme activity, stabilization of cell membranes, regulation of stomatal movement, and modulation of gene expression (Martinez-Rios et al., 2024). Zinc has also been shown to strengthen the plant's ability to absorb other nutrients such as calcium and magnesium, while reducing harmful sodium accumulation under salt stress, thereby improving plant stress resilience (Ramesh et al., 2024). Finally, the molecular mechanisms underlying Zn deficiency responses involve regulation through F-group bZIP transcription factors and epigenetic regulators such as microRNAs, which maintain a precise control of Zn homeostasis in plants (Recena et al., 2021).

5. Forms of Zinc in Soil

Zinc (Zn) occurs in soils in a variety of forms, but only a very small portion is present in the soil solution and readily available to plants. The major fractions are:

5-1 Soluble Zn

Exists as Zn^{2+} ions or as soluble complexes with organic ligands. Represents the immediately available pool for plant uptake, but usually constitutes less than 0.1% of total Zn in soil (Sebhaleab et al., 2025).

5-2 Exchangeable Zn

Held on the cation exchange sites of clay minerals and organic matter. Readily available to plants under favorable soil moisture and pH conditions.

5-3 Zn Bound to Carbonates and Oxides

In calcareous soils, zinc frequently precipitates as $ZnCO_3$ or becomes strongly adsorbed onto calcium carbonate surfaces.

Zn can also bind to iron and manganese oxides, reducing its solubility (Xiong et al., 2025).

5-4 Organic Zn

Complexed with soil organic matter through chelation.This pool can be important in soils rich in organic inputs, where microbial activity slowly mineralizes organic Zn into available forms (Suganya et al., 2020).

5-5 Residual Zn

Bound within the crystal lattices of primary and secondary minerals. Represents the largest pool of total Zn in most soils, but is unavailable to plants except over geological timescales (Shah et al., 2023).

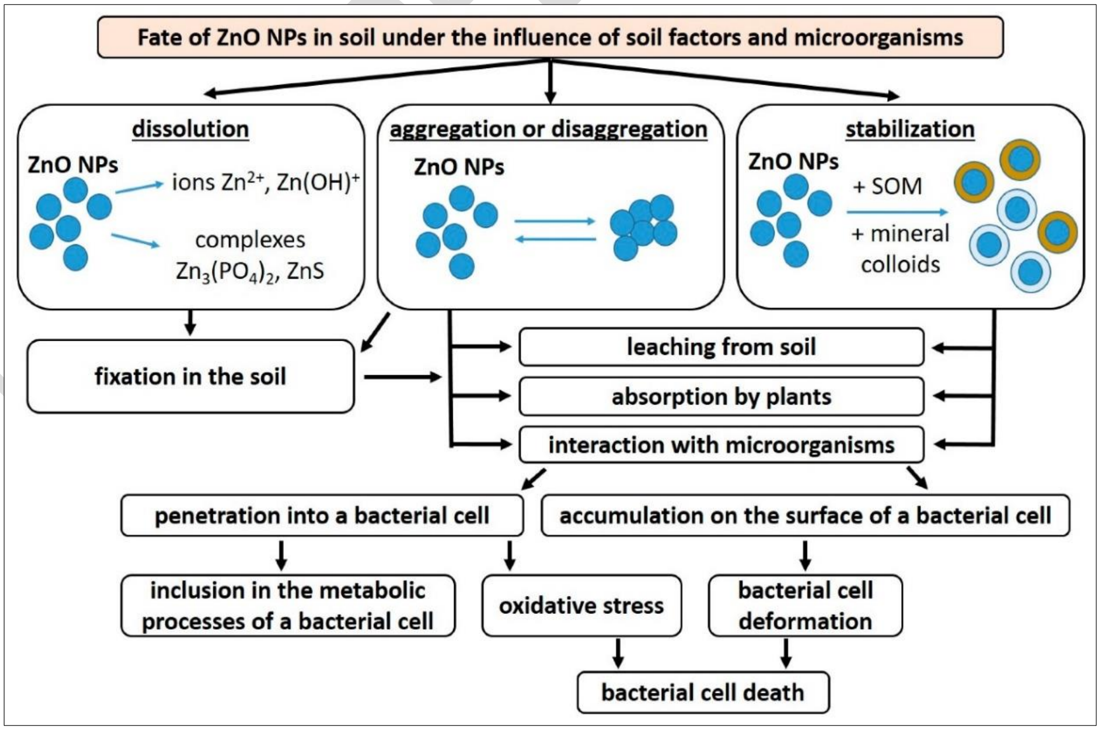

Figure (2) : Key processes determining the fate of ZnO NPs in soil under the influence of soil factors and microorganisms. SOM—soil organic matter.

6. Major Processes of Zinc Transformations in Soil and Plants

6-1 Dissolution and Precipitation

Zinc is commonly present in soils as poorly soluble compounds such as zinc hydroxide ($Zn(OH)_2$) and zinc carbonate ($ZnCO_3$). Their solubility is strongly affected by soil pH and the presence of organic ligands, which can enhance dissolution into Zn^{2+} ions or lead to precipitation into insoluble forms (Zhao, 2023).

Zn(OH)2⇌Zn2++2OH−Zn(OH)_2 \rightleftharpoons Zn^{2+} + 2OH^-Zn(OH)2 ⇌Zn2++2OH− ZnCO3⇌Zn2++CO32−ZnCO_3 \rightleftharpoons Zn^{2+} + CO_3^{2-}ZnCO3⇌Zn2++CO32−

6-2 Adsorption–Desorption

Zn^{2+} ions are adsorbed onto the surface of clay minerals and Fe/Al oxides, thereby reducing their availability to plants. Desorption occurs when soil pH or competing cations shift, releasing zinc into the soil solution (Shkur et al., 2025).

≡FeOH+Zn2+→≡FeOZn++H+\equiv FeOH + Zn^{2+} \rightarrow \equiv FeOZn^+ + H^+≡FeOH+Zn2+→≡FeOZn++H+

6-3 Complexation with Organic Ligands

Zinc interacts with organic acids such as fulvic and humic acids, forming soluble or insoluble complexes. These interactions significantly affect Zn mobility and plant uptake, Mathpal et al.,2022).

Zn2++RCOO−→[Zn(RCOO)]+Zn^{2+} + RCOO^- \rightarrow [Zn(RCOO)]^+Zn2++RCOO−→[Zn(RCOO)]+

6-4 Redox-Related Transformations

Although zinc itself is not easily oxidized or reduced, redox conditions in the soil influence its solubility. Under anaerobic conditions, Zn^{2+} may precipitate as insoluble zinc sulfide (ZnS), especially in flooded soils (Vahedi et al.,, 2022).

Zn2++S2−→ZnS↓Zn^{2+} + S^{2-} \rightarrow ZnS \downarrowZn2++S2−→ZnS↓

6-5 Biological Uptake and Recycling

Plants absorb Zn^{2+} primarily through ZIP transporter proteins in the root system. In conditions of deficiency, plants remobilize Zn from older leaves to actively growing tissues, while soil microorganisms recycle zinc during decomposition (Korkmaz et al.,2021)Znsoil2+→ZIP TransportersZnroot cells2+→redistributed to new tissuesZn^{2+}_{soil} \xrightarrow{ZIP\ Transporters} Zn^{2+}_{root\ cells} \quad \to \quad redistributed\; to\; new\; tissuesZnsoil2+ZIP TransportersZnroot cells2+ →redistributedtonewtissues

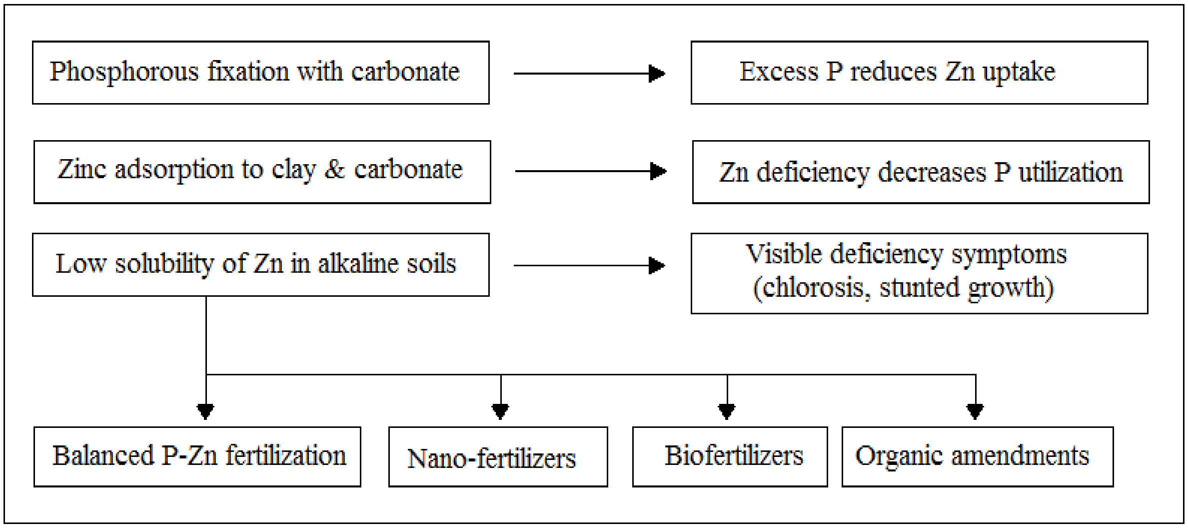

Figure (3): Interactions of Phosphorus and Zinc in Soil–Plant Systems

7. Critical Limits of Phosphorus and Zinc

7-1 Phosphorus (P):

In soils, the critical limit for Olsen-P is generally **3–5 mg/kg**; values below this threshold indicate P deficiency and result in restricted crop growth (Liu et al., 2023).

In plant tissues, the critical concentration of P is **0.2–0.3%** in leaves at early growth stages; lower values are associated with yield reduction and visible deficiency symptoms (Ortiz et al., 2023).

7-2 Zinc (Zn):

In soils, the critical limit for available Zn (DTPA-extractable) is generally **0.5–1.0 mg/kg**, below which Zn deficiency is expected (Shen et al., 2023).

In plant tissues, the critical concentration of Zn is **15–20 mg/kg dry matter**; concentrations below this cause stunted growth, chlorosis, and reduced grain.

8. Deficiency Symptoms of Phosphorus and Zinc in Plants

8-1 Phosphorus Deficiency:

- Phosphorus-deficient plants ty AIDSally exhibit **stunted growth**, with leaves becoming **dark green** and in some cases developing **purpling due to anthocyanin accumulation**.
- Root systems remain poorly developed, reducing the plant’s ability to explore soil for water and nutrients.
- Grain formation is severely affected when deficiency occurs during reproductive stages (Mendez et al., 2020).

8-2 Zinc Deficiency:

- Characterized by **stunted plants**, **shortened internodes**, and small leaves with **interveinal chlorosis** (yellowing between veins).
- Severe Zn deficiency leads to **“white bud” in maize**, where newly emerging leaves are almost white due to loss of chlorophyll.
- In cereals, Zn deficiency reduces grain number and size, leading to poor nutritional quality (Zaho et al., 2025).

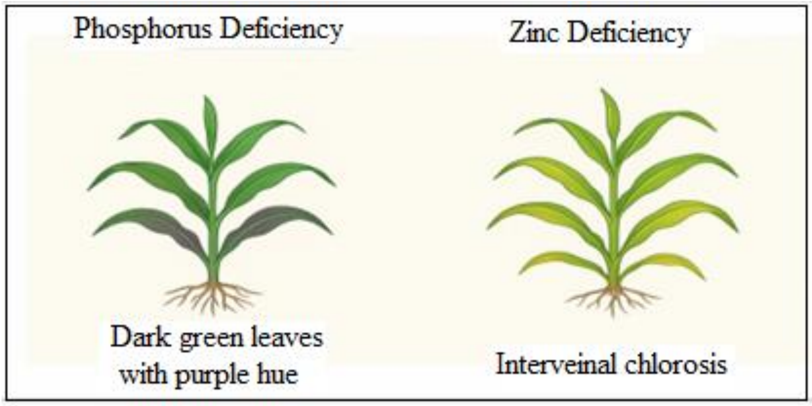

Figure (4) : phosphorus and zinc deficiency in plants

9. Phosphorus–Zinc Interactions in Soil and Plants

The interaction between phosphorus (P) and zinc (Zn) is one of the most widely documented nutrient interactions in calcareous soils. Excessive application of phosphorus fertilizers frequently induces zinc deficiency in crops, primarily due to antagonistic effects at both soil and plant levels (Shkur et al., 2025). In soils, high levels of phosphate ions compete with Zn^{2+} for sorption sites and can also enhance Zn precipitation as Zn-phosphate, reducing its solubility and mobility (Sary et al., 2025). In plants, excessive phosphorus reduces Zn translocation from roots to shoots, leading to deficiency symptoms even when soil Zn levels are near adequate (Recena et al., 2021). Conversely, zinc deficiency can impair phosphorus utilization by reducing root surface area, enzyme activity, and the formation of mycorrhizal associations that facilitate phosphorus uptake (Nath et al., 2024). This bidirectional antagonism highlights the importance of balanced fertilization strategies.

Field studies in cereals have consistently shown that unbalanced P application leads to severe Zn deficiency symptoms such as interveinal chlorosis, stunted growth, and reduced grain quality. However, combined or balanced application of P and Zn fertilizers significantly improves nutrient uptake efficiency, crop yield, and grain nutritional quality (Jamal et al., 2023).

10. Strategies to Improve Phosphorus and Zinc Availability in Calcareous Soils

10-1 Nanofertilizers

The application of nanofertilizers has been reported to significantly improve P and Zn availability in calcareous soils. For example, nano-calcium phosphate increased available P by 45% and enhanced wheat productivity by 18% compared to conventional fertilizers (Mathpal et al., 2022). Similarly, foliar application of nano-ZnO improved Zn uptake efficiency and reduced deficiency symptoms in cereals (He et al., 2021).

10-2 Biofertilizers

Phosphate-solubilizing bacteria (PSB) such as *Bacillus* and *Pseudomonas* release organic acids that solubilize calcium phosphates, while zinc-solubilizing bacteria mobilize insoluble Zn compounds, thereby enhancing nutrient availability (Mandez et al., 2020). The integration of these microbial inoculants with mineral fertilizers has shown synergistic effects on crop growth and nutrient uptake.

10-3 Fertilizer Management

Balanced fertilization practices, including split application of P fertilizers, foliar sprays of $ZnSO_4$, and combined application of P and Zn, are effective in minimizing nutrient antagonism and maximizing crop yield (Shaaban, 2023). Site-specific nutrient management is particularly important in calcareous soils to match fertilizer inputs with crop requirements.

10-4 Soil Amendments

The use of organic matter such as compost, manure, and biochar improves soil structure, microbial activity, and nutrient availability. In northern Iraq, the application of compost along with P fertilizers increased available soil P by 30% and significantly enhanced wheat productivity (Sary et al., 2025).

10-5 Foliar Application

Foliar sprays of phosphorus (as phosphoric acid) and zinc (as $ZnSO_4$) are efficient methods to overcome soil fixation problems and directly supply nutrients to plant leaves. For example, combined foliar application of phosphoric acid and $ZnSO_4$ improved wheat yield by 20% compared to soil-only fertilization (Stamm et al., 2022).

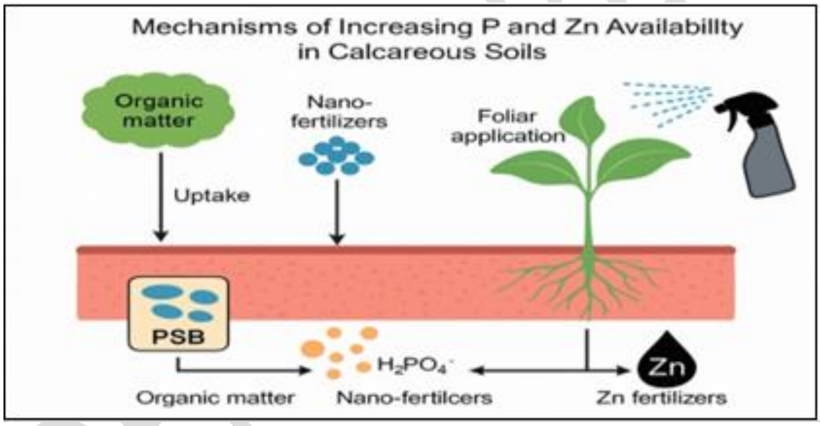

Figure (5) : Mechanisms of increasing P an Zn availability in calcareous soils.

11. Applied Studies in Iraq, Middle East, and Globally

Field experiments across different regions have demonstrated the importance of balanced phosphorus and zinc management in improving crop productivity and grain nutritional quality.

11-1 Iraq:

Several studies have confirmed widespread P and Zn deficiencies in calcareous soils of Iraq. For instance, Adana et al. (2025) reported that combined application of P and Zn fertilizers significantly improved wheat yield and grain Zn concentration. Similarly, observed increased barley productivity and nutrient uptake under integrated P–Zn fertilization, while Vahedi et al. (2022) documented improved maize growth and yield.

11-2 Middle East:

In Egypt, Lakshmi et al. (2021) found that the combined use of phosphate fertilizers and $ZnSO_4$ increased wheat grain yield and improved Zn biofortification. In Iran, Martinea-Ali et al. (2025) observed that balanced application of P and Zn enhanced maize nutrient uptake and yield stability, while in Turkey, Liu et al(2023) demonstrated similar findings for wheat and chickpea under calcareous soils.

11-3 Global Studies:

In India, Sebhatleab et al. (2025) showed that integrated use of nano-ZnO and phosphorus fertilizers improved rice productivity and Zn concentration in grains. In China, Nadeem et al. (2024) documented enhanced maize yield and nutrient use efficiency under combined P–Zn management. In Australia, Bibi et al. (2024 highlighted the importance of P and Zn co-application in sustainable cereal production systems.

12 .Conceptual Framework

The interaction between phosphorus and zinc, along with appropriate management strategies, plays a pivotal role in achieving sustainable crop production in calcareous soils. illustrates the conceptual framework linking P and Zn dynamics with modern fertilization strategies and the broader goals of sustainable agriculture, including improved nutrient use efficiency, enhanced crop productivity, and better grain nutritional quality (Mendez et al.,2020).

Discussion

The evidence from reviewed studies clearly highlights that both phosphorus (P) and zinc (Zn) play complementary yet often antagonistic roles in plant nutrition. Variations in soil type, pH, organic matter content, and fertilizer management practices largely explain the inconsistent responses observed across different regions. For instance, while integrated P–Zn fertilization significantly improved wheat yields in Iraq (Gerenfes&Negasa, 2021), similar results in India and China were attributed to nanofertilizer application and advanced foliar feeding strategies (Korkmaz et al., 2021). This suggests that site-specific nutrient management (SSNM) is critical in calcareous soils to minimize antagonistic interactions and maximize nutrient use efficiency (Sanchez-Rodriguez et al., 2021). Furthermore, the synergy between biofertilizers and nanofertilizers represents a promising frontier for simultaneously improving soil fertility and plant nutrition, yet their large-scale field validation remains limited (Xie et al., 2021 ; Zhao et al.,2025).

Conclusion

Phosphorus and zinc are essential nutrients that strongly influence plant growth, yield, and grain nutritional quality. Their interaction is complex and often antagonistic, particularly in calcareous soils, where excessive phosphorus can induce zinc deficiency and vice versa. However, integrated nutrient management practices, including the use of nanofertilizers, biofertilizers, organic amendments, and foliar applications, have demonstrated significant potential in enhancing the availability and utilization of both nutrients. Field studies across Iraq, the Middle East, and globally confirm that balanced P and Zn fertilization not only increases crop productivity but also improves the nutritional quality of grains, contributing to food and nutrition security. Therefore, adopting innovative and sustainable fertilization strategies is critical for addressing nutrient imbalances, improving soil fertility, and achieving the United Nations Sustainable Development Goals (SDGs) related to zero hunger and sustainable agriculture (Food and Agriculture Organization, 2021).

Future Perspectives

Future research should focus on integrating advanced fertilizer technologies with sustainable farming practices to optimize P and Zn availability under calcareous conditions. The use of nanofertilizers and biochar-based amendments, combined with microbial inoculants, can help reduce nutrient fixation and enhance long-term soil fertility (Adnan et al., 2025). In addition, molecular approaches such as gene editing and omics technologies hold potential for developing crop varieties with enhanced P–Zn uptake efficiency and stress tolerance (Zhao et al., 2023). Digital agriculture tools, including remote sensing and AI-based decision support systems, can further assist farmers in implementing precision fertilization strategies tailored to soil variability (Sary et al., 2025). These approaches align with global sustainability targets, particularly the United Nations Sustainable Development Goals (SDGs) on zero hunger and climate-smart agriculture.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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