Benefits of Zeolite Application in Agriculture

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ABSTRACT

Zeolites, naturally occurring crystalline aluminosilicates, possess a unique three-dimensional pore structure resembling a honeycomb, enabling them to retain nutrients and water effectively. Their application in agriculture significantly enhances soil's physical, chemical, and biological properties by improving nutrient availability, reducing leaching, and increasing water retention. Zeolites contribute to higher crop yields and reduced nitrate pollution across various soil types. They facilitate the slow release of nutrients and exhibit selectivity for specific cations, such as ammonium ($NH4^+$) and potassium (K^+). Additionally, zeolites improve the quality of cattle manure, compost, and sewage sludge by minimizing nitrogen losses and reducing odors. They are highly effective in heavy metal remediation, making them ideal for reclaiming mined or polluted soils. Zeolites also serve as excellent soil conditioners, enhancing water-holding capacity, nutrient use efficiency, and cation exchange capacity (CEC). Beyond agriculture, zeolites are widely used in wastewater treatment and as dietary supplements for livestock to improve health, establishing them as environmentally safe and sustainable minerals.

INTRODUCTION

Zeolites, first identified in 1756 by Swedish mineralogist Axel Fredrik Cronstedt in a copper mine in Sweden, derive their name from the Greek words zeo (to boil) and lithos (stone), due to their ability to release water vapor when heated. This discovery marked the beginning of zeolite research, with significant advancements occurring between 1954 and 1980, often referred to as the "golden age" of zeolite development (Zimmermann *et al.*, 2016). Commercial production and widespread use of zeolites began in the 1960s in many countries, while in Turkey, zeolites were first identified in 1971 (Payra *et al.*, 2003). Over 50 natural zeolite types, including clinoptilolite, chabazite, erionite, phillipsite, mordenite, and analcime, have been documented, primarily of sedimentary origin. Since the 1960s, Japanese farmers have utilized zeolites to enhance crop yields in volcanic soils, leveraging their unique properties.

Artificial zeolites, first synthesized in 1862, have expanded the range of applications. According to the International Zeolite Association (IZA), over 250 synthetic zeolites, such as ZSM-5, beta, Y, CHA, and X, have been developed, with many successfully commercialized. In 2022, China alone produced 2.04 million tons of zeolites, reflecting their global demand. Structurally, zeolites consist of $[SiO_4]^{4-}$ and $[AlO_4]^{5-}$ tetrahedra linked by oxygen atoms, forming cages of varying sizes classified as small, medium, or large pores (Zhang *et al.*, 2018). The silicon-to-aluminum (Si/Al) ratio determines their classification into low-silica (Si/Al = 1–2), medium-silica (Si/Al = 3–10), and high-silica (Si/Al ≥ 10) zeolites, influencing their catalytic and industrial applications (Sunil *et al.*, 2023). This article focuses on their agricultural applications, highlighting their role in sustainable farming practices.

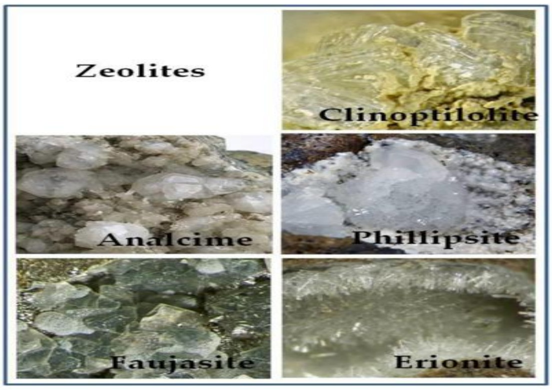

Fig.1. Minerals with zeolite structure (Source: Mastinu *et al.*, 2019)

Uses of Zeolite in agriculture:

1. Fertilizer additive

i. As slow-release fertilizer

Zeolites serve as effective slow-release fertilizers, improving nutrient uptake and reducing environmental impacts. A study comparing unmodified natural zeolite-based composites (UNZC) and surfactant-modified natural zeolite-based composites (SMNZC) demonstrated that both significantly enhanced nitrogen uptake in maize compared to control soils. The optimal application rate was found to be 200 kg ha^{-1}, with nutrient uptake peaking at this level (Das *et al.*, 2021). Zeolites' porous structure allows nutrients to bind within their pores, ensuring sustained availability to crops. This slow-release mechanism is influenced by pore size, adsorption capacity, and binding strength, which collectively reduce nutrient leaching and enhance soil fertility. The benefits of zeolite-based fertilizers are attributed to improved soil properties, including enhanced physical structure, chemical composition, and microbial activity. Studies have shown that synthetic zeolite slow-release fertilizers (SRFs) increase the availability of nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca) in soils, benefiting crops like lettuce compared to conventional chemical fertilizers (Khan *et al.*, 2021). Similarly, Soca and Daza-Torres (2016) reported that zeolite application significantly improved nutrient use efficiency (NUE) for N, P, and K in maize, with higher application rates correlating with increased nutrient uptake. In Rhodes grass, zeolite amendments enhanced leaf nutrient content, surpassing the performance of chemical fertilizers.

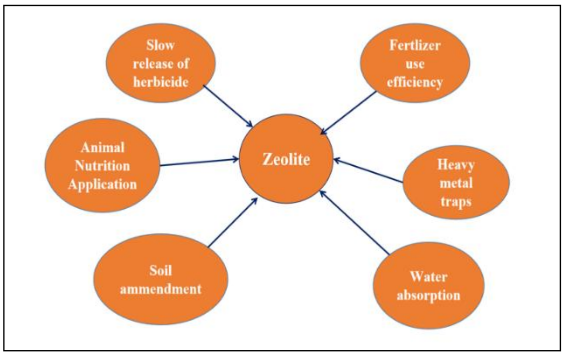

Fig.2. Role of Zeolite in agriculture

ii. Improving Fertilizer Efficiency

Nitrate contamination of groundwater and surface water, particularly in sandy soils, is a significant environmental concern due to nitrogen leaching from irrigated croplands. Zeolites, both natural and synthetic, mitigate this issue by acting as fertilizer amendments that reduce nitrate pollution and enhance crop yields. Their high cation exchange capacity (CEC) and selectivity for cations like NH_4^+ and K^+ make them ideal for slow-release applications. By exchanging ammonium and phosphate ions, zeolites ensure prolonged nutrient availability, minimizing losses and improving fertilizer efficiency (Khan *et al*., 2021). Clinoptilolite, chabazite, phillipsite, and mordenite, abundant in nature, are particularly effective due to their large surface area, high porosity, and ion-exchange properties.

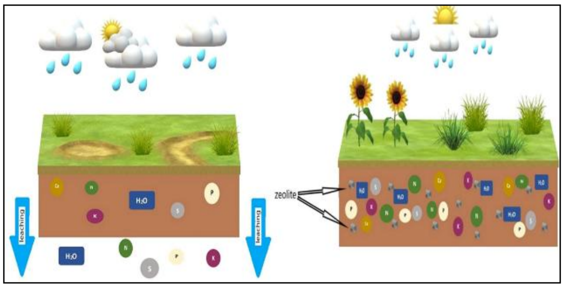

Fig.3. Zeolite to increase fertilizer use efficiency (Source: Jarosz *et al*., 2022)

iii. Composting

Composting transforms organic matter, such as crop residues, animal manure, and municipal waste, into nutrient-rich humus through aerobic microbial decomposition. However, compost often suffers from high electrical conductivity (EC), nutrient losses (especially nitrogen via NH_3 emissions), and low water-holding capacity (WHC). Zeolites address these issues by enhancing compost quality. Their high CEC and WHC reduce nitrogen losses, improve water retention, and mitigate odors in animal manure-based composts. Zeolite-amended composts offer agronomic, environmental, and economic benefits, particularly in revegetating barren or heavy metal-contaminated lands. For instance, adding synthetic zeolite P to sewage sludge compost significantly reduced metal mobility and soil-plant transfer (Nissen *et al*., 2000). A study combining green waste, sewage sludge, and clinoptilolite zeolite (up to 20% w/w) in contaminated soil (34,470 mg kg^{-1}) found that a 15% compost and 5% zeolite mixture effectively reduced arsenic uptake in plants, promoting revegetation (Gadepalle *et al*., 2008).

2. Soil Amendment

a. As soil conditioner

Zeolites improve soil properties by increasing moisture retention, hydraulic conductivity, and nutrient availability, making them excellent soil conditioners. They enhance soil CEC, facilitating better nutrient retention and exchange. In acidified soils, zeolites mitigate pH imbalances, promoting higher crop yields. Their ability to retain water and nutrients is particularly beneficial in sandy or degraded soils, where water and nutrient losses are common.

b. Problematic soils reclamation

Soil salinity, primarily due to sodium chloride (NaCl), inhibits crop germination and growth, rendering land unsuitable for cultivation. Zeolites mitigate salinity stress by acting as chelators, enabling crops to germinate and grow even under high NaCl concentrations. For example, ammonium-exchanged clinoptilolite increased root weight in radishes by 59% in medium clay soils and 53% in light clay soils in greenhouse experiments, demonstrating its efficacy in reclaiming saline soils.

3. Environmental safety

a. Heavy Metal Remediation

Heavy metal pollution, including lead (Pb), cadmium (Cd), zinc (Zn), nickel (Ni), manganese (Mn), chromium (Cr), copper (Cu), and iron (Fe), poses a significant threat to agriculture, driven by industrial activities and excessive fertilizer use. Low soil pH exacerbates heavy metal solubility, increasing their entry into the food chain. Zeolites, with their high affinity for cationic pollutants, effectively sequester heavy metals like Cd, Pb, Cr, Zn, and Cu, supporting crop growth while reducing contamination risks. For instance, adding 1% zeolite retained 3.6 mmol Pb kg^{-1} (750 mg kg^{-1}) in soil, demonstrating its potential for remediating mined or polluted sites (Ponizovsky & Tsadilas, 2003).

b. Nutrient leaching and other losses

Zeolites' negative charge attracts cations such as sodium, potassium, barium, calcium, and ammonium, as well as water molecules. This property reduces nutrient leaching, particularly nitrates and carbonates, by trapping them within the zeolite structure. The weakly bound cations can be exchanged using standard ion-exchange techniques, making zeolites effective nutrient carriers and ion exchangers.

c. Waste water treatment

Zeolites are widely used in wastewater treatment, particularly for removing heavy metals from textile wastewater. Studies show that zeolites achieve over 50% removal of initial heavy metal concentrations, with copper (Cu) removal at 64.74%, followed by chromium (Cr) at 56.26%, lead (Pb) at 55.34%, and cadmium (Cd) at 50.20%. Combining zeolites with 10 mg/L alum enhances removal efficiency compared to zeolite alone, making it a cost-effective solution for industrial wastewater treatment.

4. Animal Nutrition

Incorporating zeolites, particularly clinoptilolite and mordenite, into the diets of swine, poultry, and ruminants improves growth and feed efficiency (weight gain per pound of feed consumed). Zeolites also reduce intestinal disease incidence in young animals. In Japan, adding 2–5% clinoptilolite to cattle diets yielded positive results, while in the United States, 1.25% zeolite increased feed efficiency by 12% during the first 37 days of supplementation.

5. Hydoponics

Zeoponics, a plant-growing medium combining zeolite, compost, and cocopeat, enhances vegetable crop performance, including green mustard, tomato, and eggplant. Zeoponic systems increase plant height, root length, and shoot fresh weight by improving nutrient uptake, particularly nitrogen, due to zeolites' high CEC and ammonium absorption capacity. They also maintain low electrical conductivity, promoting faster plant growth compared to other media.

CONCLUSIONS:

Zeolites significantly enhance soil's physical, chemical, and biological properties, making them invaluable in sustainable agriculture. Their application improves nutrient use efficiency, reduces leaching, and increases water retention, leading to higher crop yields. Zeolites' selectivity for cations like NH_4^+ and K^+ enables slow-release fertilization, while their ability to sequester heavy metals mitigates soil pollution and prevents their entry into the food chain. Additionally, zeolites enhance compost quality, reclaim problematic soils, treat wastewater, and improve animal nutrition, establishing them as versatile, environmentally friendly minerals. Their widespread adoption in agriculture promises a more sustainable and productive future.

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