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POTENTIAL USE OF ZEOLITES IN AGRICULTURE: A REVIEW

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ABSTRACT

Zeolites are crystalline aluminosilicates that exist naturally, and they are the most common mineral in sedimentary rocks. These minerals are called tectosilicates, and they have an open, three-dimensional structure with the cations required to maintain equilibrium of electrostatic charge between the aluminum framework and silicon tetrahedral units. Most common zeolites are chabazite, clinoptilolite, phillipsite, erionite, stilbite, heulandite, and mordenite. Zeolites are harmless for the environment and living things. Their multipurpose application in agriculture is mainly due to their high porosity, sorption-ion-exchange capability, and well-developed specific surface area. Applying zeolites directly to the soil improves its sorption capacity while simultaneously decreasing acidity and boosting nutrient uptake efficiency. Increased yields and less nutrient dispersion in the environment are achieved through better nitrogen utilization from fertilizers. This contributes to the closed-loop economy, the depletion of environmental resources, and the principles of sustainable development. Thus, zeolites have the potential to directly enhance agricultural environments.

Keywords: Agriculture, Synthetic fertilizer, Water stress, Zeolite

INTRODUCTION

The increasing demand of food for the ever increasing population creates serious pressure on agriculture resulting increasing use of synthetic fertilizer specially nitrogen and phosphorus into ecosystems to levels of about 121 million tons of nitrogen (N) and 9 million tons of phosphorus annually, (Passaglia and Prisa, 2018). The different way of nitrogen loss from the soil are ammonia (NH_3) volatilization source of nitrogen loss in agricultural systems, which leads to low fertilizer nitrogen usage efficiency, harm to human health and the environment, and indirect emissions of nitrous oxide (Pan et al. 2016).

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Sustainable agriculture seeks to address these challenges by adopting practices that minimize the negative environmental impacts of farming while simultaneously improving crop yields and soil health (Kremen and Miles, 2012). Crop yields are essential for global food security, and soil health plays a critical role in supporting productive and resilient agricultural systems (Lal, 2016).

According to Chmielewska 2014b and Enamorado-Horrutiner et al. (2016), zeolites are one of the most commonly used naturally occurring inorganic soil conditioners to enhance the physical and chemical characteristics of soil, including water holding capacity, infiltration rate, saturated hydraulic conductivity, and cation exchange capacity.

Zeolites enhance a variety of physical characteristics of soil, the most significant of which are hydraulic conductivity and infiltration (Gholizadeh-Sarabi and Sepaskhah 2013). It is well known that adding zeolitic minerals to soil enhances water retention and keeps water from penetrating deeply, which can reduce water use for farming (Polat et al. 2004; Talebnezhad and Sepaskhah 2013). Cation exchange capacity (CEC) of natural zeolites ranges from 100 to 200 cmol (+) kg^{-1} (Inglezakis et al. 2015). One feature that sets zeolite apart from other silicate minerals is the abundance of large pores and channels in its structure (Chmielewska and Lesný 2012).

Cations like calcium (Ca^{2+}), potassium (K^+), and sodium (Na^+) are abundant in natural zeolites. They each possess unique, noteworthy qualities. First, they have a high CEC that is higher than that of soils (Inglezakis et al., 2015); second, they have a lot of free water in their structural channels; and third, they have high surface area strong adsorption capabilities. Environmental research has made use of these qualities to improve soil quality and water quality (Cobzaru and Inglezakis 2012).

The following are the most significant applications for zeolites: agriculture (fertilizer efficiency, soil amendment, slow release of herbicides, heavy metal traps, water absorption, gas absorption, antifungal activity, photosynthesis enhancement in crops, heat stress and sunburn of zeolites in crops, aquaculture, animal feed additive); industrial application areas (petroleum refining, synfuel and petrochemical productions) (Li et al., 2017); water and wastewater treatment (Collins et al., 2020); ecology and environmental protection (Szerement et al., 2021); remediation (Cadar et al., 2021). Zeolites are frequently employed in catalytic processes. According to Ennaert et al. (2016), zeolites are also being used in a novel way to catalyze numerous chemical conversions of biomass, where biomass components can serve as an alternate feedstock in place of crude oil.

However, it is believed that the fertilizer sector is a source of natural radionuclides and heavy metals (Savci, 2012). Most heavy metals, including mercury (Hg), cadmium (Cd), arsenic (As), lead (Pb), copper (Cu), nickel (Ni), and natural radionuclides, including uranium (U-238), thorium (Th-232), and polonium (Po-210), are found in synthetic fertilizers. Thus, fertilizer may have an impact on the build-up of certain heavy metals in soil and plant systems (Adhikari, 2020). The majority of agricultural soils are therefore either naturally low in fertility or have been rendered less fertile by improper or insufficient replenishment as a result of inefficient use of inputs (water and fertilizers) due to nutrient losses through a variety of loss mechanisms, including water deficit, runoff, non-absorption, and volatilization.

The scenario of declining soil resources is combined with the issue of climate change, which has resulted in a variety of ecological reactions in crops (Malhi, 2021). Increased evapo-transpiration results from higher temperatures, which also affects plants' ability to collect and use moisture. As a result, crops are more frequently exposed to extreme temperatures due to global warming, which raise the danger of a water deficit and can harm crop quality and productivity. The application of zeolites in agriculture, water stress, heavy metals, and soil fertility management takes on more importance in this setting (Ramesh, 2011). This research examines the vital characteristics of natural zeolites and highlights their significant applications in agriculture.

ORIGIN OF ZEOLITES

Because of its intriguing surface and structural characteristics, which have been used in a variety of industries, including biotechnology, agriculture, industrial technology, animal husbandry, and cosmetics, the discovery of natural zeolites has opened a significant chapter in the field of mineralogy. First, naturally occurring zeolites were discovered in cavities and vugs in basalt rocks. Later (19th century), they were also found in sedimentary rocks. Natural zeolite was originally recognized as a mineral in 1756 by Swedish mineralogist Alex Fredrik Crönstedt, who took a sample of crystals from a Swedish copper mine. The mineral scientist found that the novel mineral created a lot of water vapor when heated rapidly after absorbing water (Mahesh et al., 2018). He dubbed the material zeolite "boiling stones" (from the Greek words "boil" and "stone") based on this behavior (ability to froth when heated to roughly 200 °C) (Polat, et al., 2004). Following a number of geological investigations, scientists identified the following genetic categories in the development of zeolites:

i) Crystals found from hot-spring or hydrothermal activity (reaction with basaltic lava flows);
ii) Sediments originating from volcanic deposits in saline and alkaline lake systems;
iii) Deposits originating in alkaline soil from volcanic sediments;
iv) Deposits formed from marine sediments’ low-temperature or hydrothermal alteration;
v) Formations resulting from low-grade burial metamorphism.

The years 1954 to 1980 are considered the zeolites' "golden age" of development while many countries started using and producing them commercially in the 1960s.

Numerous research groups have reported on about 50 different forms of natural zeolites so far, including clinoptilolite, chabazite, erionite, phillipsite, mordenite, and analcite. Natural zeolites are rarely found in pure form in sediments; rather, they are frequently tainted with other minerals, quartz, and metals.

STRUCTURE OF ZEOLITES

One of the most significant mineral families in microporosis materials is zeolite. According to Ghasemi et al. (2018), the term "zeolite" refers to a crystalline aluminosilicate or silica polymorph based on multiple corner-sharing TO_4 (tetrahedrals, often silicon and aluminum) forming a three-dimensional four-connected framework with regularly sized pores of molecular dimension. According to Nakhli et al., (2017), zeolites are tectosilicates, which are hydrated crystalline aluminosilicates of alkaline and alkali earth elements (cations).

The structure of the "roca magica" is open, endless, and three-dimensional. In a nutshell, they are solids with an open, three-dimensional crystal structure made of a variety of elements, including oxygen (O), silicon (Si), and aluminum (Al), along with alkaline or alkali metals, like potassium (K), sodium (Na), and magnesium (Mg), and trapped water molecules. The sizes of the pores are around 12 ångström (Å); the pores are connected by channels that have a diameter of about 8 Å; these cages are made up of rings that are roughly 12 linked tetrahedrons (Sangeetha and Baskar, 2016). One of the most significant properties of zeolites is their Si/Al ratio, which really establishes the mineral's ion exchange properties. The Si/Al ratio was used to differentiate zeolite minerals until 1977, with the exception of clinoptilolite ($Si/Al \geq 4.0$) and heulandite ($Si/Al < 4.0$). The following is a classification of zeolite minerals based on the silica/alumina ratio (Ramesh et al., 2010): (i) Zeolites erionite and mordenite—high Si/Al ratio (from 10 to several thousands); (ii) Zeolites Y—intermediate Si/Al ratio (2 to 5) and (iii) Zeolites A - low Si/Al ratio (between 1.0 and 1.5).

Zeolite species nomenclature was proposed following the International Mineralogical Association Commission on New Minerals and Mineral Names report. Dehydration, overhydration, and partial hydration were insufficient conditions for the identification of several zeolites. A new categorization of zeolites was introduced by Jacobs et al., in 2001, based on the pore diameter or size of the pores (Table 1):

Table 1. Categories of Zeolites

Number of rings	Pore size	Free pore diameter
14 member rings	extra-large-pore zeolites	0.8–1.0 nm
12 member rings	large-pore zeolites	0.6–0.8 nm
10 member rings	medium-pore zeolites	0.45–0.6 nm
8 member rings	small-pore zeolites	0.3–0.45 nm

PROPERTIES OF ZEOLITES

A zeolite's empirical formula is Mn_2O Al_2O_3 $xSiO_2$ yH_2O, where n denotes the element's valence charge, M is an alkali or alkaline earth element, and y is a value between 2 and 7. Table 2 and 3 list some of the most popular natural zeolites along with their empirical and unit-cell formulae and physical properties respectively. Exchangeable cations are found in the first set of parenthesis in the formula, whereas structural cations which, along with oxygen, create the tetrahedral framework of the structure are found in the second set of parentheses. Molecular water that is loosely bonded is typically seen in the structures of naturally occurring zeolites.

Table 2. Representative formulae and selected physical properties of important zeolites.

Zeolite	Representative Unit-cell Formula	Void volume	Channel Dimension, A	Thermal Stability	CEC, meq/g
Analcime	$Na_{10}(Al_{16}Si_{32}O_{96})16H_2O$	18	2.6	High	4.54
Chabazite	$(Na_2Ca)_6(Al_{12}Si_{24}O_{72})$ $4H_2O$	47	3.7×4.2	High	3.84
Clinoptilolite	$(Na_3K_3)Al_6Si_{30}O_{72})$ $2H_2O$	34	3.9×5.4	High	2.16
Erionite	$(NaCa_{0.5}K)_9(Al_9Si_{27}O_{72})$ $27H_2O$	35	3.6×5.2	High	3.12
Faujasite	$(Na_{58})(Al_{58}Si_{134}O_{72})$ $240H_2O$	47	7.4	High	3.39
Ferrierite	$(Na_2Mg_2)(Al_6Si_{30}O_{72})$ $18H_2O$	28	4.3×5.5	High	2.33
Heulandite	$(Ca_4)(Al_8Si_{28}O_{72})$ $24H_2O$	39	4.0×5.54.4×7.24.1 ×4.7	Low	2.91
Laumonitte	$(Ca_4)(Al_8Si_{16}O_{48})$ $16H_2O$	34	4.6×6.3	Low	4.25
Mordenite	$(Na_8)(Al_8Si_{40}O_{96})24H_2O$	28	2.9×5.76.7×7.0	High	2.29
Phillipsite	$(NaK)_5(Al_5Si_{11}O_{32})20H_2O$	31	4.2×4.42.8×4.83.3	Medium	3.31
Linde A	$(Na_{12})(Al_{12}Si_{12}O_{48})27H_2O$	47	4.2	High	5.48
Linde X	$(Na_{86})(Al_{86}Si_{106}O_{384})26H_2O$	50	7.4	High	4.73

High water-holding capacity in the free channels in soil and pots, high cation-exchange capacity, and high adsorption capacity are the three major qualities of zeolites that make them attractive for use in agriculture. Zeolite's crystal structure contains vast, open "channels" that allow for cation exchange and adsorption despite the mineral's extremely complicated structure (Morris and Nachtigall, 2017). Zeolites' interior channel surface area makes them incredibly efficient ion exchangers. Additional beneficial characteristics are its high cation-exchange capacity of 150–250 cmol/kg (CEC), low density (2.1–2.2 g/cm3), high void volume (50%) and cation selectivity, particularly for cations like potassium, cesium, and ammonium (Bhattacharya, 2015).

Table 2. Some physical properties among the most well-known zeolites are (Polat et al. 2004):

Zeolites	Heat stability	Porosity (%)	Specific gravity (g/cm^3)	Bulk density (g/cm^3)	Ion exchange capacity (meq/g)
Analcite	High	18	2.24–2.29	1.85	4.54
Chabazite	High	47	2.05-2.10	1.45	3.84
Clinoptilolite	High	34	2.15-2.25	1.15	2.16
Erionite	High	35	2.02-2.08	1.51	3.12
Heulandite	Low	39	2.18-2.20	1.69	2.91
Mordenite	High	28	2.12-2.15	1.70	4.29
Phillipsite	Moderate	31	2.15-2.20	1.58	3.31

To summarize, zeolites' properties that are structure-related are; (i) behavior of 'zeolitic' water: high potency of hydration and dehydration, (ii) extensive void volume and low density when dehydrated, (iii) molecular sieve property, (iv) stability of the crystal structure of many dehydrated zeolites when 50% volumes of the dehydrated crystals are void, (v) dehydrated crystals, homogenous molecular-sized channels, (vi) cation exchange features and the removal of heavy metals, (vii) electrical conductivity, (viii) gases and vapors adsorption and (ix) catalytic properties.

APPLICATION OF ZEOLITES IN AGRICULTURE

The various ways that zeolite is used in agriculture highlight how important the current environmental situation. Clinoptilolite, a type of zeolite that belongs to the heulandite group naturally occurring in soils and sediments, is the most prevalent type of zeolite utilized in agricultural practices (e.g., as a soil amendment and to help retain nitrogen in soils) (He et al., 2002). Zeolites are excellent carriers of mineral nutrients and have the ability to regulate their delayed release following application. They can also enhance crop yield and improve water retention in sandy soils and increase porosity in clay soils (Bhattarai et al., 2015).

Zeolite and water holding capacity of soil

Zeolite can retain upto 60% of their weight in water molecules because of the greater porosity of their crystalline structure. Compared to untreated soil, treated soil with natural zeolite increased water holding capacity by 0.4 to 1.8% in drought and 5 to 15% in general condition by and, respectively (Chmielewska, 2010). Zeolite have the ability to raise soil water content by increasing bulk density and total porosity, because of their incredibly porous nature, zeolites increase soil water-holding capacity (Nakhli, 2017).

Zeolites on soil hydraulic conductivity and infiltration

The chemical, physical, and biological characteristics of a soil are changed by the addition of synthetic or natural zeolites. Zeolites have the ability to alter the structure and texture of soil, which can have an immediate effect on the hydrological parameters of the soil because of their intricate internal structure (Comegna et al., 2023).

According to Gholizadeh-Sarabi and Sepaskhah (2013), zeolites can generally alter the total porosity, pore size distribution, pore channel connectivity, and tortuosity of soils. The effects of these modifications can vary depending on a number of factors, including the nature of the zeolites, the water's properties, soil texture and structure. Zeolites' effects on soil infiltration rate (Szerement et al., 2014), saturated hydraulic conductivity (Jakkula and Wani, 2018), soil water content and water retention capacity (Ravali et al., 2020), and their function in preventing pesticides and fertilizers (such as ammonium NH^+, phosphate PO_4^{3-}, potassium K^+, and sulphate SO_4^{2-}) from leaching into soils (Ramesh et al., 2015, Nakhli et al., 2017) have all been covered in a number of studies .

Zeolite addition typically results in increased soil water retention and water holding capacity in light-textured soils, such as sandy and loamy soils, and decreased hydraulic conductivity at saturation (Ks) and infiltration rate (Colombani et al., 2015). Zeolites may have radically different impacts in heavy-textured soils (such as clay soils and silty-clay soils) (Jarosz et al., 2022). It is difficult to draw broad conclusions about the relationships between soils and zeolites and their anticipated effects on the physical and hydraulic properties of soils because some aspects of the literature that is currently available still seem contradictory and unclear.

Zeolites may benefit plant development and productivity from an agronomic standpoint (Jarosz et al., 2022). Zeolites have been found to be particularly useful in mitigating the issues associated with intensive agriculture, which have a significant impact on soil and soil-water quality, particularly in arid and semiarid regions (Belviso et al., 2022). Such studies should specifically look into how zeolites affect the whole range of water retention curves (i.e., from saturated to dry zone), with an emphasis on the water domain that is available to plants (Nakhli et al., 2017). Zeolite application significantly reduced soil bulk density and boosted water-holding capacity by up to 48.54%, according to Ravali et al. (2020). Additionally, zeolite significantly affects the pH, EC, and CEC of soil (Ravali et al., 2020).

Zeolites and soil nutrient availability to plants

Zeolites have a high porosity and CEC, which allows them to raise the CEC of soil and improve the soil's capacity to keep and absorb nutrients like potassium (K^+) and ammonium (NH_4^+) and naturally occurring zeolites have extremely high CECs, ranging from 100 to 200 cmolc /kg. Since only a small portion of chemical fertilizers are actually absorbed by the soil, their widespread usage poses major environmental risks. The excess fertilizer is washed off, and as a result, surface water bodies experience eutrophication high amounts of potassium, nitrogen, and phosphorus or groundwater nitrates. By enhancing the delayed release of these elements for crop uptake, zeolites improve the soils' ability to retain nutrients (Li, 2003). The zeolite-A surface was positively changed to enhance its ability to hold anion phosphate (PO_4^{3-}). In a greenhouse test, zeolite treated with potassium and ammonium (NH_4^+) increased the yield of spinach and the plants' ability to absorb nutrients (Li et al., 2013). The results showed that the zeolite and fertilizer combination had a considerable positive impact.

Furthermore, the addition of zeolite obviously altered the nutrient concentrations found in the tissues of maize (Zea mays L.); the use of inorganic fertilizers combined with zeolites significantly boosted the uptake of N, P, and K as well as the efficiency with which they were used in the roots, leaves, and stem (Ahmed et al., 2010). In comparison to an ammonium sulfate control, it was discovered that radish tops' nitrogen adsorption increased following zeolite treatment.

Soil health and environmental pollutant management

Zeolites is also able to absorb and retain some environments pollutants. By absorbing and retaining pollutants in their porous structure, zeolites can lower the hazards of contamination to water bodies. It is frequently employed as soil conditioners to improve the physio-chemical properties of soils. According to Doni et al. (2020), zeolite enhanced the cation-exchange capacity of vineyard soils, which in turn affected nutrient availability and induced changes in soil organic matter and microbial metabolic activity stimulation (an increase in dehydrogenase activity). According to de Campos et al., (2013), applying Brazilian zeolitic sedimentary rocks as a soil conditioner greatly boosts the yields of rice, lettuce, tomatoes, and Andropogon grass. Utilizing 6 tonnes ha^{-1}, clinoptilolite (15 tonnes ha^{-1}) increased the yields of sugar cane, potatoes, barley, and clover in sandy soils in Ukraine.

Amend Heavy Metal

One of the most important problems facing modern agriculture is soil pollution from heavy metals like lead, cadmium, zinc, nickel, manganese, chrome, copper, and iron; the misuse of fertilizers and the growth of industry both contribute significantly to this problem. Low pH is the primary determinant of heavy metal solubility in soil and is linked to the possibility of their trophic chain inclusion (Zwolak et al., 2019). Zeolites are frequently employed for the sequestration of cationic pollutants, including heavy metals like Cd, Pb, Cr, Zn, Cu, etc. This is because zeolites generally have a high cation-exchange capacity and they attract positive-charged ions (Kumar et al. 2007). Several writers have shown how naturally occurring zeolites have a strong affinity for heavy metals (Tashauoei et al., 2010); for example, 1% additional zeolite could retain 3.6 mmol Pb kg^{-1} or 750 mg kg^{-1} of soil. Particles sized 3.3-4.0 mm in sewage sludge compost can be treated with clinoptilolite to extract heavy metals.

Reduce gas emissions

In order to collect gases or control odors, zeolites, both natural and synthetic, can absorb a wide range of gases, including methanol (CH_3OH), formaldehyde (HCHO), sulfur dioxide (SO_2), carbon monoxide (CO), carbon dioxide (CO_2), hydrogen sulfide (H_2S), water (H_2O), ammonia (NH_3), molecular hydrogen (H_2), argon (Ar), oxygen (O_2), nitrogen (N_2), xenon (Xe), helium (He), krypton (Kr), and many more. The zeolites' abilities to adsorb ammonium varied, ranging from 8.149 mg N g^{-1} to 15.169 mg N g^{-1}. At pH 4 - 7, the estimated clinoptilolite ammonium-adsorption capacity increased linearly and it was 9.660 to 13.830 mg N kg^{-1}. Moreover, zeolite can be widely employed in conjunction with other additives to lower gas emissions, salinity, and nutrient loss throughout the composting process (Awasthi et al., 2016). According to Wang et al., (2018), the use of wood vinegar in combination with zeolite and biochar to compost pig manure reduced emissions of methane (50.39–61.15%), carbon dioxide (33.90–46.98%) and nitrous oxide (79.51–81.10%) respectively, and decreased ammonia loss by 64.45–74.32%.

Antifungal properties

Several writers looked into using zeolites to keep dangerous insects at bay (Floros et al., 2018). These include the rice weevil, *Sitophilus oryzae* L., the confused flour beetle, Tribolium confusum Jacquelin du Val (Coleoptera: Tenebrionidae), the maize weevil, Sitophilus zeamais Motschulsky (Coleoptera: Curculionidae), the red flour beetle, Tribolium castaneum (Herbst) (Coleoptera: Tenebrionidae), and the lesser grain borer, *Rhyzopertha dominica* F. (Coleoptera: Bostrychidae) (Eroglu et al., 2019).

Increase photosynthesis

Carbon dioxide molecules can be absorbed by zeolites, which then progressively release them into the environment (Montanari and Busca, 2008). Zeolites sprayed on plant leaves have the potential to increase carbon dioxide levels close to the stomata. For C_3 plants, which include vines, tomato plants, apple trees, and orange trees, this occurrence may result in a higher rate of photosynthesis, a decrease in carbon dioxide loss by the photo-respiratory system, and an improvement in the efficiency of net carbon CO_2 (velocity of carboxylation) uptake. This leads to increased growth, an increase in the pace at which the leaf surface is formed, and a decrease in the rate of transpiration.

Reduce heat Stress

Rubisco, the enzyme in plants that fixes carbon dioxide, has a decreasing affinity for CO_2 and becomes less soluble in O_2 as the temperature rises. As temperature rises, the carboxylation to oxygenation ratio decreases (Ainsworth and Rogers, 2007). Numerous investigations revealed that apple trees and vines have a lower canopy temperature and a faster rate of leaf carbon uptake. a drop in temperature of about 4 °C brought on by the reflecting material for the leaves of kidney bean plants

(*Phaseolus vulgaris* L.), dwarf orange trees (*Citrus sinensis* L. cv. Valencia), and rubber plants (*Ficus elastica* L.).

Challenges and prospects of zeolite use in agriculture

The major challenge with zeolite application in alkaline soils could be potential increases in soil pH. Some studies have reported increases soil pH although others reported a decrease, so we have to check its effects on soil pH in test plots before applying to a larger area. Applications to compost or manure are less likely to cause unacceptable soil pH changes. Removing zeolite from the soil after application is not practical, so it's very important to initially test for effectiveness in very small areas of land. Input cost could be another problem, especially for large-scale operations. However, a plan for yearly applications of small quantities could build up zeolites economically over time.

Numerous research findings demonstrate that zeolites can improve plant growth, yet occasionally they don't operate as intended. Sangeetha and Baskar (2016) found that using zeolites that are high in sodium can have a detrimental effect on plant growth and yield. These authors emphasized the critical significance that zeolites' chemical and mineralogical analyses play in determining the best course for their deployment. Rather than the huge applicability of zeolites in agriculture, it should be considered that the zeolites are not without disadvantages.

The fine-grained synthetic zeolites are highly dispersive in nature which creates worrisome problems during their use. After mining the usable form of natural zeolites is obtained via isolation procedures like crushing and pellet generation while the application of the synthetic form of zeolites are limited into hard, wear—resistant granular forms. The practical use of granular zeolites is not yet discovered (Król, 2020). The distribution of the zeolites sources is very limited such asthezeolitic soil is confined to only 1% of the total geographic area of India and more than 50% of natural zeolites are produced in China among all over the world (Bhattacharyya, et al., 2015) that may increase the price and the gap between demand and supply. Therefore, the uninterrupted availability of zeolites for farming purposes in worldwide is another major constraint.

CONCLUSION

The use of zeolites as fertilizers demonstrates the positive effects on both agricultural productivity and the soil environment. Zeolite has a number of possible applications in agriculture, especially in nutrient utilization efficiency. Zeolites as nutrient transporter, help farmers maintain water content, lower canopy temperature and guarantee productivity in light of climate change and rising temperatures. Zeolites can also be a vital instrument for lowering harmful emissions, eliminating heavy metals from plant stems. Zeolites' application as soil amendment however, requires more investigation to confirm and comprehend the effects of these compounds on soil.

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