ZEOPONIC SYSTEMS

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Abstract: Zeoponic plant growth media is defined as cultivation of plants on enriched zeolite substrate which contains some of essential plant growth cations on their exchange sites. In addition to the cation exchange sites, the substrate contains minor amounts of other solid phase minerals supplying essential buffering ions, anions and micronutrients. Various types of zeoponic systems have been developed so far. In these systems zeolite supplies K and NH_4, apatite supplies Ca, P, Mg, S, Fe, Mn, Zn, Cu, B, Mo, Cl and other calcium bearing minerals such as calcite and dolomite provide Ca and Mg and there is no need to supply nutrient elements with irrigation water. In fact these systems act as slow release fertilizers providing the required elements which are essential for the plant growth. So far, different kinds of zeoponic systems have been developed and National Aeronautics and Space Administration (NASA) researchers had a key role in developing and modifying of this substrate. The present chapter describes some properties, advantages and problems of zeoponic systems.

INTRODUCTION

Nowadays soil less culture or hydroponic is becoming a major technique in gardening. In this technique soil as the main plant nutrition media is replaced with nutrient solution or other substrates supplying the plant growth essential elements. Different substrates have been introduced as hydroponic bedding materials. Some commonly used substrates in soil less culture systems are shown in Table **1**. In general, a good substrate needs to provide a high water retention capacity, good aeration, drainage and cation exchange capacity. On the other hand the bedding materials should not impose any negative effect on plant growth [1]. Because of high capacity of water retention, aeration, cation exchange and a low density, peat is the most important bedding substrate in soil less culture. Despite all these advantages, many researches are being carried out to replace peat with some other alternatives. The high price of peat, especially in the countries lacking in natural resources of this substrate and contamination of peat to some fungal pathogens and insufficient production of this compound in the future due to some environmental constrains encouraging the efforts to find the alternative bedding substrates.

ZEOPONIC

Zeoponic plant growth media is defines as cultivation of plants on enriched zeolite substrates that contain some of essential plant growth cations on their exchange sites. In addition to the cation exchange sites, the substrate contains minor amounts of other solid phase minerals supplying essential buffering ions, anions and micronutrients [4, 5].

Bulgarian researchers were the first producing a substrate from a combination of zeolite, peat and vermiculite that called zeoponic by Parham [5]. From then different Zeoponic systems have been developed for plant growth mainly by National Aeronautics and Space Administration (NASA) researchers.

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Table 1: Most commonly used inorganic and organic substrates in soilless culture

Substrate	Bulk density (g/cm^3)	CEC (cmol/kg)	pH	Porosity (%)	References
Sand	1.4-1.8	0	6-8	low	[1]
Tuff	0.8-1.5	10-60	8-9	medium	[1]
Pumice	0.4-0.8	-	6-7	high	[1]
Perlite	0.08-0.12	1-3	7-7.5	high	[1]
Vermiculite	0.07-0.1	150-210	7-7.7	high	[1]
Zeolite	0.6	220-460	7-9	medium	[1]
Coir	0.04-0.08	32-95	5-6	high	[2]
Peat	0.07-0.16	50-100	3.5-5	high	[1]
Rockwool	0.07-0.1	0	7-8	high	[1]

Various types of zeoponic systems have been used so far include:

1- Ammonium and potassium enriched zeolite + apatite

2- Ammonium and potassium enriched zeolite + apatite + calcite

3- Ammonium and potassium enriched zeolite + apatite + wollastonite

4- Ammonium and potassium enriched zeolite + apatite + dolomite

5- Ammonium and potassium enriched zeolite + apatite + ferrihydrite

The major components of a typical zeoponic system are presented in Fig. **1**.In these systems zeolite supplies potassium (K) and ammonium (NH_4), apatite supplies Ca, P, Mg, S, Fe, Mn, Zn, Cu, B, Mo , Cl and other calcium bearing minerals such as calcite and dolomite provide Ca and Mg. In fact these systems act as slow release fertilizers providing the required elements as they needed for the plant growth. In these systems, the kind of zeolite mineral is clinoptilolite, because of high selectivity for K and NH_4 and stability in soil-based systems [4].

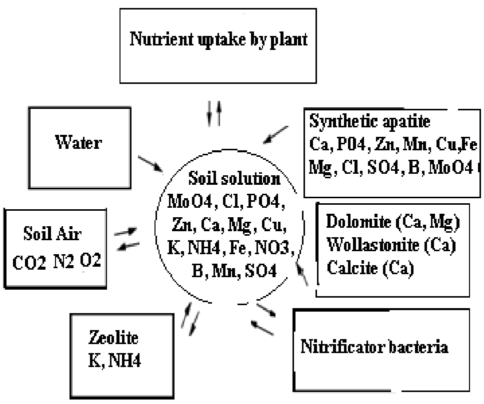

Figure 1: Dynamic equilibria for NASA's zeoponic plant-growth system [6]

CHEMICAL REACTIONS IN THE ZEOPONIC SYSTEMS

A number of chemical reactions and transport processes occur in a zeoponic system (Fig. **2**). Cation exchange and dissolution are the main chemical reactions controlling sorption and release of nutrient elements and thus providing the nutrients needed for the plant growth [7, 8]. Transport processes include:(i) Pore (intra-particle) diffusion or diffusion in the zeolite channels or apatite micropores, (ii) Film diffusion or transport across a liquid film at the particle/liquid interface (iii), Bulk diffusion or transport in the solution phase, which is rapid and (iv) surface diffusion or inter-particle diffusion.

A- Apatite Dissolution

The dissolution reaction of apatite as shown below provides essential anions and micronutrients for the plant growth [9].

$$[Ca_{5-x}M_x][(PO_4)_{3-y}A_y][(OH)_{l-z}Cl_2] \leftrightarrow (5-x)Ca^{2+} + xM^{2+} + (3-y)PO_4^{3-} + yA^{n-} + (l-z)OH^- + zCl^-$$

Where M is Mg, Fe, Cu, Zn, Mn; A is MoO_4^{2-}, $BO_3^{3-,}$ $SO4_2^-$; n is charge of anion A; x, y and z are the substitution mole fractions where $0 \leq x \leq 0.5$, $0 \leq y \leq 1$ and $0 \leq z \leq 1$.

B- Cation Exchange

Sorption of Ca on zeolite releases the exchangeable ammonium and potassium from the surface sites as shown below. Zeolite acts as a sink for Ca during dissolution of apatite [9]. This reaction provides K and NH_4 requirement of the plant and at the same time pushes the apatite dissolution reaction forward.

$$(K^+)_{2n} \cdots Zeolite + (n+m)Ca^{2+} \leftrightarrow (Ca^{2+})_{n+m} \cdots zeolite + 2nK^+ + 2mNH_4^+$$

ZEOPONIC SYSTEM PROBLEMS AND SOLUTIONS

Many greenhouse studies on zeoponic (zeolite + apatite) reported that concentrations of N, P and K provided by the system were enough for the plant growth, while the Ca concentration due to the sorption of this element by zeolite was lower than the required level. Gruener *et al.* [10] reported that the decrease in wheat yield grown in the zeoponic system was due to NH_4-induced Ca deficiency. Also the high concentration of P in the solution depressed the plant uptake of other elements such as Ca, Cu, and Zn. In a batch study, Allen *et al.* [8] showed that Ca concentration in a clinoptilolite-phosphate rock system was in the range of 0.01-0.086 mol/l. The normal Ca concentration of soil solution is generally in the range of 0.2 – 1.12 mmol/l and the minimum Ca concentration needed for a normal plant growth is about 0.037 mmol/l. Therefore, the zeoponic substrates probably cannot provide sufficient level of Ca for a normal plant growth. Some solutions to these problems are as follow:

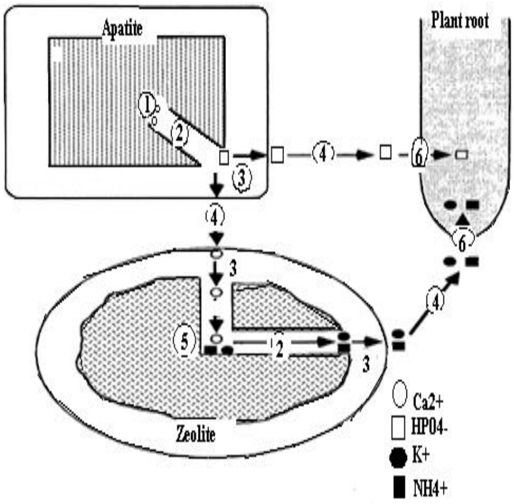

Figure 2: Chemical reactions and transport processes controlling nutrient release from a zeoponic system. Dashed lines define stagnant water layers surrounding particles. (1: Dissolution, 2: Intraparticle diffusion, 3: Film diffusion, 4: Bulk diffusion, 5: Ion exchange, 6: Plant absorption) [7].

A- Application of Nitrifying Bacteria

An ammonium- and nitrate-N balance is required for the optimum plant growth and yield [11]. Nitrification in the zeoponic systems is generally too slow. This is due to the slow release of ammonium from the zeolite exchange sites to the solution. Henderson *et al.* [12] modified the nitrification rate as well as the Ca deficiency by introducing some nitrifying bacteria to the system.

Nitrification is a process by which the ammonium-N is converted to nitrate-N as shown below.

$$NH_4^+ + O_2 \leftrightarrow NO_2^- + 4H^+ + 2e$$

$$NO_2^- + H_20 \leftrightarrow N0_3^- + 2H^+ + 2e$$

Different groups of bacteria are involved in this oxidation reaction from which the *Nitrosomonas* sp. are the most responsible group.

Henderson *et al.* [12] reported that application of nitrifying bacteria in to a zeoponic system increased the wheat dry weight and grain yield, although the calcium concentration of plants was 0.13-0.2% of dry weight which was lower than the normal range (~0.2-5.5%).

B– Application of Calcium Bearing Minerals

Addition of Ca-minerals such as dolomite ($CaMg(CO3)_2$) may correct Ca deficiency. The yield increase due to the addition of dolomite to a zeoponic system which was reported by Henderson *et al.* [12]. The dolomite dissolution is a two stage reaction [13]:

$$CaMg(CO3)_2 + H^+ \leftrightarrow MgCO_3 + Ca^{2+} + HCO_3^-$$

$$MgCO_3 + H^+ \leftrightarrow Mg^{2+} + HCO_3^-$$

Regarding the solubility products of different Ca- minerals (Table **2**), Beiersdofer *et al.* [14] suggested that addition of more soluble Ca-minerals than dolomite such as calcite ($CaCO_3$) and wollastonite ($CaSiO_3$) leads to higher concentration of Ca in the solution.

$CaSiO_3 + 2H^+ + H_2O \leftrightarrow Ca^{2+} + H_4SiO_4$

$CaCO_3 + 2H^+ \leftrightarrow Ca^{2+} + CO_{2\,(g)} + H_20$

The effect of different Ca- minerals on solution Ca concentration is presented in Fig. **3**. Calcite has the greatest and dolomite has the least effects on the change of Ca^{2+} concentration in solution, consistent with the solubilities of calcite, dolomite and wollastonite [14].

In addition to the increase of Ca concentration, introduction of Ca minerals into the zeoponic systems, decrease the apatite solubility due to the common ion effect of Ca in dolomite, calcite and wollastonite, therefore resulting a lower P concentration in the system [14]. Figure **4** shows the effect of different Ca minerals on apatite solubility. Calcite as compared with dolomite and wollastonite most reduces the solubility of apatite and solution P concentration.

Table 2: Solubility products of zeoponic constituents

Mineral	Solubility products	Reference
Apatite (synthetic)	58 1	[15]
Apatite (natural)	70	[15]
Hydroxyapatite	44.2	[16]
Calcite	9.74	[13]
Dolomite	18.46	[13]
Dolomite (ordered)	17.09	[17]
Dolomite (Disordered)	16.54	[17]
Wollastonite	12.99	[16]

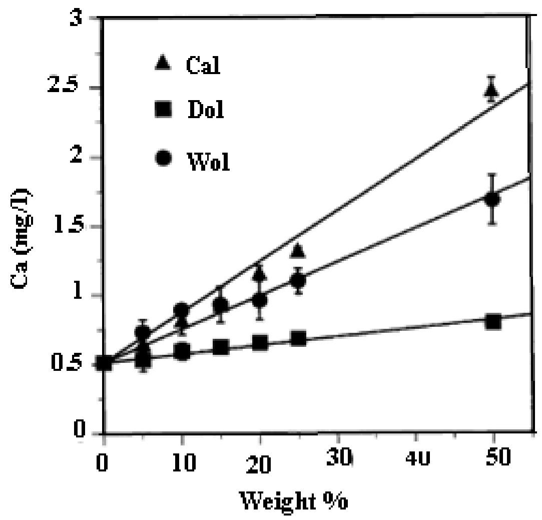

Figure3: Effects of Ca-bearing minerals on solution calcium concentration [14]

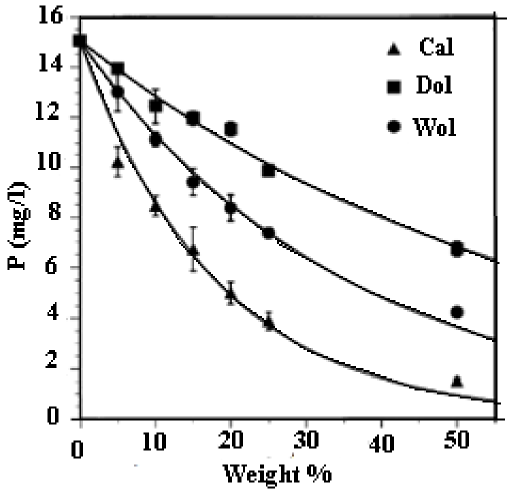

Figure4: Effects of Ca-bearing minerals (Calcite, Wollastonite and Dolomite) on solution phosphorus concentration [14].

In some reports, the decrease in P concentration, attributed to the surface P sorption or precipitation of Ca-phosphates [18], while the results of Beiersdofer *et al.* [14] did not confirm these mechanisms in the zeoponic system. Because an adsorption of P on the wollastonite, calcite and dolomite surfaces would not co-vary with the increase in Ca^2 concentrations in solution reported by Beiersdofer *et al.* [14]. A reduction on P concentrations in solution due to the precipitation of calcium phosphates as would be expected to co-vary with reduced Ca^2 concentrations in solution [14].

C– Selection of the Optimum Proportion of the Zeoponic Components

As an important factor, the proportion of different components of a zeoponic system, controls the level of different elements in the solution. Selection of a suitable proportion may provide a desired level of the solid phase's solubility, chemical reactions, and therefore an optimum level of nutrient availability and a maximum plant growth and yield.

The nutrient requirement varies among different plant species. Mengel *et al.* [19] suggested a fertilizer recommendation base on the plant nutrient uptake ratios. Having this in mind, a zeoponic system could be formulated and modified for an optimum plant growth and yield by changes in K/NH_4 ratio of the zeolite exchange sites, the zeolite type , the apatite type, the zeolite/apatite ratio and addition of other minerals. For example, results of different studies showed that increase in the zeolite (clinoptilolite; Cp) application ratio (clinoptilolite/apatite; Cp/Ap) in the zeoponic systems, decreased the dissolved NH_4, K, Ca and Mg concentrations [8, 14].The effect of type and the ratio of zeolite saturation cation (Ek=0, Ek=0.5, Ek=1) on solution P concentration in zeoponic system is shown in Fig. **5**. Ek= 0, 50 and 100 show that, 0, 50 and 100 percent of zeolite CEC is saturated with potassium, respectively.

In any Cp/Ap ratio, with a decrease in Ek, the solubility of apatite and as a result the solution P concentration increases. This shows that the sorption of potassium on zeolite (clinoptilolite) is preferred over ammonium. Therefore, calcium may replace the exchangeable ammonium more easily than the sorbed potassium [8, 14].

THE EFFECTS OF DIFFERENT ZEOLITIC AND ZEOPONIC SUBSTRATES ON THE PLANT GROWTH

Different studies have shown contradictory results on the effect of zeolitic and zeoponic substrates on plant growth and yield [10, 21, 28]. It should be noted that the zeoponic is different from zeolitic substrates. According to the definition, the zeoponic substrate is largely composed of NH4- and K- enriched zeolite along with apatite containing other macro and micro nutrients [20]. In these systems, there is no need to supply nutrient elements with irrigation water, whereas in zeolitic substrates, the zeolite mineral alone or combined with other substrates such as perlite added to the plant beddings and the plant required nutrients should be supplied with the irrigation water. The effects of different zeoponic and zeolitic substrates on the growth of various plants are summarized in Table **3.**

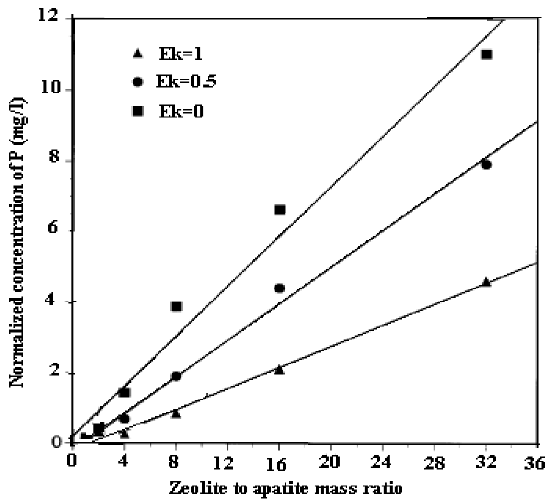

Figure5: Effects of zeolite to apatite mass ratio on phosphorus concentration [14].

OTHER BENEFITS OF ZEOPONIC SYSTEMS

In soilless culture systems the residual nutrient solutions and plant beddings may cause environmental pollution. It has been reported that one hectare of tomato soilless culture, in average, produces about 60 cubic meters of rock wool, 12 cubic meters of pots and about 2000 cubic meters of residual nutrient solution [30]. Increasing of environmental concerns in the recent decade, emphasized on developing the sustainable soilless culture systems with increase of water use efficiency and decrease in fertilizer utilization, costs, waste materials and environmental pollutions. In addition, as plant growth substrates, the zeoponic systems are also important from the environmental and economic aspects. Some other important aspects of these systems include:

Reduce Nitrate and Potash Leaching

Leaching of dissolved nutrients such as nitrogen and potassium is a general problem in soilless culture systems with bedding substrates [25]. Different researches reported that, application of zeolite as a plant growth media decreased the potassium and nitrogen leaching. Retention of ammonium ions in the structural channels of zeolite may limit the oxidation of this ion to nitrate and therefore decrease the nitrogen leaching

Long-term Nutrient Delivery

Longevity is an advantage of zeoponic over the other plant cultivation substrates. This longevity is needed for long-term space missions to Mars, where the long missions lasting will need some amount of food production to either supplement or sustain food supplies for the astronaut crews [21]. Gruener *et al.* [21] showed that 52% of original NH_4-N and 78% of original K remained in the zeoponic substrate after 3 consecutive cultivations of carrot. Similar findings were reported by Allen *et al.* [7] that about 80% of original NH_4-N and K remained in the system after one plant cultivation. As an advantage, the Zeoponic substrates contain enough levels of NH_4-N for multiple cropping.

Reduce Waste Products

In addition to the advantages mentioned above, the zeoponic substrate can be used as a soil modifier in the open fields which indeed reduces the waste production.

Table 3: Results of some studies on zeoponic and zeolitic substrates.

Plant	**System**	**Results**	**Reference (s)**
Radish	Zeoponic	Radish yields in zeoponic substrates were equivalent to yields in control substrates irrigated with nutrient solutions.	[21]
Wheat	Zeoponic	Wheat biomass production and yield were similar for plants grown in zeoponic with hydroponic culture.	[20]
Wheat	Zeoponic	Positive correlation between the percent of zeoponic materials in the substrate and dry matter production, but poor seed production was observed.	[10]
Wheat	Zeoponic	Plants grown on zeoponic produced excess tillers compared with wheat supplied by nutrient solution.	[22]
Wheat	Zeoponic	Positive plants growth on zeoponic modified by dolomite	[12]
Pepper	Zeolite	Yields of pepper plants grown in zeolite were as good as or better than those in Rockwool.	[23, 24]
lettuce	Zeolite + Perlite	Using of zeolite led to increase of plant growth, higher N and K contents in plant tissues and to reduce K leaching.	[25]
Gerbera	Zeolite + Perlite	The yield increased over the control.	[26]
Pepper	Zeolite + Perlite	The vegetative growth of shoot and root were increased.	[27]
Rose	Zeolite + Perlite	Zeolite did not exert any positive effect on rose productivity.	[28]
Tomato	Zeolite + Perlite or + Mica	The N, P, K concentrations were increased in zeolitic treatments.	[29]

OTHER APPLICATIONS OF ZEOLITE

Bio-fertilizer Carrier Material

Over use of phosphate fertilizers and cadmium accumulation in agricultural soils limits the activity of N-fixing bacteria and thus reduces the nitrogen availability for plants. Immobilization of the nitrogen fixing bacteria on the zeolite surfaces causes stimulation of microbial metabolism, protection of cells from unfavorable agents and preservation of their physiological activities. Joshi *et al.* [31] showed that the sorbed azotobacter on the zeolite fixed more atmospheric nitrogen as compared with the non-adsorbed bacteria.

Reduction in Plant Uptake and Accumulation of Heavy Metals

Application of zeolite in heavy metal contaminated soils is an appropriate and affordable approach to chemically fix the contamination due to the high retention capacity and low release power of this mineral. This method is suitable for the countries with large deposits of zeolite [32]. Different studies showed that application of zeolite in soil decreased the heavy metal concentration of plants grown in the contaminated soils. A considerable decrease in available cadmium of contaminated soils is reported due to application of zeolite samples from Iran [32], Greek [33] and Jordan [34]. As an example, Keler *et al.* [35] reported that application of one percent of zeolite in a contaminated soil significantly decreased the cadmium concentration in the tobacco leaves.

POTENTIAL HARMFUL EFFECTS

Due to sodium saturation, zeolites may be toxic to plants. Non-scientific and misuse of zeolite can therefore increase the soil salinity, soil-pH and decrease the soil physical and chemical quality resulting in plant yield reduction. In conclusion, the selection of zeolite type and its proportion in the substrate plays an important role in plant yield grown in the zeoponic systems.

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