Plant productivity and characterization of zeoponic substrates after three successive crops of radish (Raphanus sativus L.)

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Abstract

The National Aeronautics and Space Administration (NASA) has developed a zeolite-based synthetic substrate, termed zeoponics. The zeoponic substrate (consisting of NH_4- and K-exchanged clinoptilolite, synthetic apatite, and dolomite) provides all of the plant-essential nutrients through mineral dissolution and ion exchange, with only the addition of water. Previous studies have shown high productivity of wheat in zeoponic substrates; however, no experiments have been conducted on other crops. The objective of this study was to determine the productivity and nutrient uptake of radish (Raphanus sativus L.) grown in zeoponic substrates with three successive crops in the same substrate. Radish was chosen because of its sensitivities to NH_4^+. Average fresh weights of edible roots were similar for radish grown in zeoponic substrates watered with deionized H_2O (10.97 g/plant) and in potting mix control substrate irrigated with nutrient solution (10.92 g/plant). Average fresh weight production of edible roots for radish grown in same zeoponic substrate increased in yield over time with the lowest yield in the first crop (7.10 g/plant) and highest in the third crop (13.90 g/plant). The Ca plant tissue levels in radishes (1.8-2.9 wt. %) grown in zeoponic substrates are lower than the suggested sufficient range of 3.0-4.5 wt. % Ca; however, the Ca level is highest (2.9 wt. %) in radishes grown in the third crop in the same zeoponic substrates. The higher radish yield in the third crop was attributed to a reduction in an NH_4-induced Ca deficiency that has been previously described for wheat grown in zeoponic substrates. The P levels in plant tissues of radish grown in the zeoponic substrates ranged from 0.94-1.15 wt. %; which is slightly higher than the sufficient levels of 0.3-0.7 wt. %. With the exception of Ca and P, other macronutrient and micronutrient levels in radish grown in zeoponic substrates were well within the recommended sufficient ranges. After three successive

crops of radish growth, the zeoponic substrates had 52% of the original NH_4-N and 78% of the original K remaining on zeolite exchange sites. Zeoponic substrates are capable of long-term productivity of radishes for space.

Keywords

Zeolite, Zeoponics, Clinoptilolite, Apatite, Radish

1. Introduction

On January 14, 2004, President Bush provided a strategic vision of space exploration beyond earth orbit to the National Aeronautics and Space Administration (NASA) and the American people. These long-duration missions to the Moon, Mars, and beyond will require life support systems that recycle and regenerate air, water, and food. Plants may be used in regenerative life-support systems to sequester carbon dioxide and generate oxygen through photosynthesis, produce potable water through transpiration, and produce food through plant growth and reproduction [1]. NASA's Johnson Space Center (JSC) has developed a zeolite-based synthetic substrate consisting of clinoptilolite, synthetic apatite, and dolomite to provide plant-essential nutrients, pH-buffer, aeration, moisture retention, and mechanical support for plant growth in regenerative life-support systems [2].

Zeoponic plant-growth systems have been defined as the cultivation of plants in artificial soils, which have zeolite as a major component [3]. In the JSC zeoponic substrate, the native clinoptilolite cations are exchanged for NH_4^+ and K^+ cations [4], which then become the primary N and K sources for plant nutrition. The dynamic equilibria that takes place between zeolite, apatite, and dolomite in a zeoponic system are discussed in detail by Lai and Eberl [5], Ming and Allen [6,7], and Beiersdorfer et al. [8]. In brief, dissolution of the apatite and dolomite supplies Ca^{2+} to the soil solution. Through ion-exchange reactions, solution Ca^{2+} will remove NH_4^+ and K^+ from zeolitic exchange sites, thus making the NH_4^+ and K^+ cations available for plant uptake. The goal of the zeoponic research efforts at JSC is to develop a solid substrate that will slowly deliver most of the plant-essential macronutrients (N, P, K, Ca, Mg, and S) and all of the plant-essential micronutrients (Zn, Fe, Cu, Mn, B, Mo, and Cl) for many growth seasons, with the remainder of the required macronutients (H, O, and C) being supplied by the water and air used throughout a space habitat (Figure 1).

Initial plant-growth experiments with wheat grown in zeoponic substrates resulted in excellent vegetative growth [2]. However, when wheat plants were grown to maturity in another experiment with zeoponic substrates, seed yield was poor [9]. Plant-tissue analyses suggested that high P and low Ca concentrations were possible reasons for the low yield [9]. An additional experiment with wheat investigating the effects of adding nitrifying bacteria, dolomite and ferrihydrite to the zeoponic substrate resulted in better yields [10]; however only a cumulative effect was reported and it is not clear which additive had the most effect. Beiersdorfer et al. [8] and Gruener et al. [11] described a common-ion effect that occurs in zeoponic substrates amended with Ca-bearing minerals, where the solubility of the synthetic apatite is diminished by the presence of Ca^{2+} in solution from the dissolution of other Ca-bearing minerals. This resulted in higher Ca^{2+} and lower P in solution. McGilloway et al. [12] demonstrated the establishment of nitrifying bacteria populations in zeoponic substrates, using Nitrosomonas sp. and Nitrobacter sp. bacteria, and the successful oxidization of NH_4^+

to NO_2^- and then to NO_3^- during a plant growth experiment with radish. Ammonium oxidation rates for the three week experiment ranged from 1.2 to 1.78 μg N g^{-1} substrate h^{-1} and NO_2^- oxidation rates were 0.38 to 0.74 μg N g^{-1} substrate h^{-1}.

The purpose of the present paper is to expand upon previous zeoponic plant growth studies and report on a plant-growth experiment investigating the response of radish plants grown in clinoptilolite-apatite-dolomite substrates. Goyal et al. [13] have shown that growth of radish is inhibited when NH_4^+ is the sole source of N. Addition of NO_3^- equivalent to 10% or more of the NH_4^+ concentration alleviated the inhibitor effects, and NO_3^- apparently facilitated the assimilation of NH_4^+ by radish plants. Fenn and Taylor [14] demonstrated the use of Ca^{2+} as a means to increase the rate of NH_4^+ absorption by radish. Vegetative growth increased in two greenhouse experiments as Ca^{2+} concentrations increased, all at a constant NH_4^+ concentration.

The first objective of this study, was to use the growth of radish plants, which are extremely sensitive to NH_4^+ nutrition, as an indicator of the effectiveness of the addition of dolomite to create a common ion effect and increase the amount of Ca^{2+} in soil solution, and the addition of nitrifying bacteria to zeoponic substrates to oxidize NH_4^+ to NO_3^-. The second objective of this study was to determine the nutrient delivery availability of the zeoponic substrate after three successive radish crops.

2. Experimental

2.1 Materials

Clinoptilolite-rich tuff (Cp) from the Fort LeClede deposit, Sweetwater County, Wyoming and a synthetic hydroxyapatite produced in the laboratory were used as the primary components of the zeoponic substrate. The Fort LeClede clinoptilolite is nearly monomineralic as determined by X-ray diffraction analysis [15], with only trace amounts of quartz present. The Cp was transformed into either an ammonium-exchanged (NH_4-Cp) or a potassium-exchanged (K-Cp) form, using the method of Allen et al. [4]. The NH_4^+ and K^+ cation-exchange capacity (CEC) of the clinoptilolite-rich tuff were 207 $cmol_{(c)}$/kg and 202 $cmol_{(c)}$/kg, respectively, determined by a CsCl method described by Ming and Dixon [16].

The synthetic apatite (SA) is an agronutrient-substituted hydroxyapatite, produced in the laboratory according to the method of Golden and Ming [17]. In addition to Ca and PO_4, the SA has Mg, SO_4, and micronutrients (i.e., Zn, Fe, Cu, Mn, B, Mo, and Cl) incorporated in its structure [18,19,20,21]. The chemical composition of the SA is shown in Table 1.

Dolomite (Baker Grandol Regular #4, Baker Refractories, York, Pennsylvania, U. S. A.) was added as a pH buffer and additional Ca and Mg source for plant growth (Table 1). All materials (i.e., NH_4-Cp, K-Cp, SA, dolomite) were crushed and sieved to a particle size of 0.5-1.0 mm.

2.2. Methods

The clinoptilolite (Cp), synthetic apatite (SA), and dolomite were combined to form the zeoponic substrate, consisting of 36 wt. % NH_4-Cp; 36 wt. % K-Cp; 18 wt. % SA and 10 wt. % dolomite. Two control substrates were also developed: a potting mix control composed of peat, vermiculite, and perlite in a 1:1:1 volume ratio, and a K-exchanged Cp (K-Cp) control. The three substrates (i.e., Cp-SA-dolomite or zeoponic substrate, potting mix control, K-Cp control) were placed in pots with dimensions of 9.5 cm in diameter and 8.5 cm deep. The substrate volume in each pot was 440 ml and the average bulk density of the zeoponic substrates was 1 g/cm^3. Thus, each pot contained 440 grams of zeoponic materials, or 440 ml of potting mix. The zeoponic substrates (i.e., Cp-SA-dolomite substrates) were inoculated with Nitrosomonas sp. and Nitrobacter sp. bacteria to establish a nitrification process, in which the NH_4^+ released from the NH_4-Cp is oxidized to form NO_3^- (see Henderson et al. [10], McGilloway et al. [12]).

The investigation consisted of 6 different radish crop cycles, each lasting 21 days. Three radish crops were grown successively in the same zeoponic substrate, and then the experiment was repeated in time with three more crops in a new zeoponic substrate. The purpose of the three successive crops in the same substrate was to evaluate the capability of using zeoponic substrates for extended periods; although it was not the focus of this study to exhaust the nutrient capability of the zeoponic substrates. For each crop, there were eight pots per substrate treatment (i.e., zeoponic substrate, K-Cp control substrate, and potting mix control substrate), for a total of 24 pots per crop. The pots were arranged in a randomized block design. Nine radish seeds (cv. Cherry Belle) were initially planted in each pot and thinned down to 3 plants per pot 5 days after planting. The zeoponic substrates were watered with deionized water throughout the experiment, and the control substrates were watered with 1/2-strength Hoagland's potassium phosphate-based nutrient solution [22].

The radish plants were grown in an environmental growth chamber (Environmental Growth Chambers, Chagrin Falls, Ohio, Model G-15) under the following average daily conditions: 16 hr of daylight, 8 hr of darkness, temperature of 23°C, 65% relative humidity, and a photosynthetic photon flux that averaged 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$. All treatments were irrigated to excess 6 times daily with an automated watering system at an average rate of 20 ml/min, for durations of 28 s per irrigation at the beginning of the experiment up to 48 s per irrigation at peak plant water usage. Radishes were harvested at 21 days, where fresh weights of shoots, edible storage roots, and fibrous roots were measured. Oven-dried (70 °C for 72 hr) plant samples were weighed to determine the dry-matter production. Dried plant samples were ground to pass a 40 mesh sieve and sent to The University of Wisconsin at Madison soil and plant analysis laboratory for N, P, K, Ca, Mg, S, Zn, Fe, Cu, Mn, and B plant-tissue analysis. Macro- and micronutrients were measured by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) and Mass Spectroscopy (ICP-MS) using acid digestion with nitric acid and hydrogen peroxide. Total nitrogen was measured using a Kjeldahl process with sulfuric acid and a metal catalyst.

After three successive crops of radish, the zeoponic substrate was dried, and the exchange cations (i.e., K^+ and NH_4^+) on the clinoptilolite were determined by the method of Ming and Dixon [15]. Briefly, the cations on the exchange sites of clinoptilolite were determined by replacing them with Cs^+ (0.5 M CsCl solution); K^+ and NH_4^+ were subsequently determined by atomic absorption and ion-selective electrode techniques, respectively. The pH of the extraction solution was buffered by the Cp-SA-dolomite substrate (pH ≈ 8.0).

3. Results

3.1 Fresh weight production

Analysis of variance (ANOVA) was used to determine whether statistical differences exist between substrates on the basis of fresh weight/plant. ANOVA was significant for the fresh weight/plant (f ratio = 4.39; p = 0.013). Tukey-Kramer multiple comparison tests [23] were then performed to test the significance for all possible pairs (a significant F-test is a prerequisite for the Tukey-Kramer multiple comparison). For this experiment, statistical differences are defined at the 5% probability level.

Fresh weights of edible roots were similar for radish grown in zeoponic substrates watered with deionized H_2O and in potting mix substrate irrigated with ½-strength Hoagland's solution (Tables 2 & 3). The average fresh weights/plant for the three successive crops grown in the zeoponic and potting mix control substrates were not statistically different based on Tukey-Kramer tests; however, radish fresh weight grown in the K-Cp control substrate was significantly lower than those grown in the zeoponic and potting mix substrates. Although the average radish fresh weights of edible roots for all three crops together were similar for zeoponic and potting mix substrates (Table 2); there were differences in fresh weights between successive crops for the zeoponic substrates (i.e., differences between crops 1, 2, and 3, Table 3). Fresh weight production was lower in the first crop and highest in the third crop for radish grown in zeoponic substrates, i.e., the third successive radish crop grown in the same zeoponic substrate. Fresh weight production in potting mix substrates was highest in the first crop (Table 3). The production of radishes in the K-Cp control substrate was slightly higher in the second and third crops.

3.2 Harvest index

Harvest indexes (i.e., weight of fresh edible radish compared to the fresh weight of the entire plant) were slightly lower in the zeoponic substrates; although there were no substantial differences for harvest indexes between the three substrates (Table 4). The harvest indexes for the second and third crops in the same zeoponic substrates were higher than the first crop.

3.3 Plant-nutrient analysis

Average plant-tissue concentrations of the macronutrients (N, P, K, Ca, Mg, S) and the micronutrients (Zn, Fe, Cu, Mn, B) are listed in Tables 5 and 6, respectively, for 21-day old radish plants grown in zeoponic and control substrates. All radishes grown in the three substrates had similar macronutrient (i.e., primary and secondary nutrients) compositions, except for Ca where the composition of Ca was noticeably lower in the first and second crops of radish grown in the zeoponic substrates compared to radishes grown in the potting mix and K-Cp substrates (Table 5). Another noticeable difference was slightly higher P in radishes grown in the zeoponic substrates compared to the potting mix and K-Cp control substrates (Table 5).

Micronutrient compositions were similar for all three substrates, with the exception of lower Mn in radishes grown in zeoponic substrates (Table 6).

3.4 Characterization of clinoptilolite exchange sites

Prior to plant growth experiments, the NH_4-exchanged clinoptilolite had an NH_4-cation exchange capacity (NH_4-CEC) of 207 $cmol_{(c)}$/kg, and the K-exchanged clinoptilolite had a K-CEC of 202 $cmol_{(c)}$/kg. The average NH_4 was 107 $cmol_{(c)}$/kg, and the average K was 158 $cmol_{(c)}$/kg on zeolitic exchange sites after three successive crops of radish growth. Thus, after three successive crops of radish growth, the zeoponic substrates had 52% of the original NH_4-N and 78% of the original K remaining on zeolite exchange sites.

4. Discussion

Three crops of radish were grown successively in the same zeoponic substrate, and there were no significant differences for the fresh weight produced in zeoponic substrates irrigated with deionized H_2O compared to the potting mix control substrates irrigated with nutrient solution. The major difference in fresh weight of the radish edible root occurred between the first crop and the second crop, where the average fresh weight increased by 68% in the second crop. The average fresh weight of the edible root in the third crop continued the trend of increasing mass, with a 17% increase over the second crop. The highest yield in the third crop may be due to more Ca^{2+} available for plant uptake than during the first crop grown in the zeoponic substrate. The Ca plant tissue levels in radishes (1.8-2.9 wt. %) grown in zeoponic substrates are lower than the suggested sufficient range of 3.0-4.5 wt. % Ca for radishes [24]. However, the Ca level is highest (2.9 wt. %) in radishes grown in the third crop in the same zeoponic substrates. Fenn et al. [14] have shown the addition of Ca, when using urea, has also produced increased radish plant N-use efficiency and production in the field. Previous studies with wheat have also shown that NH_4^+ released from the exchange sites of the zeolite competed with the uptake of Ca^{2+} in wheat plants and resulted in a an NH_4-induced Ca deficiency [8,9,10,11,25]. The N levels in zeoponic radishes (6.2-7.1 wt. %) are slightly higher than the recommended range (3.0 to 6.0 wt. %) for the sufficient growth of radish. Nitrifying bacteria were added to the zeoponic substrates prior to plant growth to enhance the conversion of NH_4^+ to NO_3^- based upon the studies of Henderson et al. [10] and McGilloway et al. [12]. Other studies have shown that NH_4-N inhibited the growth of radish; hence, it is important to convert NH_4^+ to NO_3^- or use NO_3 fertilizers to promote production of radish [13]. The combination of higher Ca and NO_3 in "soil" solution for the third crop is likely responsible for the higher radish yield. The highest Ca contents in the third crop may be due to more Ca uptake by the plant and a reduction in NH_4-induced Ca deficiency (e.g., common ion effect of Ca from dolomite and apatite as described by [8]).

The higher yields in the second and third radish crops grown in the zeoponic substrates are also supported by higher harvest indexes; i.e., 0.62-0.63 for the second and third crops compared to a harvest index of 0.56 in the first crop (Table 4). The lower harvest index in the first crop may reflect a luxury uptake of N; which would result in the production of more leaves compared to edible root.

Nutrient uptake by radishes grown in the zeoponic substrate was sufficient for optimum growth with the exceptions of the Ca and N as discussed earlier and P. The P levels in the zeoponic substrates ranged from 0.94-1.15 wt. %; which is slightly higher than the sufficient levels of 0.3-0.7 wt. % [24]; however, there were no noticeable decreases in plant productivity for the luxury uptake of P. The other macronutrient and micronutrient levels in radish grown in zeoponic substrates were well within the recommended sufficient ranges [24].

A majority of the K^+ and NH_4^+ remained on the zeolitic exchange sites after the growth of 3 crops of radish in the same zeoponic substrate. Similar results have been reported for the extensive growth of wheat in zeoponic substrates where nearly 80 % of the NH_4^+ and K^+ remained on the zeolitic exchange sites after plant growth [26].

5. Conclusions

Radish yields in zeoponic substrates were equivalent to yields in control substrates irrigated with nutrient solutions. Zeoponic substrates provided all of the plant essential nutrients required for the growth of radish. A high percentage of NH_4^+ and K^+ cations remained on the zeolite exchange sites after three successive crops, although the amount of NH_4^+ and K^+ remaining on the exchange sites depends on a number of factors (e.g., volume of substrate, leaching, number of growth cycles), and could possibly be altered with the recycling of leachate. The increasing trend in radish crop yield after three successive crops (62 total days) and supporting data from other experiments (e.g., zeoponic wheat experiments, 270 total days), also demonstrate the potential for long term nutrient delivery of zeoponic substrates. This longevity is especially important for space missions to Mars, where missions lasting from 500-1000 days will need some amount of food production to either supplement or sustain food supplies for the astronaut crews. NASA’s zeoponic substrate has been successfully flown on Space Shuttle missions [27] in plant growth chambers that are prototypes for those planned for Mars spacecraft. Likewise, zeoponic substrates could be used at a permanent outpost on the Moon, where resupply missions will likely only occur every six months.

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Table 1. Chemical composition of the synthetic apatite and dolomite used in zeoponic substrates.

Major oxides	Synthetic[a] apatite	Dolomite[b]
	---------------wt. %---------	
CaO	46.6	35.03 (0.15)[c]
P_2O_5	34.6	-
MgO	2.77	17.66 (0.12)
SiO_2	2.56	-
SO_3	2.46	-
CO_2		46.98 (0.02)
Fe_2O_3	1.76	-
FeO	-	0.31 (0.08)
ZnO	0.06	-
MnO	0.06	0.02 (0.08)
CuO	0.02	-
Total	-	100 (0.00)

[a]Hydroxyapatite produced in the laboratory by the method of Golden and Ming [17].

[b]Dolomite analysis by Beiersdorfer et al. [8].

[c]Numbers in parentheses represent one standard deviation (n=25; where n = # of analyses)

Table 2. Average total fresh weight/plant of the edible roots for radish grown in zeoponic substrates.

	Number	Mean	Std. Dev.	Std. Err. Mean
		----- wt. % -----		
Zeoponic substrate	144	10.97[a]	4.91	0.41
Potting mix control substrate	144	10.92[a]	5.55	0.46
K-clinoptilolite control substrate	144	9.50[b]	3.78	0.32

[a]There is no statistical difference based on Tukey-Kramer tests [23] at a 5% probability level between plants grown in the zeoponic substrate and plants grown in the potting mix control substrate.
[b]There is a statistical difference based on Tukey-Kramer tests [23] at a 5% probability level between plants grown in K-clinoptilolite control substrate and plants grown in the other two substrates.

Table 3. Average fresh weight/plant of the edible roots for radish grown in zeoponic substrates.

Root fresh weight	Zeoponic substrate	Potting mix control substrate	K-clinoptilolite control substrate
	---------------------------	-mass (g)-	------------------------
Crop 1	7.10 (2.87)[a]	15.27 (3.56)	8.06 (3.52)
Crop 2	11.92 (2.07)	8.56 (3.50)	10.55 (1.99)
Crop 3	13.90 (2.56)	8.96 (1.99)	9.89 (1.37)

[a]Numbers in parentheses represent one standard deviation.

Table 4: Average harvest index for radish grown in zeoponic and control substrates for 21 days.

Root fresh weight	Zeoponic substrate	Potting mix control substrate	K-clinoptilolite control substrate
	----------------------------------	%	----------------------------------
Crop 1	0.56 (0.08)[a]	0.65 (0.03)	0.60 (0.14)
Crop 2	0.63 (0.06)	0.59 (0.09)	0.68 (0.03)
Crop 3	0.62 (0.05)	0.64 (0.06)	0.66 (0.04)

[a]Numbers in parentheses represent one standard deviation.

Table 5. Average plant-tissue analyses for macronutrients (wt. %) for radish grown in zeoponic substrates and control substrates after 21 days.

Macronutrient Treatment	Crop 1	Crop 2	Crop 3
		----------------------wt. %--------------------	
Nitrogen			
Zeoponics	6.97 (0.44)[a]	6.19 (0.39)	7.10 (1.70)
Potting Soil	6.20 (0.14)	5.56 (0.47)	6.32 (1.28)
K-Clino	6.10 (0.21)	5.49 (0.50)	6.24 (1.27)
Phosphorus			
Zeoponics	1.00 (0.01)	1.15 (0.01)	0.94 (0.05)
Potting Soil	0.86 (0.15)	0.86 (0.03)	0.70 (0.03)
K-Clino	0.59 (0.06)	0.55 (0.01)	0.55 (0.01)
Potassium			
Zeoponics	4.87 (1.12)	4.41 (0.74)	4.29 (1.20)
Potting Soil	4.72 (0.89)	4.39 (1.51)	3.94 (1.27)
K-Clino	5.60 (1.17)	4.77 (1.83)	4.57 (1.39)
Calcium			
Zeoponics	1.80 (0.05)	2.42 (0.23)	2.93 (0.24)
Potting Soil	2.20 (0.68)	2.98 (0.08)	3.67 (0.07)
K-Clino	3.27 (0.57)	3.25 (0.02)	3.05 (0.15)
Magnesium			
Zeoponics	0.96 (0.06)	0.93 (0.06)	0.81 (0.10)
Potting Soil	1.60 (0.13)	1.51 (0.60)	1.03 (0.27)
K-Clino	0.68 (0.04)	0.74 (0.16)	0.74 (0.18)
Sulfur			
Zeoponics	1.08 (0.01)	0.76 (0.03)	0.71 (0.02)
Potting Soil	1.31 (0.02)	1.44 (0.06)	1.35 (0.06)
K-Clino	1.12 (0.05)	1.27 (0.04)	1.13 (0.03)

[a]Numbers in parentheses represent one standard deviation.

Table 6. Average plant-tissue analyses for micronutrients (mg/kg) for radish grown in zeoponic substrates and control substrates after 21 days.

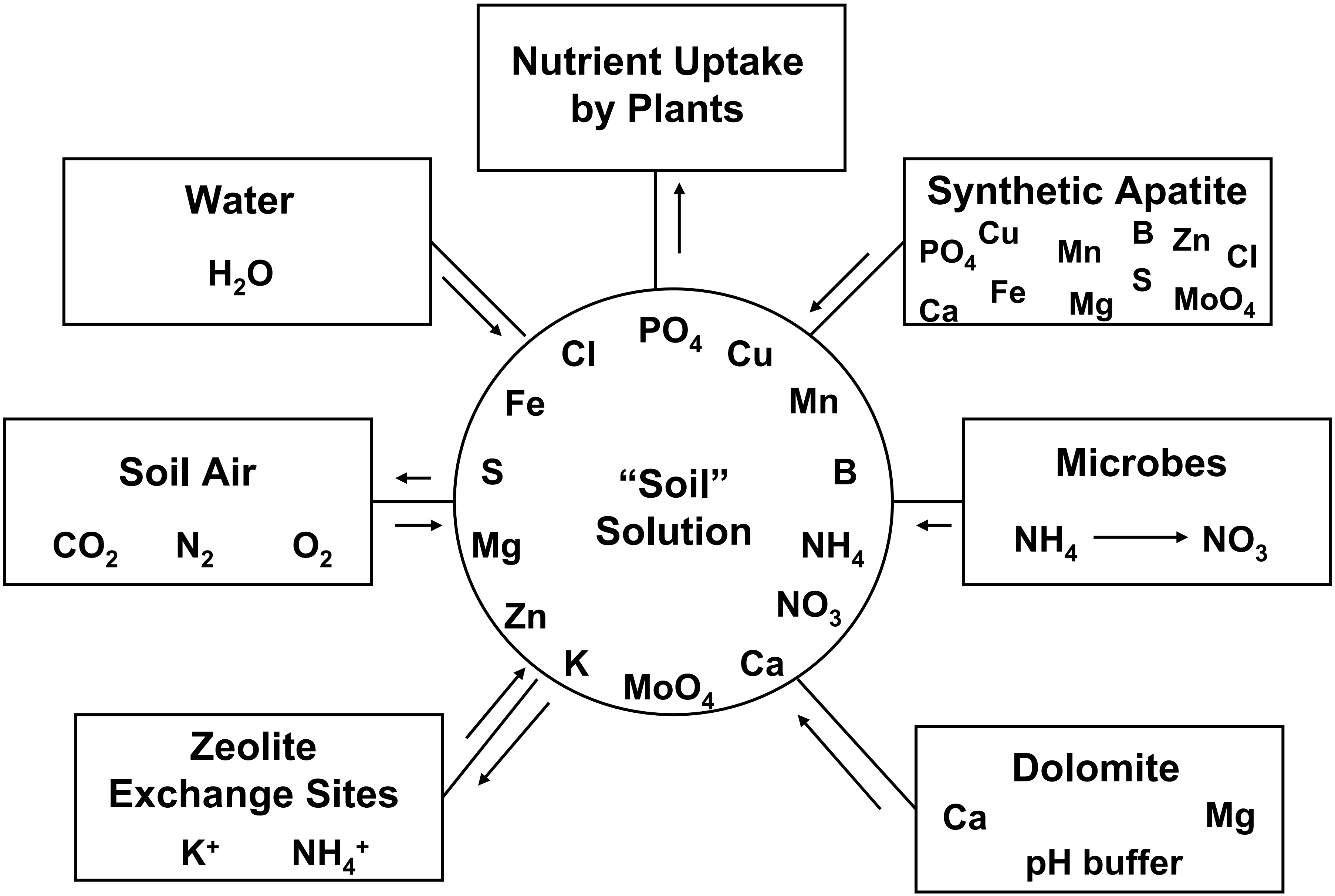
Micronutrient Treatment	Crop 1	Crop 2	Crop 3
	----------------	mg/kg	----------------
Zinc			
Zeoponics	33 (1)[a]	33 (3)	30 (3)
Potting Soil	29 (6)	19 (4)	20 (4)
K-Clino	35 (6)	26 (3)	25 (4)
Iron			
Zeoponics	136 (23)	131 (6)	106 (13)
Potting Soil	160 (35)	142 (19)	93 (34)
K-Clino	120 (22)	90 (20)	93 (27)
Manganese			
Zeoponics	55 (6)	61 (3)	68 (3)
Potting Soil	139 (6)	130 (27)	97 (26)
K-Clino	106 (6)	83 (2)	60 (2)
Copper			
Zeoponics	8 (3)	7 (0)	7 (1)
Potting Soil	8 (4)	7 (1)	7 (2)
K-Clino	8 (2)	6 (1)	8 (2)
Boron			
Zeoponics	75 (5)	70 (2)	41 (9)
Potting Soil	56 (2)	57 (4)	54 (4)
K-Clino	69 (3)	63 (7)	60 (1)

[a]Numbers in parentheses represent one standard deviation.

Figure Captions

Figure 1. Dynamic equilibria for NASA's zeoponic plant-growth system. Plant growth nutrients are slowly released from synthetic apatite (SA) and dolomite by dissolution and from clinoptilolite (Cp) by ion-exchange reactions.

Figure(s)


Nutrient Uptake
by Plants
Water
H2O
Synthetic Apatite
PO4 Cu Mn B Zn Cl
Ca Fe Mg S MoO4
Soil Air
CO2 N2 O2
"Soil"
Solution
PO4 Cu Mn B NH4 NO3 Ca MoO4 K Zn Mg S Fe Cl
Microbes
NH4 → NO3
Zeolite
Exchange Sites
K+ NH4+
Dolomite
Ca Mg
pH buffer