PLANT GROWTH EXPERIMENTS IN ZEOPONIC SUBSTRATES: APPLICATIONS FOR ADVANCED LIFE SUPPORT SYSTEMS

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INTRODUCTION

A zeoponic plant-growth system is defined as the cultivation of plants in artificial soils, which have zeolites as a major component (Allen and Ming, 1995). Zeolites are crystalline, hydrated aluminosilicate minerals that have the ability to exchange constituent cations without major change of the mineral structure. Recently, zeoponic systems developed at the National Aeronautics and Space Administration (NASA) slowly release some (Allen *et al*., 1995) or all of the essential plant-growth nutrients (Ming *et al*., 1995). These systems have NH_4- and K-exchanged clinoptilolite (a natural zeolite) and either natural or synthetic apatite (a calcium phosphate mineral). For the natural apatite system, Ca and P were made available to the plant by the dissolution of apatite. Potassium and NH_4-N were made available by ion-exchange reactions involving Ca^{2+} from apatite dissolution and K^+ and NH_4^+ on zeolitic exchange sites. In addition to NH_4-N, K, Ca, and P, the synthetic apatite system also supplied Mg, S, and other micronutrients during dissolution (Figure 1).

The overall objective of this research task is to develop zeoponic substrates wherein all plant growth nutrients are supplied by the plant growth medium for several growth seasons with only the addition of water. The substrate is being developed for plant growth in Advanced Life Support (ALS) testbeds (i.e., BioPLEX) and microgravity plant growth experiments. Zeoponic substrates have been used for plant growth experiments on two Space Shuttle flight experiments (STS-60; STS-63; Morrow et al., 1995). These substrates may be ideally suited for plant growth experiments on the International Space Station and applications in ALS testbeds. However, there are several issues that need to be resolved before zeoponics will be the choice substrate for plant growth experiments in space. The objective of this paper is to provide an overview on recent research directed toward the refinement of zeoponic plant growth substrates.

CURRENT STATUS OF RESEARCH

The first report of wheat seed yields from zeoponic substrates were considerably lower than from control substrates. Gruener *et al*. (2000) reported seed yields for wheat grown in a zeolite-synthetic apatite substrate diluted with a potting soil (peat-vermiculite-perlite) to be less than 30 % of the controls watered with ½-strength Hoagland's nutrient solution. They attributed the low seed yield to: (1) above normal contents of N and P in the plant tissue, (2) the NH_4-N source (i.e, NH_4-induced Ca deficiency), and (3) a wheat variety (var. Superdwarf) that performs poorly in non-ideal growing conditions.

Although the synthetic apatite and nutrient-enriched clinoptilolite substrates supplied adequate levels of the essential nutrients, N and P levels in plant tissues were slightly higher than required by wheat (see Gruener *et al*., 2000). In a subsequent test (Henderson *et al*., 2000), plant tissue N and P concentrations were lowered into the expected nutrient ranges for wheat by the addition of dolomite ($CaMg(CO_3)_2$), ferrihydrite, and nitrifying bacteria to the zeoponic substrate containing synthetic apatite. Seed yields were about 30% greater in the dolomite-amended zeoponic substrate inoculated with nitrifying bacteria compared with a peat-vermiculite-perlite control substrate watered with ½-strength Hoagland's nutrient solution. The dolomite addition probably reduced the solubility of the synthetic apatite due to a common ion effect (i.e., Ca^{2+}), and the nitrifying bacteria aided in the conversion of NH_4^+ to NO_3^-, which appeared to enhance seed production. The addition of dolomite reduced the P content of wheat from 1.4 wt. % in treatments without dolomite additions to 1.1 wt. % in substrates containing dolomite. The addition of the nitrifying bacteria further reduced the P plant tissue content to about 0.8 wt %. Grain yields increased from 4 to 8 grams/pot after the addition of nitrifying bacteria.

Steinberg *et al*. (2000) conducted a side-by-side comparison of wheat (var., USU-Apogee) growth and yield in a hydroponic system and a zeoponic system in a controlled environment chamber. The hydroponic system was a nutrient-film technique (i.e., seeds were place between fiberglass wicks inserted into a recirculating nutrient solution) with a modified ½-strength Hoagland's nutrient solution; the zeoponic substrate consisted of K- and NH_4-exchanged clinoptilolite, synthetic apatite, dolomite, and nitrifying bacteria (described by Henderson *et al.*, 2000). The substrate was diluted with 70 vol. % porous ceramic (heat-expanded clay) soil and watered with deionized water in a microporous tube irrigation system that maintained the soil matric potential at -0.5 kPa (Steinberg and Henninger, 1997). Temperature, light, and humidity were kept constant throughout the experiment at 23°C, 1700 $\mu mol/m^2/s$, and 70%, respectively, with a 24-hr photoperiod. The seed yield and harvest index at 64 days for the zeoponic substrate was 1.3 ± 0.2 kg/m^2 and 37% vs. 1.8 ± 0.3 kg/m^2 and 51% for the hydroponic system. Thus, the wheat seed production in the zeoponic substrate was equivalent to about 200 bushel/acre.

The formulation for zeoponic substrates was further refined by independently adding three calcium minerals (calcite, dolomite, and wollastonite). Calcium minerals were added to determine their effect on calcium and phosphorous uptake by wheat (var., USU-Apogee). Seed yield (13-22 g/pot) and harvest index (41-54 %) of plants grown in the zeoponic substrates were not significantly different from plants grown in control substrates watered with ½-strength Hoagland's solution (16-24 g/pot seed yield and 51-57 % harvest index). Wheat grown in zeoponic substrates amended with more soluble Ca minerals (e.g., calcite) had higher plant calcium.

FUTURE PLANS

Experiments are currently underway to evaluate the productivity of salad crops in zeoponic substrates. Several root crops (e.g., carrot and radish) may be more productive when grown in solid substrates, such as zeoponics, as compared to those grown in hydroponic culture systems. Recent experiments are directed towards supporting plant growth in ALS testbeds (i.e., BioPLEX) and planetary transfer vehicles (e.g., microgravity salad machine on Mars transfer vehicle).

REFERENCES

Allen, E.R. and Ming, D.W. (1995) Recent progress in the use of natural zeolites in agronomy and horticulture. In D. W. Ming and F. A. Mumpton, Ed., Natural zeolites '93: Occurrence, properties, use. 477-490. International Committee on Natural Zeolites, Brockport, New York.

Allen, E.R., Ming, D.W., Hossner, L.R., Henninger, D.L., and Galindo Jr., C. (1995) Growth and nutrient uptake of wheat in clinoptilolite and phosphate rock substrates. Agron. J., 87, 1052-1059.

Gruener, J.E., Ming, D.W., Henderson, K.E., and Carrier, C. (2000) Nutrient uptake of wheat grown in diluted clinoptilolite-natural/synthetic apatite substrates. In C. Colella and F. A. Mumpton, Ed., Natural Zeolite '97: 5th International Conference on the Occurrence, Properties, and Utilization of Natural Zeolites, De Frede Editore, Napli, Italy.

Henderson, K.E., Ming, D.W., Carrier, C., Gruener, J.E., Galindo, Jr., C., and Golden, D.C. (2000) Effects of adding nitrifying bacteria, dolomite, and ferrihydrite to zeoponic plant growth substrates. In C. Colella and F. A. Mumpton, Ed., Natural Zeolite '97: 5th International Conference on the Occurrence, Properties, and Utilization of Natural Zeolites, De Frede Editore, Napli, Italy.

Ming, D.W., Barta, D.J., Golden, D.C., Galindo Jr., C., and Henninger, D.L. (1995) Zeoponic plant-growth substrates for space applications. In D. W. Ming and F. A. Mumpton, Ed., Natural zeolites '93: Occurrence, properties, use. 505-513. International Committee on Natural Zeolites, Brockport, New York.

Morrow, R. C., Duffie, N. A., Tibbitts, T. W., Bula, R. J., Barta, D. J., Ming, D. W., Wheeler, R. M., and Porterfield, D. M. (1995) Plant response in the ASTROCULTURE™ Flight Experiment Unit. SAE Technical Paper Series, #951624. San Diego, California.

Steinberg, S.L. and Henninger, D.L. (1997) Response of the water status of soybean to changes in soil water potentials controlled by the water pressure in microporous tubes. Plant Cell Environ., 20, 1506-1516.

Steinberg, S.L., Ming, D.W., Henderson, K.E., Carrier, C., Gruener, J.E., Barta, D.J., and Henninger, D.L. (2000) Wheat response to differences in water and nutritional status between zeoponic and hydroponic growth systems. Agron. J., 92, 353-360.

Figure 1. Dynamic equilibria for NASA's zeoponic plant growth system. Plant growth nutrients are slowly released from synthetic, nutrient-substituted apatite by dissolution reactions and from the zeolite (clinoptilolite) by ion exchange reactions. The reactions in soil solution (i.e., nutrient release) are driven towards the root-soil interface by the uptake of nutrients by the plant.