A New Hydroponic Substrate
GREENHOUSE CULTIVATION OF TOMATOES ON EARTHSTONE BAGS

Comparison between cultivation in Earthstone substrates and Rockwool
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SUMMARY
Fruit production, plant development and fruit quality were compared for tomatoes (cv. *Clermont,* T.O.V.*)* hydroponically grown in Earthstone and Rockwool substrates at the University of Arizona[1] during the 2006-2007 crop season. In the study, results clearly showed that Earthstone's recycled glass substrates are a suitable alternative to rockwool. Plant development and yields were similar in rockwool and two Earthstone recycled glass formulations when using a system which has been optimized for rockwool for over 30 years. Also, due to Earthstone's drier nature, sugar content (Brix, %) in fruit grown in Earthstone was significantly higher than fruit grown in rockwool. Furthermore, preliminary results from a new bag design and water delivery method indicate that yields may be significantly improved by maximizing the wetted Earthstone volume and the root volume. Further trials are underway at the University of Arizona to evaluate this hypothesis.

INTRODUCTION
Hydroponic commercial agriculture, raising mostly tomatoes, cucumbers, peppers, and lettuce, is a rapidly growing industry. The annual rate of growth is approximately 15-25%. The center of growth is in the desert southwest of the United States, primarily in Texas and Arizona, and extends into Mexico. This region is favored because of ample winter sunlight and low winter heating costs.

However, in the near future, increased environmental constraints are expected to limit the production of mined substrates as well as make the after-use disposal of hydroponic substrates such as rockwool more difficult. The ability to respond to such constraints will become increasingly important. One effective approach is to promote the use of industrial by-products as alternative hydroponic substrates.

Earthstone hydroponic substrates are an environmentally friendly alternative. Manufactured from recycled glass bottles, these substrates reduce environmental impact at both ends of the production chain. They replace strip-mined materials like pumice, perlite, and rockwool, reducing environmental degradation. At the same time, since the product consists of 99% recycled glass, a large amount of waste material is given a new life, keeping it from the landfill. Also, being a non-toxic, chemical-free manufactured material, Earthstone substrates can be simply disposed of after a crop season by using the material as a soil amendment that increases the water holding capacity of marginal soils. Given that Earthstone substrates satisfy environmental concerns for both production and disposal, they constitute an important earth-friendly alternative to commonly used mined substrates.

Furthermore, Earthstone recycled glass substrates are engineered to provide an effective balance of aeration and moisture, a set of characteristics that favor root growth. Other substrates maximize either air or moisture, but foamed glass substrates such as Earthstone are designed to allow for rapid moisture absorption, controlled drainage, and oxygenation.

Earthstone's extensive research to test the suitability of these substrates in commercial hydroponic systems includes a wide range of trials with Universities located in different climatic zones—from arid climates at the University of Arizona in Tucson, to moderate climates at the University of Wageningen, The Netherlands.

Results have clearly shown (with continuous trials underway) that recycled glass substrates perform as well as rockwool, even with water delivery and bag geometry that are not optimized for their use, and at times, have added advantages over rockwool. Ongoing trials with systems being optimized to take advantage of Earthstone's well-balanced moisture and air properties have indicated tomato yields can be increased in Earthstone-based production systems compared to traditional rockwool production systems.

EXPERIMENT

Tomato plants (cv. *Clermont*, T.O.V.) were grown in different substrates in an A-frame greenhouse at the Controlled Environment Agriculture Center (CEAC), at the University of Arizona in Tucson.

The purpose of this research trial was to compare the performance of the new hydroponic substrate manufactured from recycled glass and rockwool for hydroponic greenhouse tomato production in an arid climate. The ultimate goal was to establish whether or not foamed glass substrates made from recycled glass were a suitable alternative to rockwool, for decades the industry standard hydroponic growing media for vegetable crop production.

The experiment consisted of a randomized block design in a side-by-side comparison of plant balance, yields, and fruit quality between three different growing media: crushed foamed glass with large pore size (ES-2), crushed foamed glass with small pore size (ES-3), and rockwool (control). Both Earthstone formulations are shown in Figure 1.

Figure 1. Two different formulations of Earthstone crushed foamed glass. Left, ES-3 characterized by small pore size for increased water retention and perfectly balanced water to air ratio with 45% water and 45% air at saturation (v/v, %). Right, ES-2 characterized by larger pore size with 40% water and 52% air at saturation (v/v, %) for increased drainage.

Environmental conditions

The crop season extended from transplant into the greenhouse on October 12, 2006 to June 30, 2007. Day/night air temperature regime was 25 ºC / 16 ºC (77 ºF / 61 ºF). In the hot summer months, average daytime temperature was difficult to maintain and varied between 27 ºC and 28 ºC (80.6 ºC and 82.4º F) while nighttime temperature was 19 ºC (66.2 ºF).

Relative humidity varied between 40 and 60% depending on the season due to different ventilation demands as a function of heat load. Relative humidity was higher in the spring and summer months due to the continuous need to run the evaporative cooling system.

Radiation levels were characteristically high throughout the entire crop season. Inside photosynthetic active radiation (PAR), varied from a minimum of 17 moles per m^2 per day in December to a maximum of 39 moles per m^2 per day during the months of May and June.

Crop management

Crop management followed standard practices for commercial greenhouse tomato production.

Plant density was 2.4 plants per m^2 during the entire season with 6 plants per bag in all substrates. Side shoots and bottom leaves were pruned weekly to maintain 15 to 18 leaves on the plant. Fruit pruning was performed weekly to keep 6 fruits per truss between transplant and week 30 after transplant (May 7, 2007). Afterwards, the number of fruits per truss was reduced to five. This was thought necessary to alleviate plant stress due to increased air temperatures inside the greenhouse.

Mature fruit trusses were harvested weekly from January 22 (15 weeks after transplant) to May 22 (32 weeks after transplant), and twice weekly for the remainder of the experiment. Trusses with 80% ripe fruit were considered ready for harvest.

The irrigation schedule (frequency and duration) for each substrate changed throughout the crop season. In general, Earthstone substrates were irrigated with twice the frequency and half the duration of rockwool. This corresponded to an irrigation cycle every 19 minutes for 1 minute for young plants, and every 13 minutes for 2 minutes for fully grown plants. This was determined to be necessary in order to maintain 30 to 40% drainage in all substrates during the fall-winter months and 40 to 60% during the warmer spring-summer months. It was also necessary to keep the drainage electrical conductivity (EC) level below 3.0 mS per m, and drainage pH close to 7.0. With increased root volume in the current trials that are underway, it is expected that the required irrigation frequency in Earthstone will decrease. EC at the drip was kept at 2.5 mS per m, and pH between 5.5 and 6.5. All plants were provided the same modified Hoagland nutrient solution.

Plant balance
Growing a successful tomato crop depends on the ability to maintain an optimum balance between plants' vegetative and reproductive growth throughout the entire crop season.

Stem thickness is often used by growers to assess the balance of a tomato crop. A stem diameter of approximately 10 mm measured at 15 cm from the growing tip is usually considered the threshold for a balanced tomato plant. Keeping a balanced plant is important since excessive vegetative or reproductive growth can lead to reduced yields in the short or long term.

Stems thicker than 10 mm are often associated with excessive vegetative growth, with larger leaf area and abundant side shoots, poor fruit set and reduced short term yields. Thinner stems reveal an excessive reproductive growth with smaller leaf area, and reduced lateral shoots. This limits production of photoassimilates, which results in slow growth and reduced yields in the long term.

Small departures from this threshold do not seem to be of consequence but large ones are matter for alarm. However, the acceptable departure from the threshold varies across different climate zones. During this study, stem diameters were measured weekly in 18 plants in each substrate in order to determine any substrate-induced unbalanced plant growth.

Preparation of slabs
Prior to transplant, all slabs needed to be properly rinsed to remove residual salts. The use of a diluted acid solution is recommended for this initial rinse. Therefore, all six drippers were placed in their final position in the slab and the slabs were filled with a diluted solution of nitric acid to adjust the pH to 5.5 – 6.0. Once full, slabs were allowed to overflow. Overflow was collected at the drainage channels and allowed to run to waste. Overflow occurred from the top cuts on the slab made to accommodate the 3" rockwool blocks carrying the tomato seedlings at transplant time. The next day, just before transplant, a slit was cut at approximately 0.5 cm from the bottom of each slab to allow for proper drainage for the remainder of the crop season. Nitric acid concentration at the drip was 0.09 ml of nitric acid per liter of water.

pH stability
For the duration of the crop season, acid injection into the nutrient solution followed the regular industry practice of adjusting pH of the nutrient solution to 5.5 – 6.0. No special pH adjustments were necessary for any of the three substrates.

RESULTS

Balanced plant growth
Ideally a stem diameter of 10 mm is desired. However, in arid climate regions such as the southwestern USA, it is normal to observe thinner stems during the crop season. During most of the growing season stem diameters in all substrates were thinner than

10 mm and varied between 8 and 9 mm. This was due to high radiation levels and high transpiration demand common in arid climates, which tend to promote reproductive plant growth, and thus thinner stems. Stem diameters were slightly larger in rockwool plants and smaller in ES-2 plants. This was expected given the respectively wet and dry nature of these two substrates. Stem diameter in ES-3 fluctuated between the two, particularly during the hot spring and summer months (Figure 2). This was likely the result of the higher water holding capacity of ES-3 compared to ES-2, and higher drainage and aeration compared to rockwool.

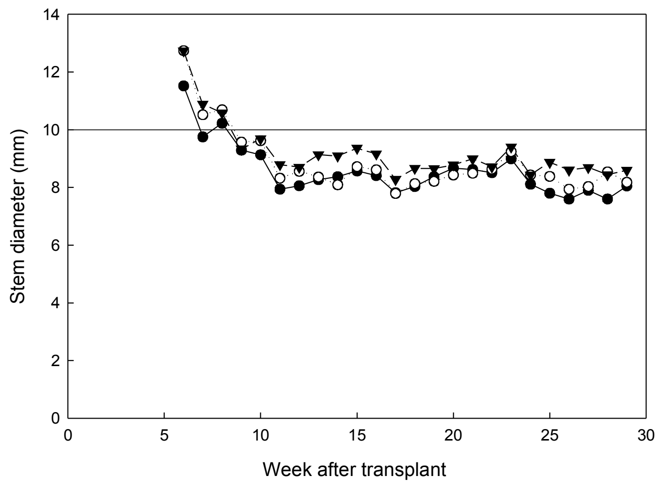

Figure 2. Stem diameter variation over time in plants grown in ES-2 (-●-); ES-3 (-○-), and rockwool (-▼-). Stem diameter measured at 15 cm from growing tip. Averages calculated from 18 plants per substrate. (N=18).

Yield

In all substrates tested, yield per plant fluctuated weekly. Weekly fluctuations were similar between all substrates and increased with increased radiation during the spring and early summer months (Figure 3). When temperatures inside the greenuouse were hard to maintain in the peak of the summer (after week 33), yields per plant declined at similar rates for ES-3 and rockwool. In ES-2 yields declined faster. However, by the end of the trial, yields per plant were higher in ES-3 and ES-2 compared to rockwool. (Figure 3).

Over the course of the crop production cycle, average yield per plant per week was the same in rockwool and ES-3 (0.70 kg per plant per week in both cases), while ES-2 produced a slightly lower average of 0.66 kg per plant per week. However, the yield difference was not statistically significant.

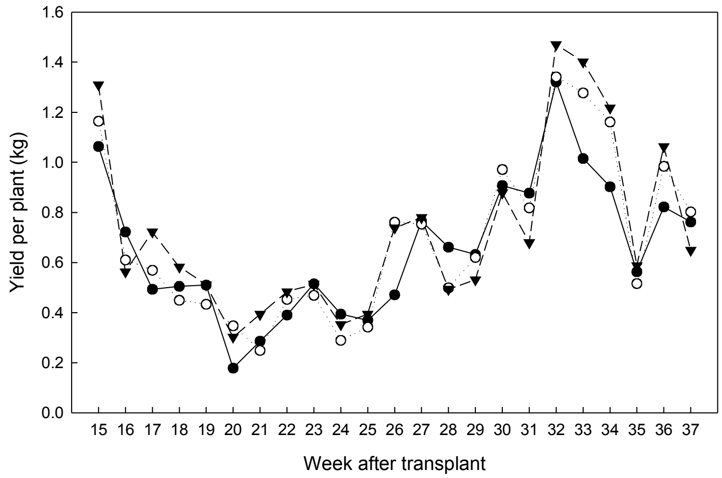

Figure 3. Average yields per plant per week in ES-2 (-●-); ES-3 (-○-), and rockwool (-▼-). Averages calculated from 18 plants per substrate (N=18).

Cumulative yields were very similar in all substrates with a slight advantage for rockwool. Cumulative yields in ES-3 fell within 2% of rockwool (statistically non-significant difference) and 8% of ES-2 (Figure 4).

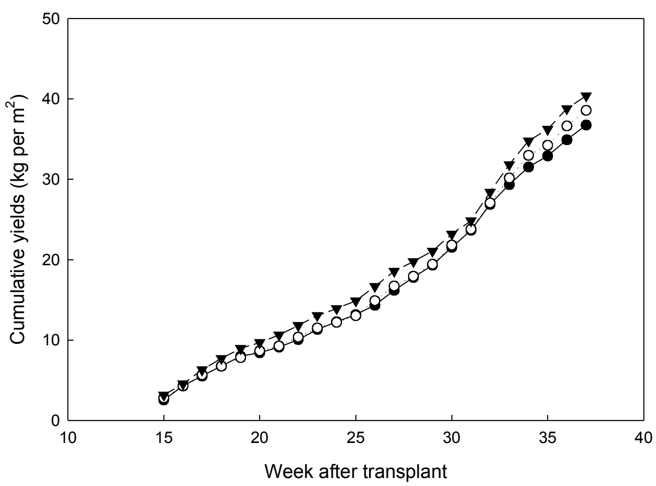

Figure 4. Cumulative yields (kg per m^2) during crop production cycle (January to June 2007) from tomato plants growing in recycled glass ES-2 (-●-), ES-3 (-○-), and rockwool (-▼-). Averages calculated from 18 plants per substrate (N=18).

At the end of the crop production period (over 5 months) rockwool plants had produced 40 kg per m^2, ES-3 plants 38 kg per m^2 and ES-2 plants had produced 37 kg per m^2 (Figure 4).

In all substrates, total yields at the end of the crop season were above industry levels. In fact, when summers are not excessively hot, inter-planting techniques allow for continuous greenhouse production year round. If one could assume a linear increase in cumulative yields with time, these results would correspond to total production of 81 kg per m^2 in ES-2; 83 kg per m^2 in ES-3; and 87 kg per m^2 in rockwool for year-round production with inter-planting. For a medium level technology greenhouse such as the one in the trial, tomato yields around 75 kg per m^2 are considered common in the industry.

Fruit quality - Brix, %

Tomato fruit quality as evaluated by its sugar content (Brix, %) was significantly higher in ES-2 (4.9%) and ES-3 (4.8%) than in rockwool (4.6%) (Figure 5).

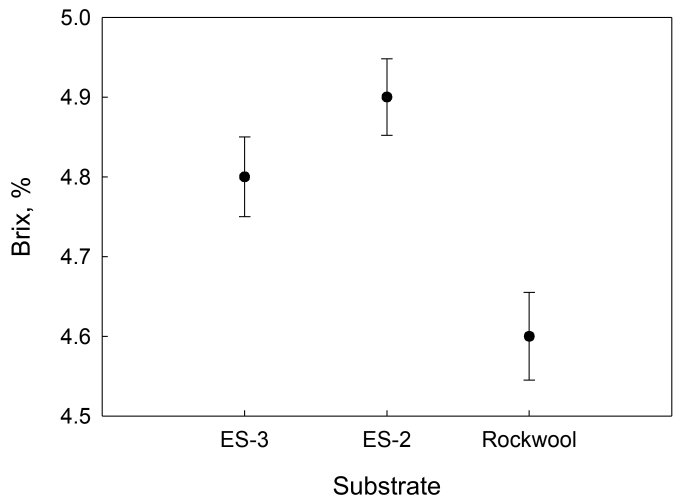

Figure 5. Earthstone substrates resulted in a significant increase in sugar content of tomato fruits (Brix, %) compared to rockwool. Average of 6 fruits per substrate from 7 harvest dates over a period of 13 weeks at the University of Arizona, Tucson, AZ.

Increased sugar content in Earthstone fruit was likely due to the drier nature of these substrates, as drier substrates tend to suppress water influx into fruits compared to wetter substrates. Thus, for the same amount of sugars produced through photosynthesis and with abundant water and nutrient supply, sugar concentration is higher in fruits from drier substrates. This agrees with the higher brix observed for ES-2 compared to ES-3. The characteristic larger pore size results in faster drainage and thus in a drier root environment in ES-2 compared to ES-3.

FUTURE PRODUCT DEVELOPMENT AND YIELD INCREASE

To take full advantage of higher levels of oxygen available to roots due to Earthstone substrates' higher porosity, the University of Arizona developed and is currently testing a new bag design. In this new design, Earthstone material is distributed in layers across the vertical profile of the bag. For this reason, the new design is referred to as the Earthstone "lasagna design".

Preliminary results from guard row plants growing in the Earthstone "lasagna design" bags in the same greenhouse as the previous study showed that cumulative yields per plant from the "lasagna design" bags were 25% higher compared to those from plants growing in bags simply filled with either ES-2 and ES-3 formulations, and 18% higher than in rockwool (Figure 6).

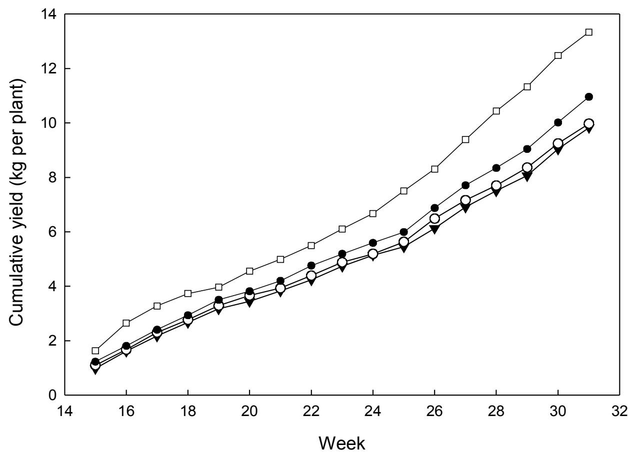

Figure 6. Cumulative yields per plant in large pore size ES-2 (-▼-), small pore size ES-3 (-○-), rockwool (-●-), and "lasagna" design in guard rows (-□-). Data from January 22 to mid May 2007. Averages calculated from 18 plants per substrate (N=18).

Plants growing in the "lasagna design" bags not only showed higher average yields but also a more homogeneous root distribution pattern throughout the bag volume compared to traditional Earthstone bags.

Given the direct effect between root development and distribution on water and nutrient uptake by roots, and thus on overall plant vigor and fruit yields, it is reasonable to assume that the better root distribution inside the "lasagna design" bags (due to better water distribution) was responsible for the increased yields observed. Although not part of the statistical design, the success obtained with the "lasgna design" led to further research trials in which this new design, as well as a few other designs which seek to maximize wetted volume of roots, are being tested ina controlled experimental design. Results will be forthcoming in summer, 2008.

Optimized water distribution in the root zone associated with the high number of macropores present between the crushed recycled glass Earthstone aggregates, and thus higher root oxygenation and overall gas exchange capacity, explain the more homogenous root distribution inside the bag. Higher root oxygenation and overall gas exchange capacity are important plant growth factors, and are currently being quantified at the University of Arizona.

CONCLUSION

Yields in both Earthstone substrates were not significantly different than rockwool when grown in a system optimized for rockwool. In all substrates, cumulative yields for the production period were higher than industry standards. For most of the trial period, stem diameter was similar between ES-3 and rockwool. In addition, fruit sugar content was significantly increased in all Earthstone substrates compared to rockwool. These results confirm that Earthstone is a suitable and environmentally friendly alternative to rockwool.

As a first evaluation of Earthstone recycled glass substrates for hydroponic production of tomatoes using a crop production management strategy and bag geometry optimized for production in rockwool slabs over the past 30 years, this is considered a highly positive result.

With ongoing testing, where the physical characteristics of Earthstone substrates are being optimized through innovations including bag design and water delivery, preliminary results show us that optimization of the root zone environment with respect to physical characteristics such as moisture distribution, oxygen levels, and irrigation schedule can lead to significant increases in tomato yields, as much as 18%, compared to those from rockwool.

Variations in Earthstone formulations

In arid and semi-arid regions with very high radiation levels, ES-3 resulted in higher tomato yields. Therefore, under high light and high temperature conditions, ES-3 is to be preferred over ES-2 formulations for tomato greenhouse production.

Irrigation and nutrient savings

Furthermore, water flow/retention and oxygenation properties of the Earthstone material require slight adjustments in the crop irrigation schedule compared to rockwool. Initial tests suggest that these irrigation adjustments may lead to savings in irrigation water and nutrients. Future studies, focused on irrigation schedule optimization, will be conducted to quantify water and nutrient inputs in Earthstone-based hydroponic systems.

Price and Disposal

Earthstone substrates have the potential to become a highly competitive alternative for hydroponics: not only can they compete directly on price terms with the market leaders but post-use disposal issues dramatically favor Earthstone. While rockwool, the current industry standard, is produced by mining of basaltic rock, and in the U.S. is currently disposed of in landfills, Earthstone recycled glass substrates can be simply disposed of by using it as a soil amendment to increase water holding capacity in marginal soils.

Acknowledgements

[1]The study was conducted at the Controlled Environment Agriculture Center by Research Assistant Jose Choc Chen Lopez under the guidance of faculty members Gene A. Giacomelli, Peter Waller, Pat Rorabaugh, and Merle Jensen from the Departments of Agricultural and Biosystems Engineering and Plant Sciences.

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