Solar on-farm fertilizer production for subsurface-irrigated tomatoes

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Abstract: Tomatoes at the Center of Irrigation and Technology in Fresno, California, were grown with fertilizer produced on-site using electricity from a 2.4-kW solar array. Nitrogen from the air and irrigation water were used to produce nitric acid, which was neutralized using either limestone or potassium hydroxide to form aqueous solutions of calcium or nitrate. Tomatoes of the AB 314 variety were planted in 40-ft-long, 4-ft-wide beds and divided into two equal groups – test and control - with 12 beds per group. The control group was fertigated using 200 lbs N/acre of UAN-32 and followed UC Davis reference tables to determine application rate. The test group was integrated with the on-site fertilizer generator and fertigated each time water was applied to the field. The solar-fertilizer system is on-track to produce 200-lbs N/acre in the course of a year. However, based on the start date, the fertilizer production system produced and injected 70 lbs N/acre this first season. Soil, fertilizer, petiole, and Brix samples were collected over the course of the season for both groups. Crop yields from the test and control plot were 33±14 tons/acre and 35±9 tons/acre, respectively. Despite applying 35% of the nitrogen fertilizer to the test plot with respect to the control, yields and fruit quality between the plots were comparable. The ability to fertigate frequently is intrinsic to on-site fertilizer generation, and these results suggest that such application may decrease the required amount through the increased use-efficiency of fertilizer for a given crop.

Keywords: solar, fertilizer, fertigation, nitric acid, calcium nitrate, potassium nitrate, tomatoes, irrigation, plasma

1. Introduction

For the past century, nitrogen fertilizer has been produced as ammonia (NH_3) in Haber-Bosch facilities often situated very far from farmers who need and use fertilizer.[1,2] State-of-the-art Haber-Bosch factories require hydrogen production via coal or methane reforming and use high-pressure and -temperature reactors to transform hydrogen and nitrogen gas into ammonia. World-scale fertilizer facilities can cost billions of dollars and are located in proximity to low-cost hydrocarbons, rather than farmland. Market inefficiencies and safety hazards are incurred in the distribution of fertilizer to farmers, which lead to a 2-5x difference in price between the factory gate and the farm.[3]

There are substantial greenhouse gas emissions (GHG) associated with the production and application of nitrogen fertilizer today. The ammonia industry is responsible for 1.4% of global CO_2 emissions from the production process [4,5]; this does not include methane emitted from such facilities, which is thought to be underestimated by as much as 50x.[6] The application of nitrogen fertilizer is responsible for more GHG emissions in the form of nitrous oxide (N_2O) produced by nitrification and denitrification of fertilizer by soil microbes. Nitrous oxide is nearly 300 times more potent of a greenhouse gas than CO_2 and accounts for 3-6% of annual anthropogenic CO_2-equivalent emissions.[7,8] Fertilizer type, quantity applied per acre, and application rate have been observed to influence the N_2O emissions.[9–12]

Distributed, on-farm fertilizer production using air, water, and renewable energy would avoid the need for distribution and could mitigate GHG emissions.[13–16] This concept is generally recognized as on-farm technology connected to either solar or wind that manufactures nitrogen fertilizer intermittently. On-farm production couples well with farming practices that involve more-frequent, less-intensive application rates because the production rate is gradual and intermittent. High-frequency, low-dose fertigation is an effective strategy to decrease nitrous oxide emissions and increase nitrogen utilization efficiency (NUE).[17,18]

There are several proposed pathways for distributed fertilizer production, including chemical ammonia (NH_3) production[19–22], biological nitrogen fixation pathways[23,24], and chemical nitric acid

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production. Chemical ammonia production can be thermochemical, electrochemical, or both[14,25] Ammonia processes are known to achieve reasonable energy efficiencies with their greatest challenge associated with capital cost. Biological fixation pathways typically generate ammonia through an enhanced nitrogenase biological pathway but are currently limited by the amount of fertilizer that they can provide and the type of crops and soils that they are compatible with.[26] The distributed production and fertilization with nitric acid is relatively underexplored. Known nitric acid production methods require about 3 times more energy per pound of nitrogen than ammonia processes. At this time, the capital cost associated with distributed nitric acid production is not well documented. However, on-farm nitric acid production does not require the same high-pressure equipment that leads to high capital cost for ammonia production, as demonstrated by this work.

In the current study, we focus on a plasma-based production process that fixes nitrogen as nitric acid on-site for a plot of irrigated processing tomatoes. The objectives of the current study are to 1) demonstrate the feasibility of distributed fertilizer production and discuss the challenges and opportunities associated with solar and irrigation integration, 2) discuss the outcomes of this trial on a test and control group of processing tomatoes.

2. Background

2.1. Processing tomatoes and California fertilizer guidelines

First found wild in the high Andes, tomatoes are now domesticated and the second-most consumed vegetable in the world.[27] About one quarter of all tomatoes are known as "processing tomatoes" and processed immediately after harvesting for foods such as soup, juice, sauce, salsa, ketchup, powder, and concentrates.[3,28,29] Modern processing tomatoes have been selectively bred over 60 years to obtain thicker skins and higher structural strength than fresh market tomatoes. These characteristics allow the tomatoes to endure mechanical harvesting and transport involving over 50,000 lbs per truck.[30] In 2019, 37 million metric tons of processing tomatoes were grown globally, with 27% of all tomatoes produced in California.[30]

Most processing tomatoes are seeded in greenhouses and seedlings are transplanted into the field in the spring. In California, 66-inch or 60-inch beds are common and tomatoes are spaced by 9 or 12 inches.[3,28] Irrigation is essential and furrow, sprinkler, or drip irrigation common. Drip irrigation was used in the current study and involves burying drip lines 8-12 inches in the center of the beds. Depending on the initial planting day and weather, tomatoes are mechanically harvested between July and October and involve collecting the entire plant and separating the vine and fruit. Typical harvest values are 40-70 tons of tomatoes produced per acre.[28,31]

Nitrogen fertilization of processing tomatoes varies considerably; however, 178 lbs N/acre (200 kg N/ha) has been commonly cited as most effective in California for high-yield tomato production.[3,27,28,32] As low as 100-120 lbs N/acre has been reported as sufficient in certain conditions and as high as 264 lbs N/acre is recommended in UC Davis crop production cost studies.[3,31]

Phosphorous fertilization studies performed in California have recommended the need for only 17-53 lbs P/acre.[31] Although, some cost studies also recommend the use of more phosphorus in the form of phosphoric acid (up to 80 lbs P/acre), which may equally be to pH control of the soil.

Reported rates of potassium fertilizer varies considerably in the literature.[3] This large variance can be attributed to potassium present in different soils where tomatoes are grown, with California soils having a good potassium content for high-yield tomato production. Tomatoes are known to have large quantities of potassium in the product and may require large amounts of potassium input.[27] In total, 50-150 lbs K/acre or more is recommended, depending on the soil availability.

2.2. *Solar-fertilizer production overview*

On-site nitrogen fertilizer production is a popular scientific concept and methodology proposed to reduce greenhouse gas emissions from fertilizer manufacture. In the current study, fertilizer was produced on-site using a system produced by Nitricity Inc, a startup company out of San Francisco (www.nitricity.co). Nitrogen from air, water, and renewable electricity from a solar array were used to produce 1% nitric acid diluted in water. Nitric acid is an acidic fertilizer itself and a source of irrigable nitrate (NO_3^-). To increase the pH of the liquid solution nitric acid can be neutralized with calcium carbonate (limestone) or potassium hydroxide (KOH).

3. Experimental Methods

Figure 1 provides photographs of the solar-fertilizer system on the Center for Irrigation and Technology (CIT) farm. The system was installed in March and started production in April. The solar system was a 16-panel ground-mount array and outputted 75-85 V with a maximum power of 2.4 kW. The fertilizer system was installed under the solar array. A fertilizer storage tank underneath the solar array was connected to a particulate filter and an injection pump.

A schematic of the coupling of the fertilizer generator and the irrigation system is shown in Fig. 2. The nitric acid generator was situated underneath the solar array, which provided the input electricity for the process. Nitric acid was slowly concentrated and, in batches, released into a 200-gallon storage tank. Limestone and KOH were added to the storage tank depending on the time of the season. Nitric acid was primarily neutralized using limestone at the beginning of the season and KOH at the end of the season. An outlet at the bottom of the 200-gallon tank was connected to a particulate filter and a fertilizer injection pump.

A pressure transducer was installed in the irrigation line and monitored when water was flowing to the test plot. The fertilizer generator was connected to the internet and used to monitor when irrigation and the injection pump were running.

Figure 3 provides photographs and a schematic of the irrigation setup. Figure 3 (a) shows the plot shortly after transplanting the tomatoes and (b) near the end of the growing season approximately 100 days after transplant. Fig. 3 (c), provides a schematic of the irrigation setup. Three water lines were routed to the field including one for the test plot (green), another for the control plot (yellow), and another to a set of buffer rows (blue) on the outside of the plot. The test and control plots were organized in four different groupings of three rows, alternating between test and control groupings. Pressure regulators were installed before the irrigation lines were split to ensure 10-psig pressure for the drip lines. Fertilizer from the Nitricity system was injected at the same upstream location as the control grouping and as the buffer rows. The buffer grouping received the same fertilizer treatment as the control group and was used to have all test and control rows have tomato plants on either side.

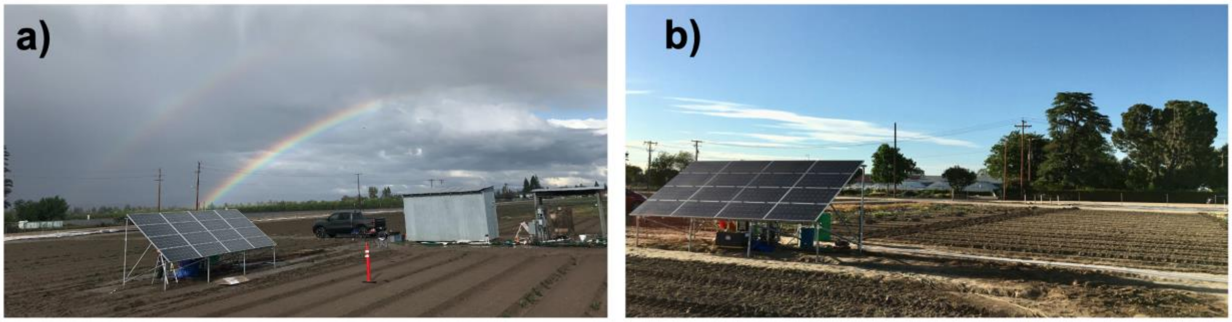

Fig. 1. Two photographs of the on-site solar-fertilizer generator with the 5-ft wide, 40-ft long tomato beds visible in the background. The nitric acid generator is positioned underneath the 3-kW solar array. The image in a) was taken before the season in April and b) after the tomatoes were transplanted in May.

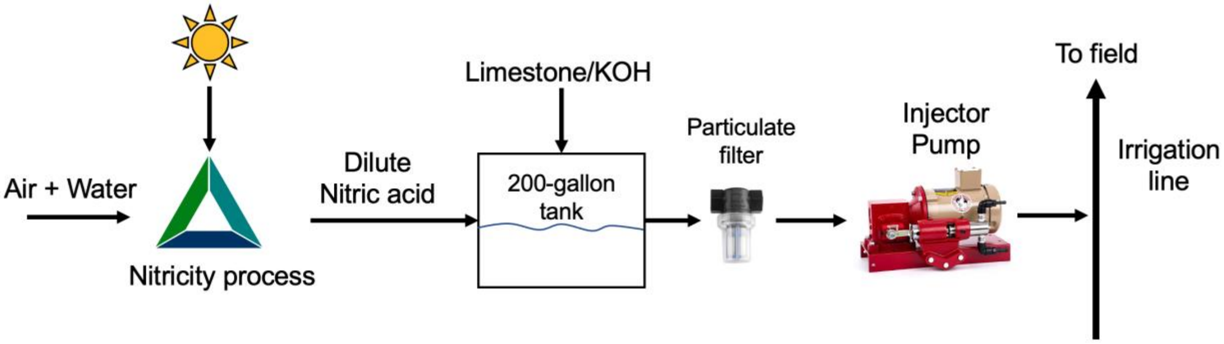

Fig. 2. Block diagram showing the integration of the nitric acid generator and irrigation system. Air, water, and solar inputs are shown left and converted to dilute nitric acid, which was routed to a 200-gal storage tank. Limestone and potassium hydroxide (KOH) were added to this storage tank to neutralize the pH of the liquid solution. A particulate filter and injector pump were connected to the bottom outlet of the storage tank and used to inject fertilizer into the irrigation line.

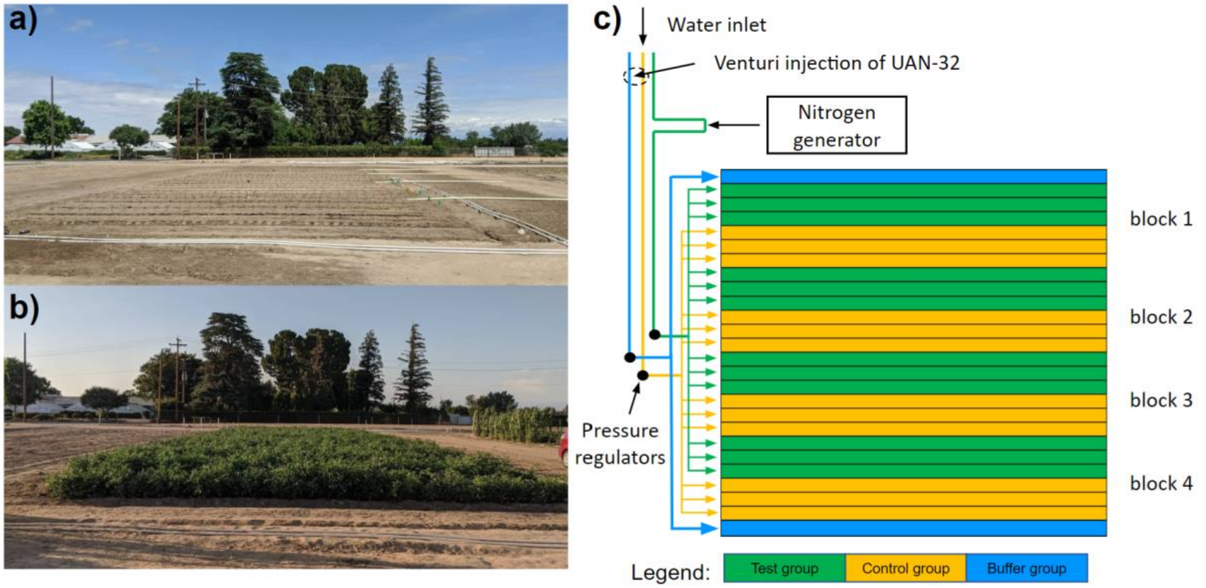

Fig. 3. An overview of the experimental test plot shown day 1 (a) and day 100 (b) after transplant. Subplot c) provides a top-down schematic of irrigation layout. The test group (green) received fertilizer produced on-site injected by the nitrogen generator before the final pressure regulators. Both the control and buffer group had UAN-32 injected using a venturi pump at the location indicated by the dotted circle.

4. Development of the fertilizer production system

The Nitricity nitrogen generator was first constructed in Palo Alto, California, in January-March, 2020, and transported to Fresno in April. 2020. This new technology required continuous optimization over the course of the growing season, which was important to ensuring continuous operation and output. Additionally, major system upgrades were implemented to improve the production rate, connect the nitric acid generator to the internet, and in the coupling of the Nitricity system and the irrigation set. Almost every major subsystem was upgraded during the growing season and all subsequent design iteration occurred *in situ* on the CIT farm in Fresno.

While often discussed in scientific literature, on-farm production of fertilizer in practice involves a variety of implementation-based challenges worthy of comment. Notably, the fertilizer system was first installed in April during the rainy season. In contrast, the end of the season had typical central valley days with temperatures easily over 100 °F and relentless sun, leading to the breakdown of many rubbers and adhesives due to UV exposure. High winds and dust made a number of challenges associated with maintaining the electronic components of the system. Any similar efforts need to be well aware that the farm is a harsh environment. There are also increased hazards from pesticides, venomous spiders, and heavy farm equipment. Images captured throughout the growing season are presented in Fig. 4 and illustrate many of the unanticipated challenges involved with this on-field fertilizer research.

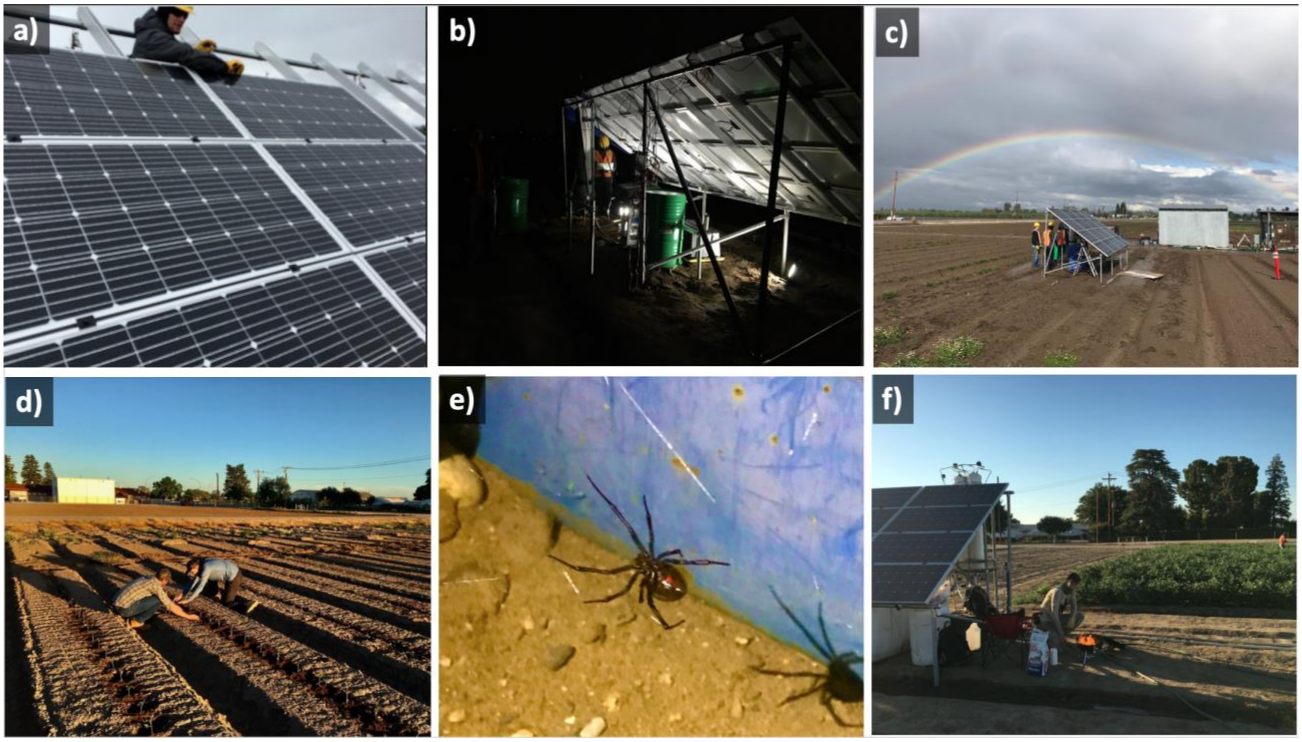

Fig. 4. Key moments for the Nitricity team. a) solar panel installation b) night-time upgrades to the system c) Final installation completed d) transplanting tomatoes e) unwelcome visitors to the field f) Nitricity enjoying locally sourced meats and vegetables while servicing the system

5. Irrigation integration

Prior fertilization studies in the literature indicate that high-frequency fertigation is able to increase nitrogen (and other nutrient) utilization efficiency in crops in some cases.[33,34] Nitricity hypothesized that with a more frequent application of fertilizer than the control group, less fertilizer would be needed overall to achieve similar yields. To test this hypothesis, the injection pump was set to inject fertilizer each time the field was irrigated, which led to near daily fertilization towards the end of the season. The conventional plot was fertilized weekly. After consulting initial soil analysis, the experts at CIT designed a fertilizer schedule that applied a total of 200 lb N/acre to the control plot in addition to the roughly 50 lb N/acre that was available from residual soil nitrate (appendix A). This fertilizer was applied through the subsurface drip irrigation system weekly, as shown in figure 6a. This N application rate is generally in line with typical practices for the San Joaquin Valley.[23–25] Nitricity injected fertilizer as it was produced with the sun, with a small amount of storage to smooth out day to day variations.

6. Results and Discussion

6.1. Final production quantities and fertigation

Figure 5 presents the fertilizer timeline for both the test and the control plot, (a) and (b), respectively. For the test plot shown in Fig. 5(a), the nitrogen production rate is shown in red and the trailing nitrogen injection rate shown in blue. Over the course of 1 year, production is projected to reach approximately 200 lbs N/acre. However, for the 2020 growing season, installation and operation of the fertilizer system began 30 days before tomato transplant; therefore, only 70 lbs N/acre was produced and inject by the on-farm generator for the 2020 season. The control plot received a complete 200 lbs N/acre injected at 11 instances. A major difference between the test and the control plot were the application rate over the season.

After the growing season concluded on day 130, Nitricity spent several weeks conducting upgrades on the fertilizer hardware. Fertilizer hardware downtime is shown between day 110 and 170 on Fig. 5(a). These upgrades greatly increased production rate for several weeks. The production rate was then observed to decrease around day 250 due to a decrease in the solar-peak hours of sunlight in the winter.

Throughout the season we observed even watering of both the control and test plots. For fertigation with a new fertilizer product, clogging irrigation lines is always a concern, however, a major method for clearing clogged irrigation lines is through the application of nitric acid.[35] We note that we observed only one instance of possible clogging in our system. The slow-down in application near day 80 was related to one-way valves in the injection pump becoming poorly seated, resulting in a loss of flow. Consultation with the manufacturer suggests that this is typical for this model of pump and we have no reason to believe that our fertilizer caused any unexpected issues. On the contrary, we anticipate that having nitric acid on demand will be a valuable asset for cleaning clogged fertigation lines.

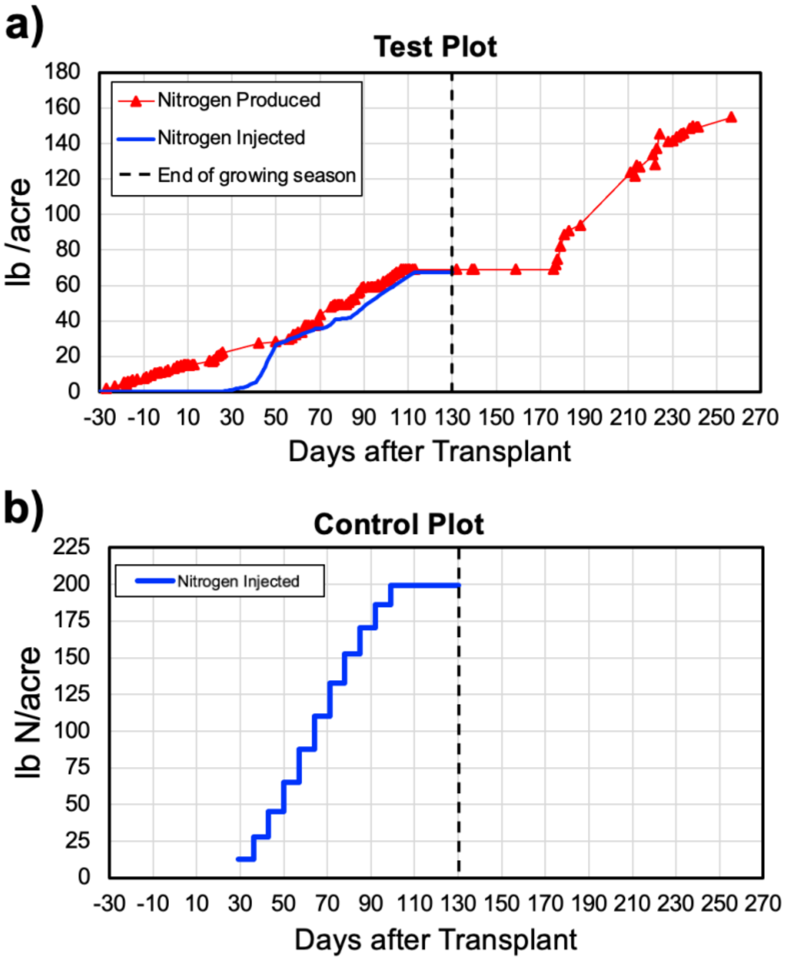

Figure 5: a) Nitricity treatment. The red line shows fertilizer produced and delivered to the 200-gallon tank and triangles indicate days where measurements were taken. The blue line shows fertilizer delivered to the field via the injection pump and drip tape. b) Control treatment applied by CIT. All data is reference to days after fertilizer transplant on May 20th, 2020.

In addition to tracking the amount of nitrogen applied to the test crops, Nitricity also analyzed the fertilizer composition for other metals. As described above, the dilute nitric acid from the nitrogen fixation process was neutralized with organic limestone sourced from the Blue Mountain Minerals quarry in Columbia, CA. Nitricity sent two samples of neutralized acid to Dellavalle laboratory in Fresno for third party evaluation. The results are shown below in Figure 6. In the left panel, you can see that for both samples the amount of calcium detected is greater than what would be expected for calcium nitrate, the expected dominant species. This is likely due to some amount of other soluble calcium species. The right panel shows minor components in mg/kg. There are detectable amounts of a variety of potentially beneficial elements like magnesium and zinc. The evaluation also tested for possible undesirable elements, such as cadmium and mercury. The lack of a bar on Figure 6 indicates a species below the detection limit.

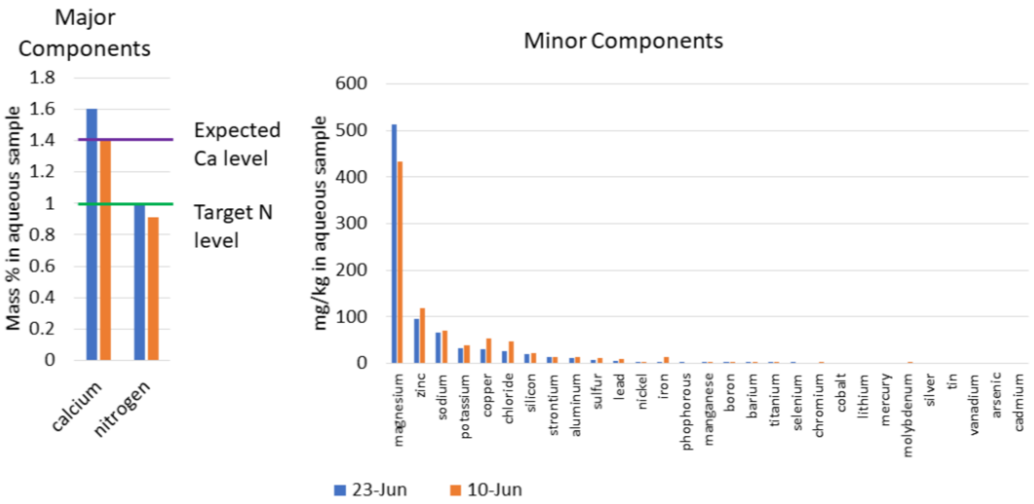

Figure 6: Analysis obtained from Dellavalle laboratory, Fresno CA using EPA method 3051A. Elements with no bar were reported below detection limits.

6.2 Tomato Crop Growth, Development, and Yields

Fig. 7: Photographic timeline of visual observations of the tomato plants. Top row, left to right: Nitricity and CIT panting the tomatoes on day 0 (May 20). Tomato plants on day 22 (6/11) from the South side of the field. Early fruit seen day 55 (7/14). Middle row, left to right: photograph of rows 6-9 showing early signs of virus impact on the plants. First observation of red color in the fruit on day 84 (8/12). Bottom row, left to right: Example damage from the tomato virus in block 3 and harvested tomatoes, both day 112 (sept. 9).

Nitricity and CIT worked together to transplant the tomatoes on May 20, 2020 as shown in the top left image of Fig. 7. Observations of the early growth mirrored the ultimate yield results. Both the control and test treatment plots in block 4 lagged behind the other blocks in plant size and fruit yield. Visual observation of the irrigation did not suggest any issues with the drip tape for this area. We note that it is the closest block to a farm road. Fruit was first observed around day 55 (July 14) and first color was observed around day 84 (August 12). Throughout the growing season there were noticeable impacts to the tomato plants from a virus vectored by leaf hoppers. CIT treated the tomatoes with Admire® Pro (Bayer) on day 63 (July 22). Despite this treatment, there were impacts to the tomato plants, especially in blocks 3 and 4 which already had poor growth.

To estimate the yield of tomatoes, 10 plants from the middle of each treatment were harvested. For blocks 1-3, 10 consecutive plants starting five feet from the East side of the field were harvested. Dead plants were skipped, although there were never more than two per row for these blocks. For block 4, there were many damaged plants and the control treatment had to be collected from a modified sample, choosing a ten-plant section in the last row that was relatively healthy. The tomatoes were shaken from the vine, loose tomatoes collected by hand, and then sorted into categories based on color. The results are shown in Fig. 8(a). In addition, three ripe tomatoes were collected from each block and tested for sugar content using the Brix technique at the CIT graduate laboratory. Shown in Fig. 8(b), readings for all samples were similar, and within typical ranges for processing tomatoes (4.7-6.0).[36]

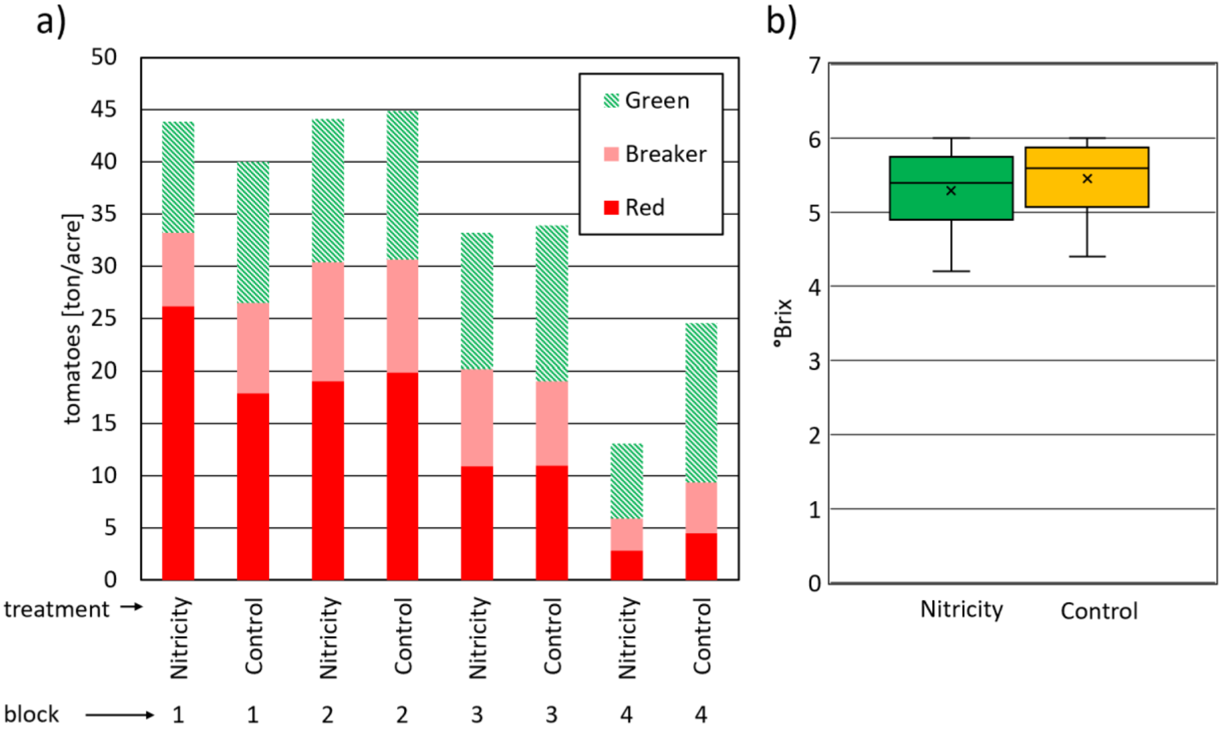

Figure 8: a) The yield in tons per acre was measured by harvesting 10 plants for each treatment in each block, each block contains 6 rows, 3 fertilized with the Nitricity treatment and 3 fertilized with the control treatment. The fruit was sorted into different categories: red, green, breaker, and non-marketable. Data with non-marketable fruit is in tabular form in appendix A. b) Brix analysis of ripe tomatoes done by the graduate

lab at CIT. Plot shows the statistics over all four blocks, three tomatoes per treatment. All blocks had similar Brix readings.

Based on this data, the harvested tomato crops were nearly identical for all blocks except the last, which suffered from poor growth throughout the season. The slow initial growth observed in block 4 was compounded by the effects of the tomato virus. The browning and death of tomato crops in block 4 was most visibly apparent on 5 rows out of the 6 total rows in the block (control+test), with a single control row less visibly impacted. Block 4 should be considered an outlier due to the virus impact, however, we have included block 4 in the data to show the effect. Nitricity's high-frequency fertilizer test application, using only 35% nitrogen fertilizer as the control, was able to produce 93.5% of the control plot yield (112.6% if the block 4, heavily infected region is omitted). Furthermore, analysis of petiole and leaf tissue samples throughout the season, shown in table 1, show that both the control and Nitricity treatments had nitrogen, potassium, and phosphorous content within expected values for most of the season. The exception is nitrogen on 7/22, where both were slightly below the recommended range of 6,000-10,000. As the nitrogen content of the petioles and tissue drops as the fruit matures, it is also possible that the fruit was more developed than we realized.

Table 1: Petiole and tissue analysis throughout the season. All analysis performed by Dellavalle laboratory, Fresno CA. Petiole analysis values for leaching with 2% acetic acid. Red highlighting indicates below typical values and green highlighting indicates values in typical range for the phase of growth.

	7/22 Nitricity	7/22 Control	8/13 Nitricity	8/13 Control	9/9 Nitricity	9/9 Control
Petiole extracted N [mg/kg]	5120	2700	5010	5380		
Petiole extracted P [mg/kg]	3970	3590	3460	2830		
Petiole extracted K [mg/kg]	4.2	4.6	4.6	4.7		
Tissue N%					3.23	3.77
Tissue P%					0.23	0.28
Tissue K%					2.06	1.84

5. Conclusions

Nitricity installed and improved on a solar powered fertilizer production unit at the Center for Irrigation Technology (in Fresno, California. Rapidly prototyping and iterating at CIT allowed Nitricity to improve the reliability and performance of their fertilizer production unit, while also improving their energy efficiency. Nitricity applied calcium nitrate fertilizer via high-frequency drip irrigation and observed no significant difference between the tomatoes grown with the control treatment and the Nitricity treatment, despite lower fertilizer application overall in the Nitricity treatment. This work contributes to studies indicating that high frequency fertilizer application can be an effective way to improve nutrient utilization efficiencies. Future work will explore the effect of high-frequency applications of Nitricity fertilizer with lb N/acre matching that of the control on the ability to improve crop yields. Ultimately, Nitricity sees an opportunity to provide on-site, on-demand fertigation which intrinsically provides for a more efficient use of sustainable nutrients through renewable power and high frequency application.

Appendix A: initial soil characterization

	mg/kg	mg/kg	mg/kg
	NO_3-N	PO_4-P	K
Nitricity	29	45	**263**
Nitricity	16	**23**	**156**
Control	**56**	**57**	**383**
Control	20	32	**245**

Soil analysis performed before transplanting by Dellavalle laboratory, Fresno CA. Purple indicates very above typical values, red indicates above typical values, and blue indicates below typical values.

Appendix B: tabulated tomato data

	Red	**Breaker**	**Green**	**non-marketable**
1 Control	17.86213	8.61913	13.54106	6.34887
2 Control	19.85639	10.79068	14.2138	6.646908
3 Control	10.97276	8.061388	14.88463	9.263121
4 Control	4.504104	4.843349	15.2277	4.247274
1 Nitricity	26.13914	7.077193	10.60381	2.601839
2 Nitricity	19.01594	11.34843	13.73848	6.212789
3 Nitricity	10.86927	9.344578	12.96224	5.598505
4 Nitricity	2.84621	3.067582	7.130859	2.654546

Tomatoes sorted by color. Non-marketable indicates rot, bug damage, or excessive scarring. Numbers in pounds of tomatoes for a ten-foot sampling section.

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