Horticulture Innovation Australia

Final Report

Aerated water irrigation for increased water productivity, yield and quality of processing tomato

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Summary

The project investigated the potential benefits of the use of aerated irrigation water (referred to as "oxygation") on the performance of subsurface drip irrigated tomato crops. When a crop is irrigated using a subsurface drip system, a zone of saturated soil persists for a short duration while the wetting front from the drip emitters moves through the soil profile. Low levels of available oxygen associated with the wetting front may adversely affect the roots of plants growing in the soil, potentially reducing the yield and quality of susceptible crops such as processing tomato. Increasing the level of dissolved oxygen in the irrigation water will increase oxygen availability to crop plant roots, potentially overcoming oxygen deficits during irrigation. This project aimed to test this theory, examining the capacity of two different "oxygation" systems to increase dissolved oxygen levels throughout the length of drip irrigation lines in processing tomato crops and measuring crop yield and quality of "oxygation" and control treatments in commercial crop trials.

Project results showed that the "oxygation" treatment did not significantly increase crop yield or tomato quality. Both "oxygation' systems assessed in the project, a gas diffusion oxygen generator and direct injection of bottled gas into the irrigation water, were able to increase the percentage dissolved oxygen in the irrigation water by 3- to 4-fold, with only a small decrease in the dissolved oxygen concentration along the drip line for a distance of up to 340m. The direct O_2 injection system has a significantly lower initial capital cost than the oxygen generation system tested, but has higher running costs associated with supply of compressed O_2 gas or liquid O_2. A 1-4% higher yield in the "oxygation" treatment compared to control was noted in all trials apart from one (where equipment failure resulted in 'oxygation' not being delivered over the entire cropping season), but high variability in the paddocks resulted in any treatment effect not being statistically significant. Thus, while a trend appeared to exist, it cannot be concluded that "oxygation" increased crop yield.

Plant physiological responses to elevated DO were recorded, with the oxygation treatment resulting in plants maintaining a greater capacity to photosynthesize late in crop development, thus increasing yield potential while retaining or improving fruit quality. While consistent responses were recorded, the responses were small relative to the large in-field variability within processing tomato crops. It was concluded that 'oxygation' was not a commercially feasible technology to adopt in the processing tomato industry.

Keywords

Processing tomato, irrigation, oxygenation, dissolved oxygen, total soluble solids, brix

Introduction

Low levels of available oxygen in the soil profile associated with sustained wetting fronts of drip irrigation can reduce yield and quality of susceptible crops. As irrigation water exits a drip-tape emitter, it purges soil pores of soil air (containing up to 20% by volume of oxygen) with water that contains less than 10 ppm dissolved oxygen, a quantity that is used up quickly by roots and soil microbes. Research trials in crops including cotton, pineapple and melons have demonstrated that a significant increase in crop yield and quality can be achieved by introducing air bubbles into the drip irrigation water stream. Detailed physiological studies have shown that the response is linked to alleviation of root oxygen starvation caused by traditional drip irrigation methods. When grown on poorly draining soils, tomato (*Solanum lycopersicum* L.) is particularly susceptible to waterlogging stress and can suffer yield reductions from 23% to 100% depending on varieties and intensity of flooding (Ezin *et al*., 2010).

Field experiments with waterlogged tomato show reductions in growth through significant impacts on plant water relation with short term (4-6 h) waterlogging (Jackson, 2002) which, if persisting for longer durations, can have major negative repercussions in yield and quality. In cotton, a crop also susceptible to water logging, records show that under waterlogged conditions fewer bolls resulted from decreased overall growth (height, nodes, leaf area) and from lower radiation use efficiency (g dry matter per MJ^{-1} intercepted radiation), a surrogate for crop photosynthesis (Bange *et al*. 2004). Conaty *et al*. (2008) also showed waterlogging stress to cause alterations to leaf mineral nutrient levels and photosynthetic rates in cotton.

Waterlogging results in lowered levels of oxygen in the plant root zone due to the low diffusion rate of molecular oxygen in water. Low oxygen levels cause rapid changes in gene transcription, protein synthesis and degradation, and cellular metabolism (reviewed in Bailey-Serres and Voesenek 2008). While hypoxia does affect energy metabolism, and root zone hypoxia is clearly a major component of water logging stress, field observations showing altered growth rates, photosynthetic rates and mineral nutrient content in waterlogged plants indicate that waterlogging stress is more complex than just an altered energy metabolism in the roots. While studies of model plant responses to low oxygen have provided crucial insights, they have often been carried out under highly artificial conditions (entire plants are placed in low oxygen atmospheres, sometimes supplemented with sugars and sometimes in the dark) that do not mimic the effects seen in soil under field conditions. Also, studies on the molecular responses of root and leaf tissue to soil waterlogging have been comparatively scarce, with the first such study only performed recently in gray poplar (Populus × canescens) by Kreuzwieser *et al*. (2009).

In general as water resource availability decreases and water costs increase farmers are looking to irrigation methods that are more sustainable. The general public is also looking to farmers to improve upon their water use efficiency, particularly in the Murray-Darling Basin (MDB) area where most of the processing tomato industry is located. Drip irrigation is seen as a potential solution to this problem, but the high set up costs are a barrier to adoption. Higher yields and/or fruit quality in crops grown using drip systems are needed to offset set up costs, and will increasingly be required as the price of irrigation water rises. While drip irrigation has been largely adopted by processing tomato growers, its full potential may not be well realized if the sustained wetting front during irrigation events results in hypoxia in the root zone that constrains yield.

Previous research in annual crops including fresh tomatoes has demonstrated the potential of oxygation to improve yield and WUE (Bhattarai and Midmore, 2009), even when soils may be less than saturated (Bhattarai *et al.*, 2006). This research utilised venturi air injection which introduces bubbles of different sizes into the irrigation water stream. Larger bubbles tend to exit drip emitters much more quickly than micro and nano bubbles, creating gradients in oxygen content along the irrigation line. In lengthy drip irrigation lines such as those used in the processing tomato industry, this lack of uniformity of air bubble (and hence oxygen) distribution would be a limiting factor for air injection venturis making it unsuitable for use. An alternative approach is to directly increase dissolved oxygen within the irrigation water, reducing the variability associated with bubble size. This requires exposure of irrigation water to gas with a high oxygen content. In the aquaculture industry, this is done through direct injection of oxygen from compressed gas or liquid oxygen storage systems, or of high oxygen content gas generated from a gas diffusion system (GDS).

The main objective of this trial was to determine under what conditions will there be a measurable positive effect of aeration on yield and quality of processing tomato. The study was also designed to evaluate the effectiveness of a GDS and a direct injection of compressed gas system on increasing dissolved oxygen concentration in irrigation water, and maintenance of high dissolved oxygen concentration in irrigation water over the lengths of drip-line used in the processing tomato industry.

Methodology

The project was conducted over 3 crop production seasons between 2013 and 2016. In each season, replicated trials were established in commercial processing tomato crops to assess the effects of aeration of the irrigation water ('oxygation') on crop performance. Treatment plot yields were assessed using yield data from load cell monitors on commercial harvesters. Fruit subsamples from the commercial harvest were used to assess fruit quality. Additional assessments of plant physiological status and soil factors were also taken in the project.

Trial Sites

The field experiments were conducted at Kagome Farms 'Swan Lake' property near Corop (-36° 30' S, 144° 50' E) and Geltch Holdings farm, Singer Road (-36°16' S, 144° 41' E) near Rochester, Victoria. Both sites were clay loam soils, with organic carbon levels between 1.3 and 1.8%. Both sites had had processing tomatoes grown previously, and the trials in this project were either the first or second processing tomato crop in a tomato, tomato, break crop rotation.

Planting Materials and Crop Management

A commonly planted variety, a H3402/H2401 mix (70:30 mix), was direct-seeded into prepared beds following standard practice. At the Kagome site, 2 rows of tomatoes were planted per bed while one row per bed, the most common industry planting arrangement, was used at the Geltch site. Subsurface drip irrigation was used at both sites. The drip tape (Ozline), consisting of pressure compensated typhoon emitters at 40 cm intervals with flow rate of 1.6 L/hr and irrigation outputs of 2.0 mm/hour, was laid at the depth of 300 mm from the soil surface. The drip tape was laid at 30 cm depth in the middle of each bed, directly under the crop row at the Geltch site and running between the two crop rows at the Kagome site. All fertilizer applications, irrigation scheduling and pest, weed and disease management practices were managed by the growers at the two sites and followed commonly accepted industry practice.

Experimental Design

The project used a simple replicated experimental design incorporating 2 treatments, a 'control' consisting of standard irrigation water and an 'oxygation' treatment in which dissolved oxygen (DO) concentration in the irrigation water was increased. Two irrigation submain lines were installed at each site allowing 'control' and 'oxygation' treatments to be delivered from a single pump, with timing and rate of irrigation identical for the two treatments. Within each site, alternating blocks of 3 (Kagome) or 5 (Geltch) beds received the 'control' and 'oxygation' treatments. This experimental design allowed for sampling in the middle row of each treatment plot to eliminate edge effects. The alternating five-row 'control' and 'oxygation' plots at the Geltch site were replicated 6 times resulting in a total of 30 rows receiving the 'oxygation' treatment and 30 rows receiving untreated irrigation water ('control' treatment). The alternating 3 row plots at the Kagome site were replicated 10 times. Row length at the

Geltch site was 340m and at the Kagome site 196m. The large size of the trials allowed assessment of treatment effects at a commercial scale.

'Oxygation' treatment

Oxygen super saturation into the irrigation water stream for the 'oxygation' treatment was achieved using two different systems in the project. In years 1 and 2 at the Kagome site, a commercially available GDS based on pressure swing adsorption (PSA) technology was leased for the trials. In years 2 and 3 at the Geltch site, and year 3 at the Kagome site, a direct compressed gas oxygen injection system designed by industry representative Mr Tony Henry was used.

The GDS system was a SA-300-PB120 oxygen diffusion system (Seair Inc, Canada) that used PSA technology to separate nitrogen from other gases in air, allowing gas with elevated oxygen concentration to be collected for injection into the irrigation water through a Mazzei air injector. The system was installed in-line immediately before the field plot at Kagome, regulated to ingress high purity oxygen for enhancing DO concentration in irrigation for large volumes of water following the method presented by Chen et al. (2010). The inlet pressure of 45 PSI was achieved at the point of the Mazzei air injector installation. A pressure differential across the air injector was maintained at 45 and 15 PSI for the inlet and outlet, respectively, to maintain optimum air injection rate.

The second system utilized strengthened fiberglass cones were manufactured for a direct compressed gas oxygen injection system. Irrigation water is pumped into the top of the cone where compressed gas from gas cylinders is injected into the water stream. The water jet forces the water to mix intensively with the oxygen, creating a high specific interface and high turbulence at the top of the dissolver. As the cone widens, the velocity is reduced and gas bubbles that haven't fully dissolved rise against the downwards oriented water flow. Water leaving the base of the cone is super saturated with dissolved oxygen.

Figure 1. Pressure swing adsorption system (left) and direct compressed gas injection system (right) used to generate high dissolved oxygen concentration in irrigation water.

Dissolved Oxygen Monitoring

The DO concentration in the source irrigation water in the channel, in the pump station, immediately after the air injection at the outlet of the GDS, and in the soil in the vicinity of drip emitters was monitored in year 1 of the project. In the second season, sampling ports were installed in the drip lines at both sites to allow monitoring of dissolved oxygen (DO) concentration in the pressurized water in the drip lines at different points within each crop. The Geltch site had a total of forty six sampling points within the crop and the Kagome site had fifty sampling points. Distribution of sampling points along rows and across the site in replicated plots allowed comprehensive assessment of oxygen concentration in the drip lines in the crop. Sampling ports consisted of a T joiner inserted in the drip tape line with a short section of polyethylene pipe with a ball valve at the base and a flanged 'top hat' joiner on the top. An oxygen sensor inserted in the connector that fitted onto the 'top hat' joiner could then be fitted onto a sampling port, and DO concentration recorded in the irrigation water under pressured conditions when the ball valve was opened.

Figure 2. Sampling port assembly with fibox-3 oxygen meter connected.

DO was measured in the irrigation water using PSt3 O2 sensitive Fibre-optic minisensors (optical sensors) with fibox-3 oxygen meters (PreSens GmbH, Germany) as described by Klimant et al. (1995).

Harvesting and Yield Determination

Yield data were collected from each trial using the yield monitors on commercial harvesters when the crops were harvested. Only the middle bed of each 3 or 5 bed plot was harvested. In years 2 and 3, yield from each bed was assessed in the first third, middle third and final third section at the Geltch site and in the first half and second half of each row at the Kagome site. This assessment strategy allowed evaluation of variability in the paddock along both length and breadth dimensions of each site.

Fruit Quality Determination

A subsample of 20 fruit per plot was collected from each section in each plot during the harvesting for yield assessment, and analysed for %brix and pH of the fruit as a measure of quality. Individual fruit were randomly sampled from the harvester as it travelled along each row in order to obtain a representative sample. Total soluble solids (%brix) was recorded by macerating the fruit in a blender, allowing the liquid to settle and then recording the %brix using a temperature compensated benchtop refractometer. A calibrated pH probe was then used to record the pH of the blended sample.

In year 1, samples of fruit (which included all maturity group- red ripe, turning and green) were also transported to Rockhampton for development of a Near InfraRed (NIR) methodology for TSS, and dry matter assessment. Handheld NIR has been successfully utilized for assessment and prediction of sugar and dry matter content in a number of other crops such as mango and banana. Fruit samples at different times during the pre-ripening stage could be scanned with a hand-held NIR unit (Nirvana) to monitor the effects of treatments on development of TSS and dry matter non-destructively. Calibration models were developed for processing tomato for the non-invasive assessment of fruit dry matter and TSS throughout the crop growth period. At the completion of the year 1 trial, it was agreed not to proceed with the NIR work as commercial application of the technology was deemed unlikely and standard industry protocols for assessment of fruit quality were required for reporting of treatment effects in the trials.

Plant and Soil Monitoring

Small plot harvests and plant physiology measurements were taken in years 2 and 3 to test the hypothesis that 'oxygation' enabled the plants to continue photosynthesizing more efficiently late in crop development, thus enabling a greater proportion of the fruit on each plant to ripen (increasing yield) while also supporting dry matter accumulation in all ripe fruit (increasing brix). This hypothesis was based on the observed increase in both yield and brix in the 'oxygation' treatment in the 2013 trial.

Hand harvesting of 5 individual plants in each plot at site 2 was completed two weeks prior to commercial harvest. Fruit from each plant were separated into green and red fruit, counted and weighed. Randomly selected plants within the experimental plots were examined to monitor changes in plant physiological processes that were considered likely to explain any differences in yield and quality induced by the 'oxygation' treatment. Plant growth parameters measured were leaf photosynthetic efficiency (photosynthetic quantum yield) and leaf transpiration rate. The two fully-expanded topmost sunlit leaves on plants were measured using a PAR-FluorPen FP 100-MAX-LM for photosynthetic quantum yield measurement and a Decagon SC-1 portable porometer to measure transpiration rate.

In year 3, the wetting front pattern in the soil during an irrigation event was assessed to determine if the variability in yield along the rows that was noted in year 2 was linked to water availability. Trenches were dug in the rows to expose soil sections above, adjacent to and below the drip tape line. A HydroSense Soil Water Measurement System was used to measure soil moisture before, during and after an irrigation event. The soil moisture sensors were inserted at a 15 cm offset position from an emitter on the drip tape.

Figure 3. Hydrosense soil moisture monitoring probe inserted in soil profile.

Data Analysis

Fruit yield and quality data were analysed following the procedures for Student's t Test (For Paired Samples). Other data collected over the season were analysed using a factorial design of randomised complete block approach for analysis of variance (ANOVA) using GenStat Version13 (VSN International, UK). For most of the crop, soil and water parameters only main effects are presented. Interactions between the treatments and seasons have been analysed for each site, and where interactions are not significant, only as main effects results are presented. Means were separated by the least significant different (LSD) at $P \leq 0.05$.

Outputs

The project was designed to determine if aeration of the irrigation water ('oxygation') would increase yield and/or quality in processing tomato crops. Research undertaken in the project determined that:

- Both the gas diffusion system GDS using pressure swing adsorption and the direct compressed gas oxygen injection system can produce a 3 to 5 fold increase in % dissolved oxygen levels in irrigation water
- High levels of %DO can be maintained in subsurface drip irrigation lines over distances up to 340m, with a 10-15% decrease over the length of the drip irrigation line
- The increased %DO in the irrigation water in the 'oxygation' treatment did not result in a consistent, statistically significant, increase in fruit yield or quality
- Differences in physiological status of plants between 'oxygation' and 'control' treatments were recorded, with plants receiving the 'oxygation' treatment tending to retain higher photosynthetic activity later in the season than 'control' plants
- Large and consistent variability was recorded within the 2 experimental sites, with significantly higher yields recorded at the end of the fields furthest from the irrigation submain (the far end of the drip irrigation line) compared to the section closest to the submain
- Differences in wetting front patterns were recorded in soil in the areas closest to and furthest away from the irrigation submain, with more rapid wetting occurring during irrigation in the latter area
- It is unlikely that 'oxygation' will be a cost effective technology for the processing tomato industry while within-field variability in crop performance due to either soil variations or sub-optimal irrigation system operation remains high

Project deliverables

- Formal presentations on project findings were made at the APTRC annual research and development forum in 2014, 2015 and 2016.
- The project leader attended the Processing Tomato Industry field day held on the 22nd January 2015 and provided attendees at the field day with an update on project activities. The Kagome site was visited to allow inspection of current trial and to view the DO sampling strategy being used in the project.
- Articles on the projects were published in the APTRC magazine in 2015 and 2016.

Capacity of 'oxygation' systems to deliver aerated water over long driptape distances

Both 'oxygation' systems were effective in increasing the level of dissolved oxygen between 3 and 5 times in the irrigation water. The DO concentration in the water from the irrigation channels averaged approximately 20% DO across the 3 seasons' trials. The pressure swing adsorption (PSA) system increased DO concentration to a maximum of 68% DO, and the direct compressed gas oxygen injection system increased DO concentration to a maximum of 99% DO.

The increase in %DO in irrigation water in the direct compressed gas oxygen injection system was rapid, reaching maximum concentration within five minutes of commencing irrigation pumping. The PSA system required a longer period of time to reach maximum %DO in the irrigation water due to the time taken for the oxygen generating system to build up high oxygen content air for injection into the irrigation water. A trial run was conducted in the first season to optimize the performance of oxygen generation system and time course changes in DO dynamics were monitored. In this run the DO increased from a baseline of 6.17 to 25 ppm over 80 minutes (Figure 4) when water temperature was 23.8 °C, pH was 8.1 and conductivity was 94 mS/cm. These observations suggest that the system must be operated 80 minutes prior to the beginning of irrigation, so that the crop receives fully oxygen saturated water as soon as the aerated water reaches the root zone.

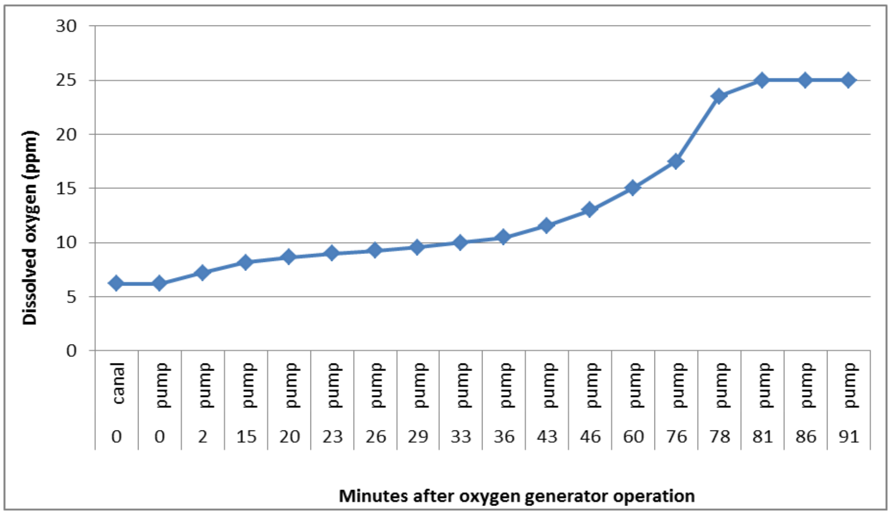

Figure 4. DO dynamics with respect to the duration of operation of oxygen diffusion system.

Increased dissolved oxygen levels were maintained within the irrigation lines with only a small decrease over the length of the irrigation line. Extensive %DO measurements were taken in the second season at the Geltch site at 46 sampling positions on three sampling dates (example from one date shown below).

The compressed gas oxygen injection system at the Geltch site increased dissolved oxygen concentration significantly and only a small decrease in concentration was noted between the point where the first drip irrigation line entered the crop and the furthermost end of the last irrigation line in the crop. Across the 3 sampling dates at the Geltch site in year 2, dissolved oxygen levels varied within the range 20.5% to 22.2% in the untreated irrigation lines and between 77.5% and 98.8% in the 'oxygation' treatment. Measurements were taken from sampling ports at the start and end of drip lines at both sites in the thirst season and were consistent with the readings obtained in the second season, confirming the capacity of the direct compressed gas oxygen injection system to maintain high %DO levels along the full length of the pressurized drip lines.

Table 1: Dissolved oxygen (%DO) levels in pressurised irrigation lines at the Geltch site (31 Jan 2015).

Treatment	Replicate	Distance along irrigation line				
		5m	85m	170m	255m	340m
Control	1	21.7	22.1	21.8	22.0	20.8
Oxygation		**98.9**	**90.9**	**88.8**	**83.0**	**77.7**
Control	2		21.9	21.9	21.9	
Oxygation			**89.6**	**89.3**	**81.7**	
Control	3		21.9	21.9	21.9	
Oxygation			**88.2**	**88.5**	**77.5**	**79.8**
Control	4		21.9	22.2	21.4	20.5
Oxygation			**91.3**	**88.9**	**85.3**	
Control	5		21.9	22.0	21.8	
Oxygation			**92.7**	**87.8**	**84.8**	
Control	6	21.8	22.1	21.9	21.9	20.5
Oxygation		**95.6**	**94.6**	**88.4**	**84.6**	**78.7**
Oxygation average			***92.1***	***88.6***	***82.8***	

Measurements at the start and end of irrigation lines were also collected in the third season at both sites, and were consistent with the second season readings (Table 2).

Table 2: Dissolved oxygen (%DO) levels in pressurised irrigation lines

Treatment	Site	Season	Submain	End of dripline
Control	Geltch	2014/15	20-22%	20-21%
Oxygation			**86-99%**	**78-84%**
Control	Geltch	2015/16	19-21%	19-20%
Oxygation			**83-95%**	**76-82%**
Control	Kagome	2015/16	19-20%	19-20%
Oxygation			**88-92%**	**85-86%**

Unfortunately malfunctioning of the oxygen generation equipment at the Kagome site in season 2 meant that recorded %DO levels in both 'control' and 'oxygation' irrigation lines were between 17.8% and 20.2% on each of the three sampling dates. The equipment supplier assured us that the equipment had been functioning until the last approximately 4 weeks of the season, and it could therefore be assumed that the equipment would have generated a similar, fourfold, increase in dissolved oxygen concentration as measured during the first season.

Dissolved oxygen concentrations were measured in both %DO and ppm units on the 31/01/2015 at the Geltch site. The oxygen concentration (ppm) was assessed in order to provide data for comparison purposes against other published studies on the effects of increased dissolved oxygen content on crop performance.

Table 3. Mean %DO and oxygen concentration (ppm) values at different distances along the irrigation lines

	%DO			ppm		
	85m	170m	255m	85m	170m	255m
Control	22.0	21.9	21.8	9.5	9.5	9.5
Oxygation	91.2	88.6	82.8	39.3	38.3	36.0

The conclusion drawn from the assessment of dissolved oxygen levels was that the 'oxygation' systems used were able to maintain a 3 to 5 fold increase in %DO over the non-oxygenated water. A decline of 8.5% in %DO occurred along the lines but was small in comparison to the difference between oxygenated and control irrigation lines.

Crop yield and fruit quality

Plots were machine harvested and fruit weight recorded using the harvester load cells. GPS measurement of plot lengths were recorded during harvesting and used to convert plot yields to a t/ha yield estimate. In year 1, fruit were randomly sampled from the field prior to harvest for quality assessment, and only %brix was recorded. In years 2 and 3, a subsample of 20 fruit per plot was collected during the harvesting operation and analysed for %brix and pH. A small increase in yield and %brix was recorded for the 'oxygation' treatment at the Geltch site in the second and third seasons, and at the Kagome site in the first and third season. A large decrease in yield was recorded at the Kagome site in the second season, with the malfunctioning of the oxygen generation equipment at the site likely to have influenced the result at that site in the second season.

Table 4. Fruit yield and quality assessment from commercial harvest

Site	Season		Yield (t/ha)	brix	pH
Kagome	2013/14	Control	85.1±4.7	4.96	
		Oxygation	**88.9±4.3**	**5.86**	
Kagome*	2014/15	Control	95.2±4.6	4.97±0.10	4.50±0.04
		Oxygation	**85.5±3.8**	**5.18±0.12**	**4.47±0.05**
Geltch	2014/15	Control	97.7±4.6	5.39±0.10	4.55±0.02
		Oxygation	**99.9±3.9**	**5.53±0.10**	**4.54±0.02**
Kagome	2015/16	Control	94.8±4.3	4.96±0.09	4.53±0.06
		Oxygation	**95.5±4.1**	**4.99±0.12**	**4.45±0.04**
Geltch	2015/16	Control	103.2±3.7	5.32±0.12	4.49±0.04
		Oxygation	**105.0±4.8**	**5.26±0.11**	**4.53±0.05**

*note that the "oxygation" equipment at site 1 failed to function properly for part of the season in 2014/15

Yield was significantly higher in the control than the 'oxygation' treatment at the Kagome site in season 2, but a failure of the 'oxygation' equipment at the site meant that the results could not be interpreted as solely due to the treatments. No other statistically significant differences were found between treatments for yield, brix or fruit pH in any season and at any site.

Within Paddock variability

While the yield measurements for the 'oxygation' treatment were higher than the controls in 4 out of the 5 trials, the variability in crop performance between different areas within the sites was greater than the difference between the treatments. To demonstrate this within crop variability, rows were divided into thirds (Geltch) or half (Kagome) and yield measurements were recorded for the within row sections (referred to as blocks) in the 2014/15 and 2015/16 seasons. Table 5 shows a typical set of results.

Table 5. Fruit yield and quality (machine harvested) in different blocks (Geltch site, 2014/15 season).

Treatment	Block	Yield (t/ha)	brix	pH
control	1	93.0	5.62	4.53
control	2	93.0	5.47	4.57
control	3	107.0	5.08	4.55
oxygation	1	92.5	5.40	4.48
oxygation	2	93.3	5.62	4.60
oxygation	3	114.1	5.57	4.53

Block 1 was the section of the crop closest to the submain, the middle third of the row was Block 2, and the section of the row furthest from the drip line entry point was Block 3.

The higher yield of the 'oxygation' treatment compared to the 'control' treatment, recorded in only one part of the paddock (Block 3), was responsible for the small increase in overall mean yield for the 'oxygation' treatment in the trial. It is of interest to note that the highest yielding section of the paddock, Block 3, was at the far end of the drip irrigation lines and so the 'oxygation' treated plants in this area were exposed to %DO levels that were on average 8.5% lower than the 'oxygation' treated plants in Block 1. It is also interesting to note that the brix readings for the 'oxygation' treatment in Block 3 remained high even though yield was also high, whereas in the 'control' treatment the increase in yield in Block 3 corresponded to a decrease in brix. This result was consistent with the results noted in the 2013 trial, where oxygation resulted in an increase in both yield and brix, and the same trend was also recorded in the data from the third seasons' trials at both sites.

Development of NIR methodology for non-destructive soluble solids and dry matter determination

TSS and DM assessment using handheld NIR (Figure 5 and 6) suggest that the predictions for these two parameters based on the calibration model developed from the samples fruits (different maturity stages) collected from field are reasonably consistent.

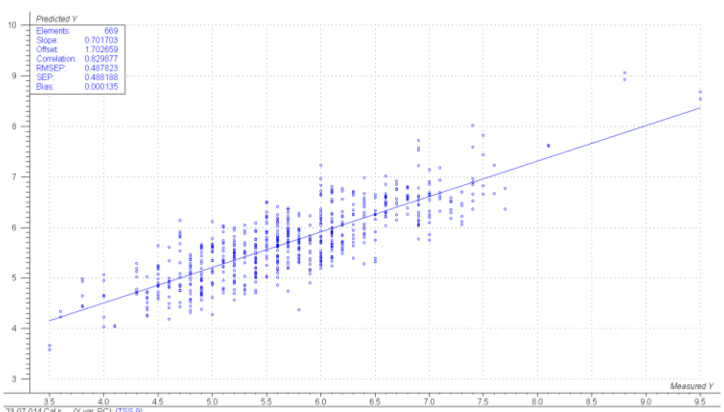

Figure 5. Regression model for total soluble solid (TSS) prediction non-destructively using Nirvana hand-held NIR.

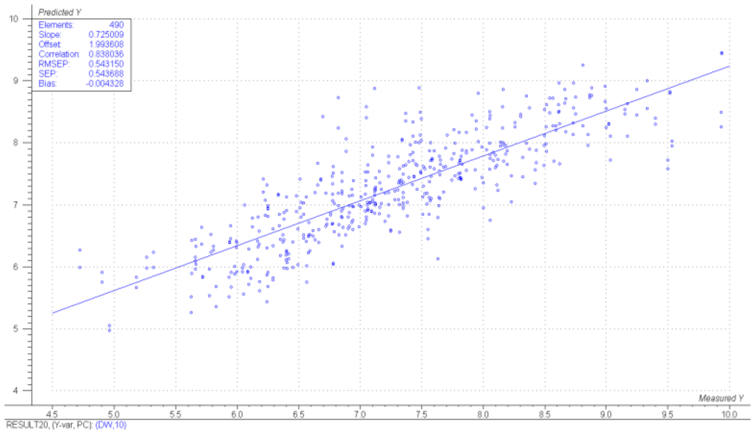

Figure 6. DM: Regression model for total dry matter (DM) prediction non-destructively using Nirvana hand-held NIR.

While the methodology was not used further in the project, the validation trials demonstrated that it has potential as a tool to non-destructively evaluate dry matter and %brix changes in fruit during crop development and so could be used in trials focused on improving fruit quality.

Plant and Soil assessments

Small plot harvests and plant physiology measurements were taken at the Geltch site in years 2, and both sites in year 3, to test the hypothesis that 'oxygation' enabled the plants to continue photosynthesizing more efficiently late in crop development, thus enabling a greater proportion of the fruit on each plant to ripen (increasing yield) while also supporting dry matter accumulation in all ripe fruit (increasing brix). This hypothesis was based on the observed increase in both yield and brix in the 'oxygation' treatment in the season 1 (2013) trial.

Similar results were recorded at both sites and in both seasons. Data from the second season at the Geltch site is shown below to highlight the trends. Hand harvesting of 5 individual plants in each plot was completed approximately two weeks prior to commercial harvest. Fruit from each plant were separated into green and red fruit, counted and weighed.

Table 6. Mean fruit number and weight per plant in different blocks (Geltch site, 2014/15 season).

Treatment	Block	Red fruit		Green fruit		Stems/leaves
		no.	wt (kg)	no.	wt (kg)	wt (kg)
Control	1	60.6	2.31	17.5	0.45	0.59
Control	2	64.0	2.34	17.2	0.47	0.61
Control	3	67.8	2.77	14.3	0.43	0.63
Oxygation	1	56.4	2.26	17.5	0.46	0.59
Oxygation	2	60.3	2.32	17.0	0.48	0.62
Oxygation	3	69.4	2.94	13.5	0.41	0.63

The small plot hand harvest data were consistent with the machine harvest data, with highest fruit numbers and weights in Block 3 for both 'oxygation' and 'control'. Plant weight was also slightly higher in this section of the paddock. The plants in Block 3 appeared more mature than those in Blocks 1 and 2, with lower green leaf area.

Block 1 Block 2 Block 3

Figure 5. Appearance of plants prior to harvest (Geltch site, 2014/15 season).

Measurement of photosynthetic efficiency (photosynthetic quantum yield) and leaf transpiration rate was completed on plants in Block 1 at the Geltch site in seasons 2 and 3 over 3 successive days, with measurements taken at approximately 10am each day. No difference in quantum yield (0.641 and 0.643 for 'control' and 'oxygation' respectively in season 2, 0.697 and 0.692 in season 3) was found. A slight increase in transpiration rate, from 2.41 to 2.46mmol/m^2/s for 'control' and 'oxygation' respectively, was found in season 2, suggesting that the 'oxygation' treatment was allowing plants to maintain a higher rate of carbon dioxide uptake (corresponding to the higher rate of transpiration or water loss) in the later stages of crop development. A smaller increase, from 2.53 to 2.56mmol/m^2/s was found in season 3. It is therefore plausible that plants receiving 'oxygation' may be able to maintain or increase brix levels when yield is also increased through this mechanism of enhanced photosynthetic carbon uptake during the later stages of crop maturation.

Differences in soil wetting front patterns in different blocks at the Geltch site

Yields assessments in the second season of the project documented a gradient in yield within each site, with higher yields recorded in the regions towards the end of the drip irrigation lines. This masked any 'oxygation' treatments effects as within-crop variability was much greater than any 'oxygation' treatment effect that may have existed. The causes of the yield gradient within the crops were not immediately evident, but variations in soil type and/or in rate of irrigation water delivery are possible explanations. Operation of irrigation systems at higher or lower than optimal water pressure could result in small changes in drip emitter uniformity along long drip line lengths, while biofouling or scaling within subsurface driplines over time can reduce drip emitter uniformity. Assessment of the pattern of soil wetting above, beside and below the drip line was undertaken in the third season at the Geltch site to determine if large differences between positions in the paddock were evident. Volumetric water content was recorded at a point 15cm along the drip line from an emitter in the 'control' treatment in block 1 (closest to the submain) and block 3 (near the end of the drip line), with 5 replicate sampling positions in each block.

Differences in wetting front patterns were recorded between soil in the areas closest to and furthest away from the irrigation submain, with more rapid wetting occurring during irrigation in the latter area.

Table 7. Soil volumetric water content before (0 hr) and during (2 and 4 hr) and irrigation event (Geltch site, 2014/15 season).

Position relative to drip line	Block	0 hr	2 hr	4 hr
5cm above	1	16.5%	18.4%	25.5%
Adjacent	1	16.9%	23.1%	28.0%
10cm below	1	17.1%	25.1%	29.7%
5cm above	3	16.6%	19.1%	28.7%
Adjacent	3	17.0%	26.2%	32.4%
10cm below	3	17.1%	27.6%	32.2%

Further investigation would be required to prove a link between differences in wetting front patterns within the paddock and crop yields in different blocks, and to identify causes of differences in wetting front patterns, but this preliminary investigation does suggest that crop yield gains may be made by improving efficiency and uniformity of irrigation in processing tomatoes. The scale of variation in yield along the length of the drip lines at both sites was much greater than the mean difference in yield between 'control' and 'oxygation' treatments, suggesting that research focus on increasing irrigation uniformity is an area that the industry should consider.

Outcomes

The project demonstrated that 'oxygation' was not a cost effective technology for processing tomato growers to use to increase yield and quality of their crops. At commencement, an anticipated outcome of the project was that, if the technology was shown to be effective, growers would have adopted the technology by the time the project was completed. While the results did not support this adoption, the provision of scientific evidence to demonstrate lack of efficacy does provide growers with independent assessment of the technology.

The high within crop variability recorded in the project, and the preliminary study evidence of a lack of uniformity in irrigation water distribution along long drip-lines, has provided the industry with a direction for future research. Further research to confirm that yield gradients in paddocks are related to irrigation outputs, and development of strategies to optimize drip irrigation systems on farms, may lead to large production gains given the size of the variability recorded in this project.

Evaluation and Discussion

The project assessed the effects of increased dissolved oxygen concentration in irrigation water supplied through a subsurface drip irrigation system on yield and fruit quality in processing tomato crops. Small changes in plant physiological responses were found in the 'oxygation' treated plants and these changes were consistent with the underpinning theory that increased oxygen supply to the roots of the plants during the period of transient waterlogging as the wetting front moves through the soil from the drip emitters in an irrigation event will support improved plant growth. In this study, transpiration rate and photosynthetic quantum yield remained higher in plants late in crop development. There are a number of mechanisms by which this response could have been caused, including reduced root loss through either disease proliferation or senescence of feeder roots, and increased capacity of roots to supply leaves with nutrients associated with leaf functionality. While of interest from a plant function perspective, the responses were relatively small and given the large variations in plant performance associated with other variables in the commercial crops the scale of response was not sufficient to induce a commercially or statistically significant increase in yield or fruit quality.

The 'oxygation' treatment did not increase crop yield or improve the quality of the fruit harvested. A total of 5 trials were conducted in the project at 2 locations over 3 seasons, with a slightly higher but not statistically significant increase in yield recorded in the 'oxygation' compared to 'control' treatment in 4 of the trials. The fifth trial resulted in a statistically significant reduction in yield in the 'oxygation' treatment compared to the 'control', but a failure in the GDS system meant that the 'oxygation' treated plants did not receive higher %DO irrigation water for the duration of the trial, so that result was disregarded.

Much greater yield differences were noted between different areas within the trial site paddocks than between the two treatments imposed in the project. A consistent yield gradient was recorded along the irrigation lines, with a higher yield recorded at the far end of the irrigation line than in the section of the paddocks closer to the submain to which the drip lines were attached. A preliminary assessment conducted in the final season of the project suggested that differences in soil properties and/or emitter efficiency may have contributed to the within-paddock variability. Clogging of drip emitter by organic or inorganic material in the irrigation lines is a known issue in sub-surface drip irrigation systems and may have contributed to variability.

The cost of installation of the equipment required to deliver 'oxygation' is high, with a GDS system capable of supply a commercial block of processing tomatoes quoted in this project at over $100,000. The GDS systems are relatively cheap to operate after initial capital investment as the oxygen injected into the irrigation water is extracted from the air by the equipment so only electricity and maintenance costs need to be factored in for system operation. Equipment malfunctions, as occurred with the GDS equipment in this project, are an additional consideration when using the equipment. In comparison, the direct injection system is very simple to operate and is unlikely to suffer from mechanical failure. The initial capital cost is also much lower, at less than $20,000 for a system capable of supplying a commercial block, but requires a supply of bottled, compressed gas or liquid oxygen to connect to the aeration cone. An additional benefit of the direct injection system is the capacity to use ozone or hydrogen peroxide in the system to reduce clogging of emitters in the drip lines to improve uniformity of irrigation along the drip lines.

The examination of a technology considered at the commencement of the project as having potential to significantly increase yield in processing tomato crops has demonstrated to the industry that 'oxygation' is not a commercially viable option. The trials were conducted in commercial crops at a scale that provides confidence in this conclusion. While measurable changes in plant physiology occur when exposed to high %DO irrigation water, the scale of the yield response is small relative to the many other factors that can influence yield and that are causing variability in yield throughout commercial paddocks. Crop management and further research attention to these factors is needed to reduce yield variability within crops and increase overall crop yield.

Recommendations

The major conclusion drawn from the project is that 'oxygation' is not a commercially viable technology for the processing tomato industry to use to increase crop yield and fruit quality, and therefore it is recommended that growers do not invest in this technology. Results from the study suggest that lack of uniformity of drip emitter efficiency may be contributing to yield variability within paddocks, and it is recommended that the industry further investigate this aspect of irrigation management.

Intellectual Property/Commercialisation

No commercial IP generated

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