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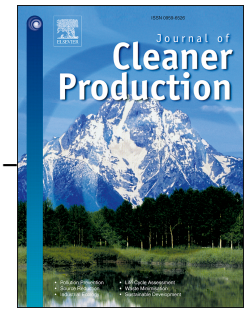

Anaerobically digested brewery effluent as a medium for hydroponic crop production – The influence of algal ponds and pH

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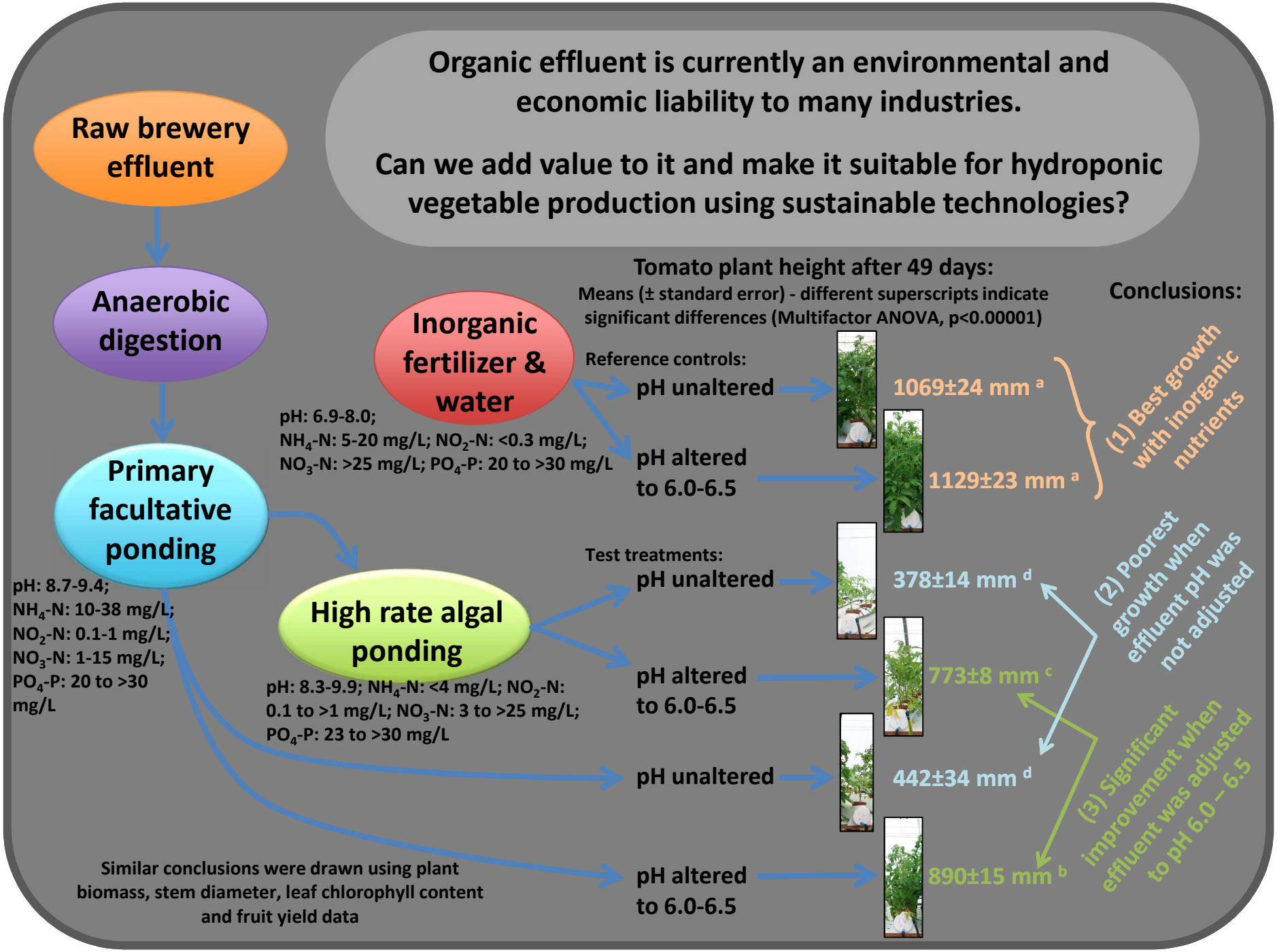
Organic effluent is currently an environmental and economic liability to many industries.
Can we add value to it and make it suitable for hydroponic vegetable production using sustainable technologies?
Raw brewery effluent
Anaerobic digestion
Primary facultative ponding
pH: 8.7-9.4;
NH4-N: 10-38 mg/L;
NO2-N: 0.1-1 mg/L;
NO3-N: 1-15 mg/L;
PO4-P: 20 to >30 mg/L
High rate algal ponding
pH: 8.3-9.9; NH4-N: <4 mg/L; NO2-N: 0.1 to >1 mg/L; NO3-N: 3 to >25 mg/L; PO4-P: 23 to >30 mg/L
Inorganic fertilizer & water
pH: 6.9-8.0;
NH4-N: 5-20 mg/L; NO2-N: <0.3 mg/L;
NO3-N: >25 mg/L; PO4-P: 20 to >30 mg/L
Tomato plant height after 49 days:
Means (± standard error) - different superscripts indicate significant differences (Multifactor ANOVA, p<0.00001)
Reference controls:
pH unaltered
1069±24 mm a
pH altered to 6.0-6.5
1129±23 mm a
Test treatments:
pH unaltered
378±14 mm d
pH altered to 6.0-6.5
773±8 mm c
pH unaltered
442±34 mm d
pH altered to 6.0-6.5
890±15 mm b
Conclusions:
(1) Best growth with inorganic nutrients
(2) Poorest growth when effluent pH was not adjusted
(3) Significant improvement when effluent was adjusted to pH 6.0 – 6.5
Similar conclusions were drawn using plant biomass, stem diameter, leaf chlorophyll content and fruit yield data

Word count: = 5822

Anaerobically digested brewery effluent as a medium for hydroponic crop production – The influence of algal ponds and pH

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Abstract

Millions of mega-litres of nutrient-rich effluent are discharged daily with environmental implications and often at considerable financial cost to the primary water user. This research aimed to develop technology that adds value to this liability, by making the effluent available for downstream use in hydroponic crop production.

Brewery effluent subject to anaerobic digestion (AD) followed by treatment in a primary-facultative pond (PFP), contained sufficient nutrients to support the growth of *Lycopersicum escolentum* "Moneymaker" tomatoes. None of the effluent-grown plants performed as well as plants grown in inorganic-fertilizer and municipal water. However, the adjustment of the effluent pH with phosphoric acid to between pH 6.0 and 6.5 significantly increased plant growth compared to those in unaltered effluent. The pH adjusted effluent-grown plants grew to a mean height of 831 ± 21 mm and a dry biomass weight of 42.3 ± 2.8 g compared to the unaltered pH effluent plants which grew to half the height (411 ± 21 mm) and about a fifth of weight (7.7 ± 0.7 g) after 49 days. Similarly, initial fruit production was higher for plants grown in pH adjusted effluent compared with those with no pH control. Effluent treatment in high-rate algal ponds (HRAP) prior to use in the hydroponic tomato system had no apparent benefits. Although the tomato plants grown in treated brewery effluent did not perform as well as those produced using inorganic fertiliser, the potential exists to use the water and nutrients in brewery effluent in downstream hydroponic production after AD and PFP treatment, particularly if the pH is maintained between 6.0 and 6.5.

Keywords: constructed wetland; beneficiation; nutrient recovery; wastewater recovery; tomato production

Highlights (if the number of characters is limited to 85 per highlight)

- Brewery effluent can be used as a hydroponic water and nutrient source
- Growth using effluent is inferior compared to plants grown in inorganic fertiliser
- Growth and fruit yield improved when pH of the effluent was maintained at 6.0–6.5
- There is potential for hydroponics in organic effluent downstream of industry
- There is a potential market for organic effluent, which is currently a liability

Highlights (if the total number of characters is limited to 85)

- Brewery effluent can be used as a hydroponic water and nutrient source if pH is maintained at 6.0–6.5

1. Introduction

Water scarcity is a growing challenge, particularly in developing countries or water stressed areas (Arnell 2004; Department of Water Affairs 2012; WWF-SA 2013). This research, conducted in a water scares area at a brewery in Port Elizabeth, South Africa, describes the potential for an alternative use for brewery effluent that could contribute to industrial resource efficiency and cost reduction among similar industries that produce an organic effluent stream. Extracting the maximum value from a given unit of water is a possible strategy to mitigate water and resource stress. This value maximisation principle applies in any region of the world, to industry or any resource experiencing a stress, scarcity, or pursuing economic and environmental efficiency.

Industrial breweries around the world are significant water consumers, producing between 4-6 hl of wastewater per hl of beer produced, with a global production of roughly 1.8 billion hl in 2010 (Fillaudeau *et al*. 2006; Brito *et al*. 2007; Ascher 2012). This effluent requires treatment before disposal into the environment, contributing to the financial and energy operating costs of the brewery. The effluent at this brewery, like many food and beverage processing facilities around the world, is treated in an onsite anaerobic digester (AD); however, at this facility a small part of the AD effluent stream is drawn into an experimental treatment system consisting of a primary facultative pond (PFP) and a high-rate algal pond (HRAP) system as part of an alternative wastewater treatment experiment. This particular brewery currently discharges around 1500 hl, roughly 65% of the total volume of bought-in water, of anaerobically digested brewery effluent per day to the municipal treatment works, at a cost of US$ 0.85 per kl (Mabuza *pers. comm*. 2012), in keeping with the discharge of breweries around the world. This is the volume of water potentially available for hydroponic production from just one facility. Developing an alternative use for this effluent stream could

save the brewery up to US$ 1000.00 per day in municipal water discharge costs alone as well as provide numerous benefits for society and the environment through crop production and improved water and nutrient management.

Anaerobic digestion is a cascade of biological conversion processes, which break down biodegradable organic matter into its most oxidised or reduced forms (Speece 1983; Batstone *et al*. 2002; Angelidaki and Sanders 2004). Organic carbon is converted into methane (CH_4) and carbon dioxide (CO_2), and other mineralised or constituent elements are released including ammonia (NH_3) and phosphate (PO_4) (Batstone *et al*. 2002; Angelidaki and Sanders 2004; Sötemann *et al*. 2005). Anaerobic digestion is a popular treatment technology because of its low energy inputs, low sludge production, and the opportunity to recover energy from the produced biogas (Tauseef *et al*. 2013). The residual nitrogen (N) and phosphorus (P) nutrient load in the AD effluent stream can pose a threat to the environment and usually requires further treatment, typically through energy intensive or financially expensive processes with their own cost-efficiencies to consider (Samuelsson *et al*. 2007).

Much attention has been directed towards the use of plants and wetlands for effluent management or nutrient removal from municipal and industrial wastewaters (Zurita *et al*. 2009; Melián *et al*. 2010; Calheiros *et al*. 2012). Effluent management and treatment objectives can also be combined with a process to derive some value from the effluent through, for example, cut flower or biomass production (Konnerup *et al*. 2009; Zurita *et al*. 2009). This is the first time that a study has applied these techniques to produce tomato plants in brewery effluent.

Generally, higher vascular plants require 17 ‘essential elements’ to grow and reproduce (Epstein and Bloom 2004; Freeman 2005). In hydroponics, solution pH is known to affect the

form and bioavailability of various nutrients and consequently plant development (Lucas and Davis 1961; Bar-Yosef *et al*. 2009; Zhao *et al*. 2013). The high pH of the brewery effluent as it moves through the HRAP treatment system (±8.5 before and up to ±9.5 after the HRAP) probably accounted for reduced nutrient bioavailability and plant performance in lettuce crops grown previously in this treated effluent (Jones *et al*. 2011; Jones *et al*. 2014). The effect of manipulating brewery effluent pH to make nutrients available to the plants needed investigation.

The objectives of this work were to compare the vegetative growth rate of tomato plants grown in brewery effluent drawn from different points in the algal ponding treatments system, with and without pH adjustment to plants grown using a conventional inorganic hydroponic solution. There was no literature available which concerned the use of brewery effluent as a hydroponic nutrient solution for tomato production so this trial was designed as a preliminary study into the relationship between hydroponically-grown tomato plants and brewery effluent. It would have been premature to attempt to produce a fruit crop without first assessing the fundamental relationship between the plant and the alternative nutrient source.

2. Methods and materials

A multifactor experiment was designed where nutrient solution (factor 1) was tested in conjunction with pH adjustment (factor 2). Brewery effluent, as the nutrient solution, was drawn either (a) after the effluent had undergone treatment in the AD and PFP (post-PFP; Table 1) or (b) after it had undergone treatment in the AD, PFP and the high rate algal ponds (post-HRAP; Table 1). The effluent systems were also compared to (c) control treatments

comprised of commercially available hydroponic inorganic-fertilizer (Hygrotech®; Registration number K5709; Act 36 of 1947, South Africa), and calcium nitrate (11.7% nitrogen and 16.6% calcium), mixed in a ratio of 1:0.8 and dissolved in municipal water to achieve an EC of 2000 $\mu S.cm^{-1}$ (Hygrotech (Pty) Ltd., South Africa). Each of these three nutrient solutions were either subject to (a) pH adjustment to between 5.8 and 6.5 with 80% phosphoric acid (Protea Chemicals (Pty) Ltd., South Africa) or (b) their pH was left unaltered (i.e. factor 2), which resulted in a total of six treatments.

Each treatment was replicated five times, with a total of 30 independent recirculating hydroponic systems making up the full experiment. Each system consisted of one 1500 mm long tubular polyvinylchloride (PVC) growth channel with a diameter of 160 mm. This channel supported five 120 mm diameter common plastic garden pots. Each pot was perforated with 5.0 mm holes and filled with 10 mm diameter quartz gravel. The growth channels that supported the pots were placed on a table in a greenhouse tunnel. The nutrient solution for each channel was contained in a 30 l plastic sump placed on the ground at the foot of each channel. This solution was pumped from the sump to each pot, using an 18 watt submersible aquarium pump (Resun®, Model: SP-2500, China) and a 15 mm delivery line. A micro-valve at each pot was used to ensure an even irrigation rate into each pot. The nutrient solution drained through the gravel of the pot by gravity into the growth channel, which drained back to the sump. The drain in the growth channel was adjusted to create a submerged zone for the root system that was approximately 50 mm deep.

There was no climate, photoperiod or light intensity control available in the tunnel. The tunnel was located at -33.835594 °S, 25.541070 °E. The mean time of sunrise and sunset over the trial (26 September 2012 - 14 November 2012) was 05:28 AM and 6:36 PM respectively.

Solanum lycopersicon tomato plants were germinated from commercially available seed ("Moneymaker" Starke Ayres, South Africa). At least two seeds were sown in 36 mm diameter, peat pellets (Jiffy-7, Jiffy®, Canada) with at least 400 seeds sown across 200 pellets. The pellets were distributed evenly between three miniature plastic greenhouses (Jiffy®, JiffyPro 70 Self-Watering Greenhouse, Canada). The pellets were soaked in municipal water before the seeds were sown and irrigated when necessary. Two weeks after sowing, the smaller seedling was cut to allow the larger seedling to thrive. Four weeks after germination the seedlings were transplanted into the 120 mm pots and surrounded with gravel. The 150 plants were randomly allocated to the various treatments and exposed to their particular nutrient solutions for the first time. The plants were grown solely on their treatment's nutrient solution for the next 49 days. The nutrient solutions were periodically replaced with fresh solutions and the old solutions were discarded.

The NH_4^+-N, NO_3^--N and PO_4-P concentration in the nutrient solution of each replicate was recorded before and after the solution was replaced on each occasion. This was carried out on filtered samples (8.0 µm), using a spectrophotometer (Merck Spectroquant Pharo 100, product number 100706, Darmstadt, Germany) and commercial test kits (Merck Pty Ltd, products: 1.14559.0001, 1.14752.0001 and 1.09713.0001 respectively). It was not possible to determine dilution ratios for each of the parameters and each of the treatments when the tested parameter exceeded the range of the test because of the time required for each test and the number of samples that needed testing. Values that were above the maximum range of the test were recorded as the maximum.

Electrical conductivity (EC) and pH were measured with a pH/EC/total dissolved solids probe (Hanna, HI 991300, United Kingdom). Readings were taken when the solutions were replaced on fresh and discarded solutions.

The average pH values were calculated by converting the pH readings to H^+ concentrations with the formula below where x is the recorded pH value.

$$H^+ = 10^{-x}$$

The H^+ concentration values were then averaged for each treatment and the mean H^+ value was converted back to a pH value using the following formula:

$$pH = -\log(H^+)$$

Plant height and basal stem diameter were measured at the start, once a week during, and at the end of the trial, to the nearest millimetre with a tape measure and digital Vernier callipers respectively. All the plants were measured in a single session when measurements were recorded. The chlorophyll concentration index (CCI) was calculated on days 2, 6, 8, 14, 20, 22 , 26, 34, 35, 41 and 42 of the experiment, by recording the chlorophyll content of the uppermost fully expanded leaf of each plant using a chlorophyll meter (CCM-200 Plus Chlorophyll Content Meter, Opti-Sciences Inc., USA). At the end of the trial the number of fruit that were present on each of the plants was recorded. At this time the plants were separated into root biomass and aboveground biomass, the samples were oven dried (Scientific, Series 9000) at 80 °C for 72 h (Borgognone *et al*. 2012) and the dried mass was weighed on a four-digit analytical balance.

Individual plant data were averaged among the five plants in each of the 30 hydroponic systems, and the mean value for each hydroponic system was used in all further analyses (n=30). These raw data were tested for homogeneity of variance (Levene's test; $p<0.05$) and normality of the residuals (Shapiro-Wilk W-test; $p<0.05$). A multifactor analysis ANOVA of the growth indices mentioned above was used to establish if there were interactions between factors (factors: water source and pH regime), at $p<0.05$. If there were no interactions, each

factor was analysed separately with a one-way ANOVA, and Tukeys multiple range analysis was used to compare means among the treatments within each factor, at $p<0.05$. Data that were collected from the same treatments over the course of the trial were compared using repeated measures ANOVA, at $p<0.05$. All statistical analyses used Statistica 64 version 11 (StatSoft Inc., Tulsa, United States of America).

3. Results

There were no plant fatalities among the effluent-irrigated plants indicating that this brewery effluent contains the essential elements needed for Moneymaker tomatoes to survive.

Plant height was affected by a significant interaction between nutrient solution and pH adjustment (Multifactor ANOVA, $F_{(2,24)}=47.78$, $p<0.00001$; Figure 1). There was a significant difference in the mean plant height of the pH corrected effluent systems (T3: 443 ± 34 mm versus T4: 890 ± 15 mm, and T5: 378 ± 14 mm versus T6: 773 ± 8 mm; Figure 1), whereas the addition of acid did not have a significant effect on the mean plant height of the inorganic-fertilizer control treatments. There was no significant difference between the plant height of the pH uncorrected effluent treatments. The pH adjusted post-PFP plants grew significantly taller than the plants grown in pH adjusted post-HRAP effluent (T4: 890 ± 15 mm versus T6: 773 ± 8 mm; Figure 1). Similar interactions and trends were found for both basal stem diameter and the accumulation of leaf and shoot biomass (Multifactor ANOVA, $F_{(2,24)}=10.59$, $p=0.0005$ and $_{(2,24)}=11.06$, $p=0.00039$, respectively; Table 2). However, there was no interaction between pH adjustment and nutrient solution in the accumulation of dry root biomass (Multifactor ANOVA, $F_{(2,18)}=2.36$, $p=0.12$). The grouped mean of the control systems developed significantly more root biomass than the effluent sources (ANOVA,

$F_{(2,18)}$=186.05, p<0.00001; Table 2). As with the other parameters, the addition of phosphoric acid was also a significant factor with the pH adjusted treatments developing significantly more root biomass than the pH unaltered systems (pH adjusted 54.54 ± 9.14 g.system^{-1}, pH unaltered 36.64 ± 9.77 g.system^{-1}; ANOVA, $F_{(1,18)}$=32.14, p=0.00002; Table 2).

Chlorophyll concentration index was influenced by a significant interaction between nutrient solution and pH adjustment. The CCl increased over the period of the experiment in all treatments, with the exception of plants grown in post-HRAP with no pH adjustment, where CCl decreased over the period of the trial (Repeated measures ANOVA, $F_{(20,240)}$=9.36, p<0.00001; Figure 2). There was no significant difference in mean CCI recorded at the end of the trial between the two inorganic-fertilizer treatments (T1 and T2) and the pH corrected post-PFP effluent treatment (T4), and these were all significantly higher than the other treatments (Figure 2). The pH correction in the effluent treatments resulted in a significantly higher CCI compared to plants grown in the same effluent, but without pH correction (Figure 2).

The mean number of fruit produced per plant at the end of the trial was not influenced by a significant interaction between nutrient solution and pH adjustment (Multifactor ANOVA, $F_{(2,24)}$=2.51, p=0.127; Figure 3). Nutrient solution on its own, however, had a significant effect on fruit production, where plants subjected to inorganic fertiliser produced significantly more fruit (3.6±0.5 to 3.8±0.9 fruit.plant^{-1}) compared to those grown in treated brewery effluent (ANOVA, $F_{(2,24)}$=21.00, p=0.0001). Plants grown in effluent without pH adjustment produced an average of 0.6 fruit.plant^{-1} (i.e., a range from 0 to 1 fruit.plant^{-1}) whereas those grown in effluent where the pH was maintained between 6.0 and 6.5 produced an average that ranged between 1.2 and 3.2 fruit.plant^{-1} within the period of the experiment (Figure 3).

There were differences between the water quality in the nutrient solutions between water source and pH adjustment factors. The post-HRAP solutions had the highest EC values, and T6 had the highest mean pH. The effluent treatments without phosphoric acid had higher mean pH values than the effluent treatments which received phosphoric acid (Table 3).

Post-PFP solutions had higher ammonium-nitrogen levels while the post-HRAP and fertilizer treatments had higher nitrate-nitrogen levels (Figure 4). The acid-corrected effluent treatments had final ammonium-nitrogen concentrations below 5.0 $mg.l^{-1}$ and nitrate-nitrogen concentrations below 6.0 $mg.l^{-1}$ in the waste solutions, apart from the reading in T4 taken from the first solution replacement (Figure 4). The brewery effluent was highly alkaline, requiring around 25 ml of 80% phosphoric acid to achieve a pH reduction into the range 5.8-6.5 for 25 l of effluent while the municipal systems required only 2.5-3.0 ml of acid per 25 l. The phosphate-phosphorus levels were not reduced to low concentrations in any of the treatments, suggesting the effluent as a fertilizer was not phosphorus limited. The acid corrected effluent treatments consistently had readings above the range of the test.

4. Discussion

The results confirmed that brewery effluent can support the vegetative growth of *Moneymaker* tomatoes and the early development of fruit. The manipulation of the effluent pH with phosphoric acid significantly improved the vegetative growth and development of the plants in all the parameters measured (stem diameter, plant height, dry biomass and CCl) and increased the number of fruit produced per plant in the period of the trial. The improvement in biomass accumulation was notable with the pH adjusted effluent plants accumulating well over 200% more dry mass than the pH unaltered effluent plants, and pH

adjustment also doubled the number of fruit that appeared on the plants within the 49 days of the experiment. The effluent plants did not grow as well as the fertilizer plants which suggests that the effluent system contained nutrient deficiencies, toxicities or plant stresses inhibiting the growth of the plants.

The acid corrected effluent plants were consuming nearly all of the available nitrogen (as nitrate and ammonium) in the effluent however phosphate levels remained high, which was to be expected given the addition of phosphoric acid. The plants irrigated with effluent drawn from after the PFP received nearly all the available nitrogen as ammonium due to the anaerobic digestion process (Batstone *et al*. 2002; Angelidaki and Sanders 2004; Sötemann *et al*. 2005). Despite being a primary source of nitrogen, ammonium-rich or exclusive nutrition has been shown to negatively influence the development of some plants through ion competition and exclusion or stress of key micronutrients (Britto and Kronzucker 2002; Horchani *et al*. 2010; Borgognone *et al*. 2012). Ammonium induced cation deficiency has been suggested to present secondary stresses in, among others, three essential elements; potassium, calcium, and magnesium in numerous studies and plants (Salsac *et al*. 1987; Gloser and Gloser 2000; Britto and Kronzucker 2002; Horchani *et al*. 2010; Borgognone *et al*. 2012). These nutrient stresses, along with the nitrogen limitation suggested by the near complete removal of nitrogen from the pH adjusted effluent systems and their restricted physical development, may have inhibited the development of the plants compared to those grown in fertilizer. Optimizing the nutrition of the crop needs to be addressed in further work.

The presence of ammonium in the effluent may have increased the CCI of the post-PFP irrigated plants. The readings over the course of the trial showed that the ammonium-rich post-PFP effluent plants had an equal or higher CCI than the other treatments. A positive correlation has been demonstrated between external ammonium concentration and the

chlorophyll concentration in tomato plants (Horchani *et al*. 2010). The effluent contains less nitrogen than the inorganic-fertilizer mixture, which would explain the lower CCI for post-post-HRAP effluent plants than those in the control systems. The slightly elevated CCI in the unaltered pH post-PFP treatment (T3) are likely due to the uptake of ammonium, however the high pH stress on nutrient uptake meant that these plants could not assimilate nitrogen as was seen in the wastewater quality results, and they were probably experiencing other pH-induced nutrient stresses (Lucas and Davis 1961).

The high alkalinity of the effluent is probably due to upstream injections of sodium hydroxide (NaOH) as a pH buffer during the neutralisation of the raw brewery effluent prior to anaerobic digestion and the AD itself, which is a source of carbonate alkalinity. The CO_2 generated in the AD partially dissolves in the digester liquor, generating carbonate alkalinity and carbonic acid (Batstone *et al*. 2002; van Rensburg *et al.* 2003). When the digested effluent is exposed to normal atmospheric partial pressure after leaving the AD, the volatile carbonic acid is stripped and the effluent loses acidity but the carbonate alkalinity remains (Musvoto *et al*. 2000; van Rensburg *et al.* 2003). This residual alkalinity contributes to the high pH and the volume of acid needed to reduce to pH to optimum levels. The influence of pH adjustment on plant growth is clearly shown in the results. Optimising the pH of the effluent will be a key step in developing a practical hydroponic system and understanding the sources of alkalinity will be an important factor in addressing the pH adjustment.

Water used in the production of crops for human consumptions needs to be pathogen free. This work did not investigate the microbial content of the treated brewery effluent; a more detailed account of the microbial content of the treated brewery effluent is presented by Mogane (2016). However, the brewery practices complete physical segregation of beer manufacturing effluent from the sewage system, because water recovery is practiced at this

facility and recovered water cannot come into contact with sewage or any other potentially contaminated effluent. As such, it is unlikely that a hydroponic vegetable crop grown in this effluent would be exposed to pathogenic bacteria that would render them unsafe for human consumption. Furthermore, HRAP systems are efficient at removing pathogens from sewage (Gaigher *et al.* 1985; El Hamouari *et al.* 1994; Craggs *et al.* 2004). This is probably due to a combination of the high pH and high dissolved oxygen concentrations in the algal ponds and due to exposure to sunlight (Oswald 2003). Algal ponding systems have been successful at the complete removal of nematodes and *Salmonella sp.* from human sewage (El Hamouari *et al.* 1994) and were more efficient at reducing ammonia, phosphate and *Eschericea coli* than that of conventional two-stage oxidation ponds in the treatment of dairy effluent (Craggs *et al.* 2004). If this technology were used in industry where there was a chance of contamination of the effluent prior to its use a hydroponic nutrient and water source, the HRAP system could be used as a step in the treatment process to counter this concern without compromising downstream hydroponic crop yields, provided the pH of the post-HRAP nutrient solution was adjusted to pH 6.0–6.5.

5. Conclusion

Tomato plants can be grown in anaerobically digested brewery effluent, and the adjustment of the effluent pH significantly improved their vegetative growth with those plants reaching a height that was, on average, double the height of plants grown without pH adjustment. However, effluent grown tomatoes did not grow as well as those produced using inorganic fertiliser since these were significantly larger than all effluent grown plants. There are

broader nutrient deficiencies or stresses that were probably responsible for this, which should be addressed in future work.

The treated brewery effluent is highly alkaline with a pH that ranged from 8.3 to 9.9, which is a consequence of numerous upstream factors including the anaerobic digestion of the raw effluent. Managing the effluent alkalinity, nutrient deficiencies and limiting downstream nutrient releases are the key challenges to using brewery effluent as a hydroponic water resource.

The experimental HRAP system did not improve the suitability or nutritional potential of the brewery effluent as a nutrient source for tomato production, since stem diameter, weight and height of the plants grown in post-HRAP effluent were similar to those grown in effluent that was only subject to treatment in the PFP. Therefore, it is suggested that the HRAP system is not needed if the effluent is to be used as a hydroponic nutrient solution, provided the effluent is free of pathogenic microbes because the HRAP can remove such pathogens.

Future research should focus on effluent drawn directly from the PFP or the AD, crop selection, and optimising the nutrient profile and pH of the effluent. The hydroponic system must address its first objective as part of a nutrient removal effluent treatment system, so balancing the nutritional requirement of the crops must be achieved without creating downstream pollution problems. The residual phosphate concentrations were above the freshwater discharge limits, demonstrating that alternative methods of lowering the AD-treated effluent's pH will have to be explored because the addition of phosphoric acid caused an excess of phosphate in the spent solutions.

Brewery and other organic effluent streams could represent an alternative nutrient and/or water resource for communal or commercial hydroponic vegetable production, but this would

need to be tested on a pilot scale first. This work demonstrates the relative simplicity of an opportunity for adding value to what was considered a costly liability to the primary water user. The work also highlights the significance of pH adjustment in improving the growth of effluent-grown tomatoes by more than 100% compared to unadjusted effluent-grown tomatoes. The research is the first exploration of a concept where value is added to brewery effluent by using it to produce crops in water stressed areas where food security remains a concern.

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Figure Captions

Figure 1 The mean (±95% confidence interval) height of *Moneymaker* tomato plants subject to treatments of municipal water and fertilizer (Control), or brewery effluent drawn after treatment in the experimental treatment system's primary facultative pond (Post-PFP) or high rate algal pond (Post-HRAP), each of which were subject to pH correction with phosphoric acid or the pH was left unaltered, for 49 days (Multifactor ANOVA, $F_{(2,24)}$=47.78, $p<0.00001$).

Figure 2 The mean (± standard error) chlorophyll concentration index (CCI) of *Moneymaker* tomato plants grown in municipal water and inorganic-fertilizer (Control; T1 and T2), post-primary facultative pond effluent (PFP; T3 and T4), or post-high rate algal pond effluent (HRAP; T5 and T6). Treatments T2, T4 and T6 were subject to pH adjustment with phosphoric acid. (Repeated measures ANOVA, $F_{(20,240)}$=9.36, $p<0.00001$).

Figure 3 The mean number of tomato fruits produced per plant in each of the thirty systems after 49 days. The plants were grown in either municipal water and inorganic-fertilizer (T1 and T2), post-primary facultative pond effluent (post-PFP; T3 and T4), or post-high rate algal pond effluent (post-HRAP; T5 and T6); treatments T2, T4 and T6 were subject to pH adjustment with phosphoric acid. The R-numbers in the X-axis labels refer to the replicate number of each treatment and these data are the average number of fruit on the five plants in each replicate.

Figure 4 Ammonium-nitrogen (NH_4^+-N mg.l^{-1}), nitrate-nitrogen (NO_3^--N mg.l^{-1}) and phosphate-phosphorus (PO_4-P mg.l^{-1}) levels from fresh samples (left) and samples from irrigation solutions just prior to being replaced (right) (n=12 for each treatment). The treatment solutions indicated are: T1 and T2 – municipal water and inorganic-fertilizer, T3 and T4 – post-primary facultative pond effluent (post-PFP), and T5 and T6 – post-high rate algal ponds effluent (post-HRAP). Treatments T2, T4 and T6 were subject to pH adjustment with phosphoric acid. Horizontal lines on graphs indicate the upper concentration limit of the test.

Table 1 The minimum, maximum and mean phosphate, phosphorus, ammonium, nitrite, natrate, chloride, electical conducitivity (EC) and chemical oxygen demand (COD) of brewery effluent after anearobic digestion and treatemnt in the primary facultative pond (post-PFP) and after anearboicc digestion and treatment in the PFP followed by treatemnt in the high rate algal pond (post-HARP) (Power 2014).

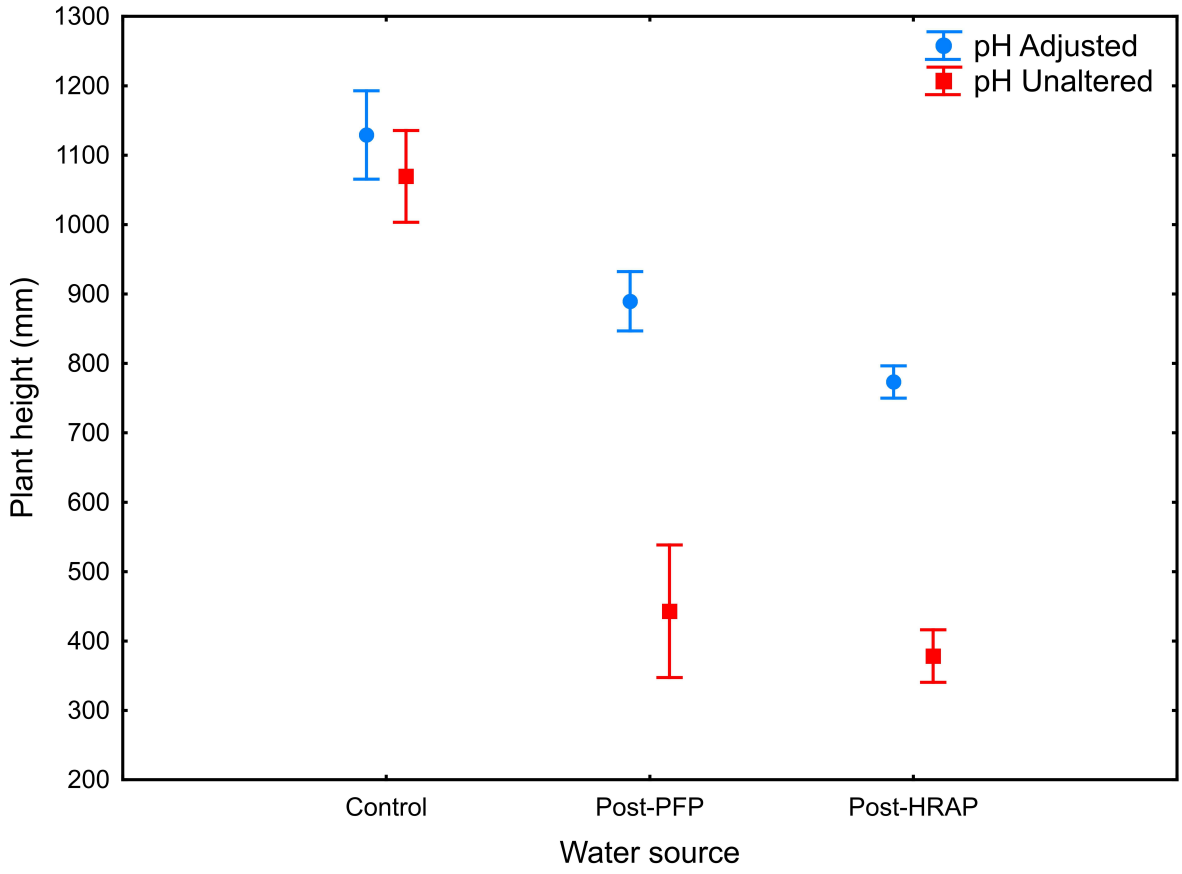
	Post-PFP			Post-HRAP		
	Min	Max	Mean	Min	Max	Mean
Phosphate ($mg.L^{-1}$)	32.7	92.0	51.1	19.5	92.0	31.7
Phosphorus ($mg.L^{-1}$)	10.7	30.0	16.5	6.3	30.0	10.4
Ammonium ($mg.L^{-1}$)	2.7	66.0	37.4	0.3	3.0	1.2
Nitrite ($mg.L^{-1}$)	0.3	1.6	0.6	0.1	3.1	1.9
Nitrate ($mg.L^{-1}$)	3.8	22.4	8.4	3.1	53.8	19.0
Chloride ($mg.L^{-1}$)	580.0	910.0	791.3	970.0	1460.0	1169.7
EC (µS/cm)	3372	3999	3868	>3999	>3999	>3999
COD ($mg.L^{-1}$)	93.0	139.0	119.8	108.0	215.0	150.7

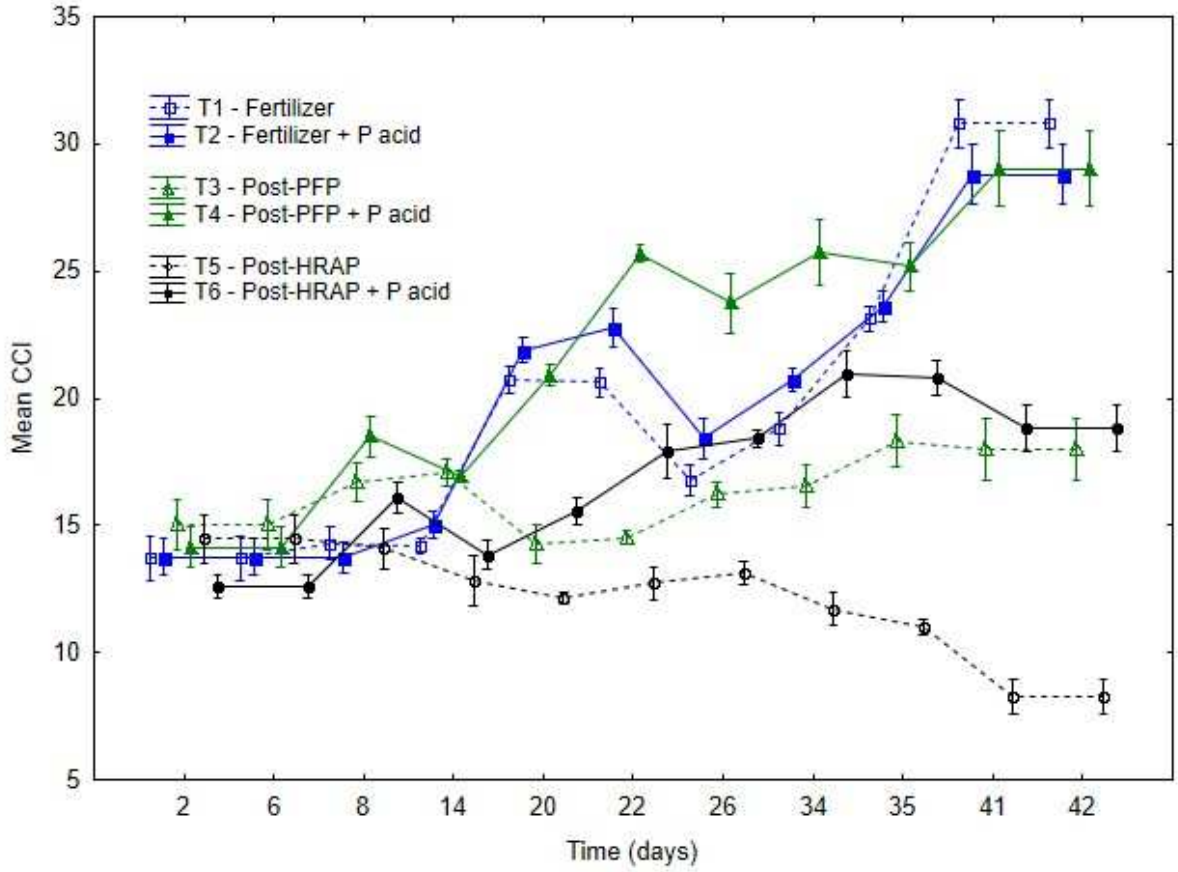
Table 2 The mean (± standard deviation) stem diameter, leaf and shoot dry weight, and root dry weight from *Moneymaker* tomato plants grown for 49 days in various nutrient sources and pH adjustment treatments. Mean values were calculated from four replicates, each containing five plants (n=20) for weights, and five replicates for height and diameter (n=25). Means within each column with a different superscript were significantly different (Multifactor ANOVA, $p<0.05$).

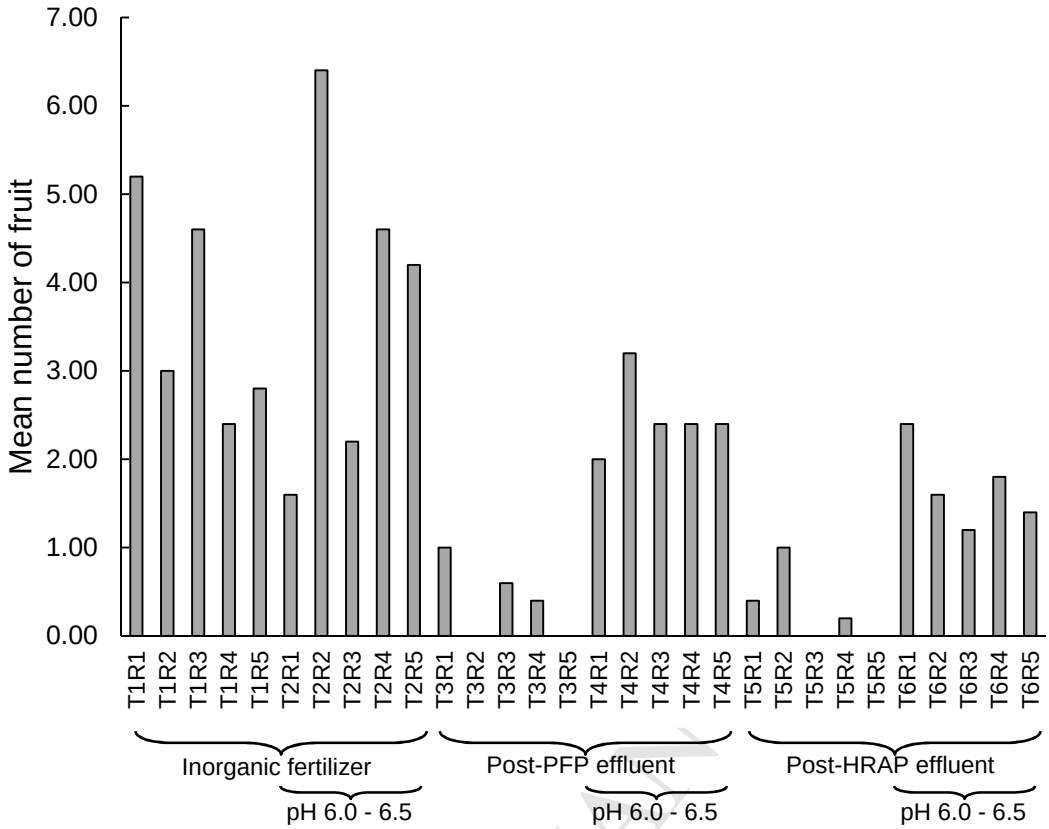
	Nutrient solution	Stem diameter (mm)	Leaf & shoot dry weight ($g.plant^{-1}$)	Root dry weight ($g.plant^{-1}$)
T1	Fertilizer	11.2 ± 0.5 [a]	112.7 ± 16.0 [a]	16.3 ± 2.3 [a]
T2	Fertilizer + P acid	11.4 ± 0.8 [a]	113.5 ± 10.0 [a]	18.9 ± 1.8 [a]
T3	Post-PFP	5.6 ± 1.2 [b]	5.2 ± 1.8 [b]	3.3 ± 0.7 [b]
T4	Post-PFP + P acid	8.5 ± 0.2 [c]	38.6 ± 4.7 [c]	8.8 ± 2.2 [c]
T5	Post-HRAP	6.0 ± 0.5 [b]	4.4 ± 0.8 [b]	2.4 ± 0.3 [b]
T6	Post-HRAP + P acid	8.7 ± 0.6 [c]	32.3 ± 5.5 [c]	5.0 ± 0.7 [c]
	Overall	8.6 ± 2.4	51.1 ± 47.0	9.1 ± 6.7

Table 3 The mean, maximum and minimum pH values and the mean (± standard deviation) electrical conductivity for the individual treatments. The treatment solutions included: T1 and T2 – municipal water and inorganic-fertilizer, T3 and T4 – post-primary facultative pond effluent (post-PFP), and T5 and T6 – post-high rate algal ponds effluent (post-HRAP). Treatments T2, T4 and T6 were subject to pH adjustment with phosphoric acid (P acid).

	Nutrient solution	pH			Electrical conductivity ($\mu S.cm^{-1}$)
		Mean	Max	Min	
T1	Fertilizer	7.38	8.05	6.90	1974 ± 93
T2	Fertilizer + P acid	5.97	6.98	5.50	1982 ± 88
T3	Post-PFP	8.91	9.43	8.71	2135 ± 84
T4	Post-PFP + P acid	6.16	7.03	5.71	2169 ± 184
T5	Post-HRAP	9.35	9.86	8.33	2451 ± 162
T6	Post-HRAP + P acid	6.16	6.98	5.65	2405 ± 283







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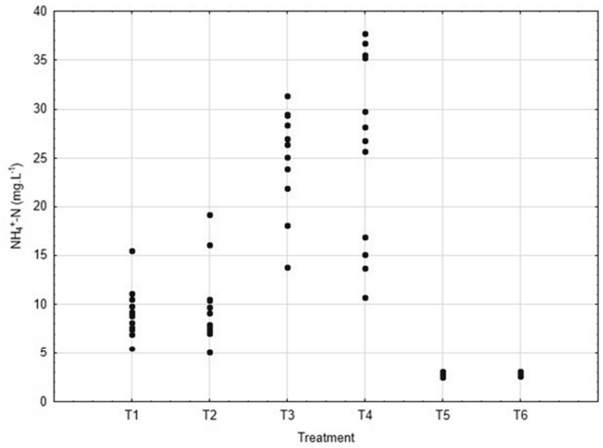
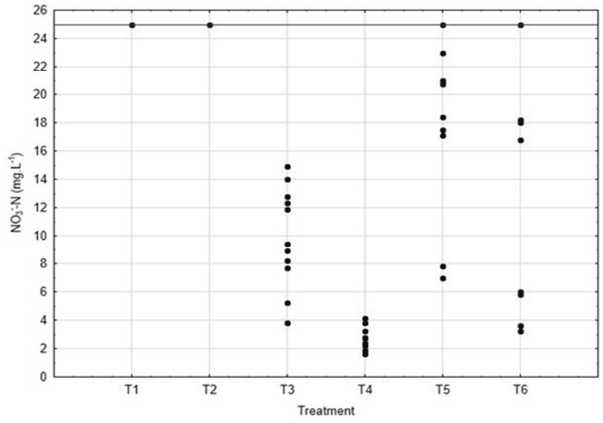
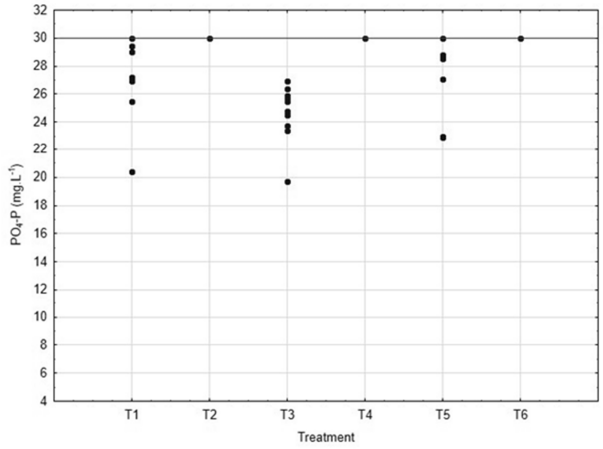
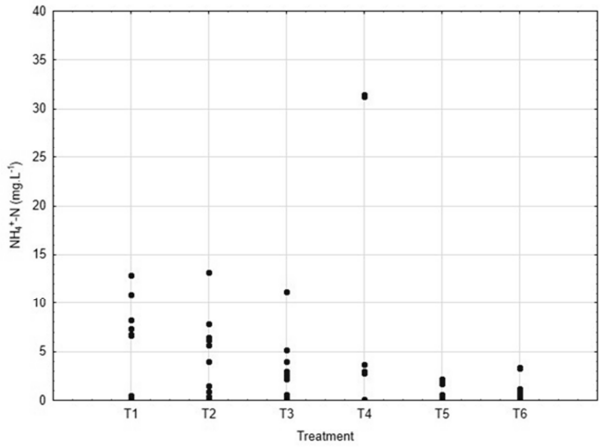
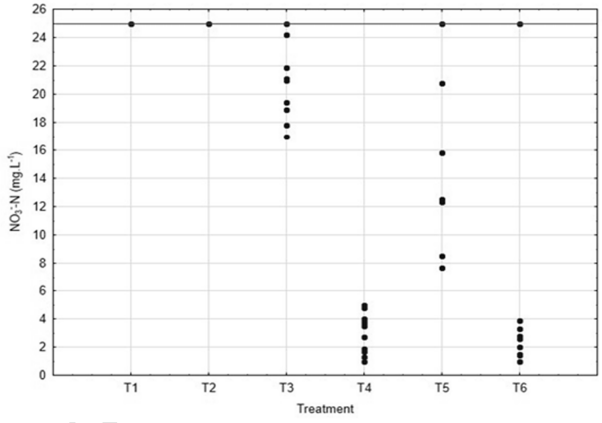


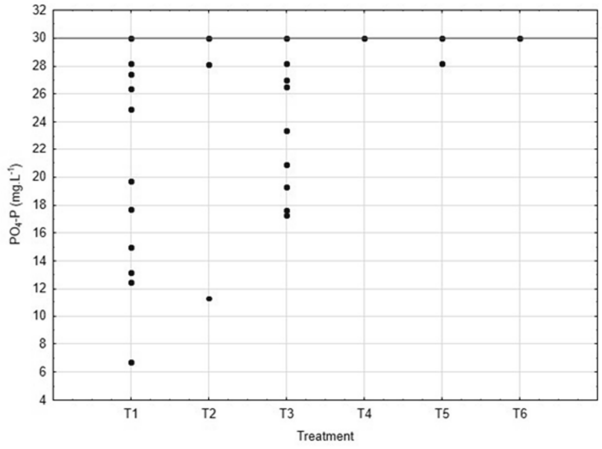




Replacement solutions:







Highlights (if the total number of characters is limited to 85)

- Brewery effluent can be used as a hydroponic water and nutrient source if pH is maintained at 6.0–6.5

Highlights (if the number of characters is limited to 85 per highlight)

- Brewery effluent can be used as a hydroponic water and nutrient source
- Growth using effluent is inferior compared to plants grown in inorganic fertiliser
- Growth and fruit yield improved when pH of the effluent was maintained at 6.0–6.5
- There is potential for hydroponics in organic effluent downstream of industry
- There is a potential market for organic effluent, which is currently a liability