Reaseheath College AD Digestate Research Project

The use of cattle slurry digestate solids in mixtures with coir and pine bark as plant growth substrates in the intensive production of glasshouse tomato crops

Summary

Following the process of anaerobic digestion, cattle slurry digestate solids were combined with coir and also pine bark. The substrates were then compared with a standard commercial coir slab to produce a late-planted, classic round, glasshouse tomato crop.

Samples of applied liquid feed, crop drainwater and tomato plant leaf tissue were taken at regular intervals and comparisons made between the standard growing medium and the substrate mixtures. Substrate samples were also taken as fresh and used samples, in January and October 2013, respectively.

Plants were affected by the high pH conditions in the substrates containing digestate and changes to the feed regime were used to improve the rootzone pH and also the iron and manganese availability for plant uptake.

Although the digestate mixtures contained comparatively high concentrations of the heavy metals chromium and nickel, plant growth did not appear to be adversely affected during the trial.

It was possible to steer tomato plant growth in both the digestate mixtures over a period of eight months and obtain similar plant yields and fruit quality to the standard coir substrate.

Reaseheath College Anaerobic Digestion Facility

Reaseheath College Substrate Trials

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1.0 General Introduction

Anaerobic digestion (AD) is a natural process involving the decomposition of biodegradable waste materials by micro-organisms, in the absence of oxygen, releasing biogas and producing digestate.

In landfill sites and slurry storage vessels, AD occurs naturally but this process may be harnessed and more carefully controlled, to capture the maximum biogas yield.

Biogas is a mixture of methane (approximately 60%) and carbon dioxide (40%), combined with traces of hydrogen sulphide and other gases.

The biogas released from the process may be utilised as a fuel in a boiler or combined heat and power unit (CHP). It may also be possible to separate the carbon dioxide from the mixture, remove impurities from the gas and then use as supplementary carbon dioxide in a glasshouse crop. One example of an anaerobic digestion project designed to utilise a proportion of clean carbon dioxide from biogas in a commercial tomato production glasshouse was commissioned in Evesham during 2013.

Digestate formed during the process contains a range of useful plant nutrients, although the actual composition of the digestate will vary, in line with the feedstock used in the process.

In addition, it is possible that the digestate will also contain other non-degradable compounds of the feedstock, such as heavy metals, pesticides and herbicides.

According to the DEFRA Anaerobic Digestion Strategy and Action Plan Annual Report 2012-13, there were 110 UK anaerobic digestion units operating in August 2013. It was also reported that more than 200 AD projects had received planning permission (Defra, 2013).

Current agricultural practice includes the treatment of fields with the digestate but there may be other outlets for this material, such as professional growing media for intensive glasshouse crops and amateur gardening applications, in the form of grow bags.

Research on the use of digestate in intensive horticultural applications has increased in the last five years. For example, Ridout and Tripepi (2011) formulated growing media for potting mixes from composted anaerobically digested cattle bio-solids (0-60%), aged pine bark (30-90%) and 10% sand. The resultant mixes had suitable physical properties (in terms of air-filled porosity, container capacity, total porosity and bulk density) but where the bio-solid component was 30% or greater, high sodium, chloride, potassium and phosphorus concentrations were thought likely to cause problems for plant growth.

Other UK WRAP funded projects examining potential uses of digestates during 2013 included:

- The use of digestates in protected strawberry production. This project included six liquid digestates produced from a range of feed-stocks, including food waste, potato waste, maize and slurry. The digestates were used as a nutrient base for liquid feeds, to irrigate intensively-produced strawberry crops at the Warwick Crop Centre.
- Mixtures with hardy nursery stock. Trials at Moulton College involving the use of digestates in novel growing media for ornamentals (bark admixtures for ferns, cyclamen and pines).
- Hardy perennials. The use of digestate as a soil improver and bio-fertiliser for biomass production on brownfield sites.

Both liquid and solid fractions of digestate are produced during anaerobic digestion but this report concentrates on a novel use of the solid digestate material.

1.1 History of Hydroponics

In commercial horticultural crop production, the move away from soil in the 1970s to peat-based systems was stimulated by the need to control problems with soil pests, diseases and nutritional imbalances.

In peat systems, practical problems with water content, water availability and nutrient balance limited its application to certain crops, such as tomatoes (Challinor, 2003). All peat systems require a constant supply of nutrients, either in the form of a slow-release fertiliser or as liquid feeds. Depending on the composition of the background water, nutrient imbalances may quickly occur.

Moderate yields of tomato fruit may be grown in peat, provided that adequate levels of nutrients are maintained throughout the production season (Adams *et al*., 1973). Depending on light received by the crop, a yield of up to 35kg per square metre of classic round tomatoes may be achieved in a peat bag system over a 9 month production season. However, the yield of tomatoes was found to decline when the micronutrient status was not sustained for example (Graves *et al.*, 1978).

The overall professional use of peat grow-bags has declined since the 1970s and most of the glasshouse food crops are now grown in alternative substrates.

Total yields of up to 70kg per square metre have been recorded in long-season UK classic round tomato crops grown hydroponically, using rockwool as a substrate.

Nutrient film technique (NFT) was developed in the early 1970s by Dr Allen Cooper and remains the ultimate nutrient re-circulation system. It consists of a water sump tank into which are dosed nutrients in various combinations (Graves, 1983). The quantity of liquid in the sump tank and the pH and electrical conductivity (EC) of the solution are both constantly monitored by a computer system and the appropriate changes made by the introduction of fresh water, acid and nutrients in liquid form, as required.

From the sump tank, the complete liquid nutrient feed is pumped to the top end of a series of closed troughs and the liquid feed then enters each trough through a delivery tube and moves evenly, by gravity, down a slope of 1 in 80 or 1 in 100 (Drakes *et al*., 1984). The root system of each plant positioned in the trough is then bathed with water, liquid feed and dissolved oxygen (Cooper, 1979). A root mat develops in the stream of water and the plants selectively remove nutrients and water from the solution, as the plant growth stage and environmental conditions dictate.

Since its early introduction, interest in NFT has waned for a number of reasons including: the high initial capital cost; system and equipment failures; nutritional problems; and plant losses through root disease. System failures have included: faulty design; incorrect installation of equipment and plant root death, due to oxygen starvation. Nutritional problems have included: low nutrient solution pH, caused by acid overdosing; an accumulation of unwanted ions over time (for example, sodium, chloride and sulphate ions) and general nutrient solution imbalance problems (Challinor, 2003). Starting with high concentrations of unwanted ions in the backgound water only serves to compound nutritional difficulties later in the crop production process.

In addition, root death and subsequent disease problems have been caused as a direct result of stagnant conditions in the root zone and lack of skills, on the part of the grower, to understand basic plant health and nutritional requirements.

The introduction of rockwool (stonewool) in the early 1970s revolutionised the crop production industry worldwide. The material is a by-product of the loft insulation industry and is produced by the heating and mixing together of two rocks - basalt and diabase - at temperatures in excess of 1500°C, with the resulting flux then being spun into fibres and formed into slabs (Smith, 1987).

In its prepared state, rockwool has a pore volume of 97% and its function is to provide root anchorage for the plant and to regulate the water and air supply. It does not contain any plant nutrients and the plant must rely entirely on the inclusion of nutrients in the water supply (Bunt, 1988).

Rockwool does, however, initially require the reduction of pH from approximately 8.0 to 6.0 and a thorough wetting with nutrient solution, prior to use by the grower.

The rockwool slab is totally inert and it does not participate in the process of movement of ions to the plant root, except that it provides air spaces and support for the root mat. If there is an imbalance in the ion content of the input feed, this will be mirrored in the root zone, as the rockwool fibres do not react with the nutrient solution.

Coir is a useful peat replacement material and its popularity as a substrate in UK glasshouse tomato crop production is increasing.

1.2 Introduction to Crop Trials at Reaseheath College

In order to assess the suitability of the cattle slurry anaerobic digestate as a plant growth substrate, an observation trial was designed using coir as the standard growing medium. Earlier work at Reaseheath College in 2012 concentrated on the incorporation of digestate in peat-based bedding plant compost mixes.

Two digestate treatments were also included in the trial: digestate mixed with coir (50:50) and digestate mixed with pine bark (50:50).

The 50% dilution rate of the digestate was chosen to reduce the risk of damage to tomato plants from the effects of high pH, potentially high EC and the high concentration of heavy metals, such as chromium and nickel.

In addition, any pesticide or herbicide carry-over from materials used in production of the original feed crop material, prior to use in the anaerobic digestion system, may have also adversely affected tomato plant growth.

‘Dometica’, a standard, long-season, glasshouse, classic round tomato variety, was selected and grafted on to an ‘Emperador’ rootstock.

The hydroponic system allowed for the delivery of water and nutrients to each plant via drip irrigation tubing. Drainwater was collected and irrigated to other crops outside the trial compartment. The decision to omit drainwater recirculation was taken to ensure that a clear nutritional picture is compiled, using regular analysis of the input liquid feed, substrate and plant leaf tissue.

1.3 Knowledge Transfer

The work has been discussed with grower members of the UK Tomato Working Party on several occasions in 2012 and 2013 and also the Horticulture Development Company (HDC).

The initial project work was also introduced to the Tomato Growers' Association Technical Committee on 05 December 2012. This was followed by a progress report and presentation to the same Committee on 14 March 2013.

The subject was also included in a presentation on 'The Use of Hydroponics', which was delivered at the Wilton Park Conference on Global Agriculture, Food and Land Use (How to create resilient agricultural systems in a world of increasing resource scarcity and climate change) held over the period 15-17 April 2013.

An Open Day on AD was held at Reaseheath College on 02 July 2013, when the interim trial results were discussed in detail.

2.0 Plant Growing Conditions and Progress of the 2013 Tomato Trial

Although the glasshouses are over 40 years old and have limited automatic environmental and irrigation controls, every attempt was made to grow the crops in line with good commercial practice.

The trial was planted on 15 February 2013, having acclimatized and established the tomato plants in the glasshouse compartment.

In order to protect the plants against pest and disease attack, the glasshouse was cleaned prior to use and the floor completely covered with a woven, polypropylene sheet. The latter ensured that any transfer of pest or disease from the soil is reduced to a minimum.

The selection criteria for the tomato variety included disease resistance – for example, 'Dometica' is tolerant to powdery mildew. To further protect the plants against disease and promote summer plant vigour, the variety was grafted onto a commercial rootstock: 'Emperador'.

Additional protection of the plants from pest infestation was provided by the introduction of biological control organisms, such as Encarsia formosa (against white fly), Macrolophus pygmaeus (against white fly, caterpillars and leaf miner) and Phytoseiulus persimilis (against red spider mite).

In addition, regular sprays of 'Serenade' (Bacillus subtilis) were applied, to protect the plants against infection by stem botrytis.

Analytical work on the unused substrates and regular analysis of the input liquid feed and plant leaf tissue was also scheduled.

January 2013
Physical damage and cold shock were kept to a minimum during plant delivery on 16 January, although the Reaseheath College external air temperature was at -2°C. Plants were initially positioned on the slab plastic sleeves and not in contact with the actual substrates.

During very cold weather, the internal glasshouse temperature dipped to 10°C but the use of temporary polythene screening helped to maintain a temperature regime based on 18°C day and 16°C night.

Bumble bees and biological control organisms were ordered for delivery in early February. The first flower was recorded on 31 January.

Propagator	Variety and Rootstock	Plant Specification
Plant Raisers Ltd, Howden, East Yorkshire 01430 432200	‘Dometica’ (Rijk Zwaan), grafted on ‘Emperador’ (Rijk Zwaan)	Four week old plants, raised under high-pressure sodium lamps
	Two grafted plants per rockwool block	Sowing: week 51, 2012 Delivery: week 03, 2013
	Plant condition: good size, with slightly thin heads and rockwool not too wet	Propagation blocks: Cultilene rockwool

February 2013
Bumble bees were introduced into the crop to help pollinate the tomato flowers and weekly deliveries of Encarsia formosa parasites commenced, the latter to protect against white fly.

Night temperatures were reduced to 14°C, to help control growth and strengthen flower trusses. In addition, one plant head leaf was removed on a weekly basis, to keep growth as generative as possible.

Plant root contact with the substrates was made on 15 February. Initial root penetration into the coir slabs was extensive, with bright white, thick roots present. In comparison, the root system development in the digestate mixtures consisted of thinner-diameter, finer white roots. Root penetration in the two types of digestate slabs appeared similar in the modules examined.

Plant growth was very leafy (vegetative) after planting and the first truss formation was vertical, rather than curved. The concentration of nitrate-nitrogen in the initial proprietary feed mixes was high, adding to the vegetative nature of the plant growth. High plant nitrate-nitrogen concentrations in all substrate systems were confirmed by leaf analysis (13 March).

There were occasional indications of iron deficiency appearing in the plant head tissue (interveinal chlorosis and yellowing of new leaves), caused by the high pH conditions in the slabs containing the digestate mixtures.

Early flower pollination was patchy, with a proportion of mis-set fruit present.

Macrolophus pygmaeus predators were introduced in week 7.

March 2013
Good root development continued in all three substrates. Although fine roots were visible in the two digestate substrate mixtures, root colonisation of the slabs was thorough, rather than roots penetrating to the lowest part of the slabs and running along the underside of the substrate material.

Plant growth remained vegetative in nature and truss habit was vertical on the first two trusses. Weekly plant head leaf removal (from behind a developing truss) continued.

Basal leaf removal was initiated, to improve air circulation around the plant stem bases and in preparation for the first layering operation.

The application of nitrate-nitrogen via the feed system was more carefully controlled, to encourage generative growth. The use of individual fertiliser compounds started, rather than continuing with a proprietary feed mix.

Slight indications of iron deficiency did not appear to be restricting the development of new leaves in the head of the plant. However, there were signs of manganese deficiency on slightly older leaves under the plant head.

As drip feed analysis results (13 March) revealed a high concentration of applied manganese (1.01 mg per litre), it is likely that both iron and manganese deficiencies were being aggravated by the high pH conditions in the digestate mixture slabs.

Early fruit shape looked good and pollination on trusses 2 to 4 was also good. Early flower pollination was patchy, with a proportion of mis-set fruit present.

There were no reports of pests or pest damage visible in the crop.

April 2013
Fruit ripening started on the first truss and the first fruit was harvested on 02 April. Early fruit size was variable, due to the absence of bees for pollination at the start of flowering and variable external light levels.

Plant growth remained vegetative, with large stem diameter measurements and long leaves. However, the plant rows were easier to access, following completion of the first plant layering operation.

The switch to a high-potassium feed recipe, based on separate fertiliser compounds, was completed.

Weekly plant head leaf removal (from behind a developing truss) continued, to help maintain a generative plant steer.

During early April, iron and manganese deficiency symptoms did not appear to have increased on plants in the two separate digestate treatments. In addition, the recent drain pH measurements were in the range 6.5 to 7.0.

However, both iron and manganese deficiency symptoms increased on plants in the two separate digestate treatments in mid-April, due to the combination of irrigation equipment dosing faults, lower feed strength inputs and increasing substrate pH levels.

The drip feed analysis results of 12 April revealed good input concentrations of phosphorus, iron and manganese. However, drainwater analysis results indicated low iron concentrations from all three systems.

Flower pollination appeared more variable, with occasional flowers falling from the trusses. This was also likely to be linked to the variation in the volume of nutrients applied, especially in terms of boron and calcium.

However, general plant nutrition appeared to have improved by late April.

The first signs of leaf damage caused by red spider mite activity were recorded. Introductions of Phytoseiulus persimilis predators then started.

May 2013
Fruit ripening accelerated and total yield increased during May.

In the absence of supplementary carbon dioxide dosing, the effect of low daytime carbon dioxide concentrations on marketable fruit size became more noticeable.

The drip feed analysis of 30 May indicated good nutrient balances between the major elements, especially potassium, nitrate-nitrogen, calcium and magnesium. Steady input concentrations of phosphorus, iron and manganese were also being maintained.

Drainwater analysis results revealed higher concentrations of iron from all three substrate systems, compared to the samples taken in April.

However, leaf analyses showed lower concentrations of iron in the leaf tissue from the two separate digestate substrate systems, when compared with the coir control.

June and July 2013

The plants coped well with the good weather conditions in July and the number of fruit affected by transient calcium deficiency, in the form of blossom-end rot, was kept to a minimum. The plants in the guard rows were most affected by blossom-end rot and a light application of shading material was applied to the external glass on the west side in an attempt to reduce plant stress.

The control of glasshouse environmental conditions was further complicated by having to manage high compartment temperatures caused by a line of broken ventilators during July.

Monthly sampling of the input liquid feed and measurement of drainwater nutrient concentrations helped to steer plant nutrition and maintain fruit quality attributes.

The average fruit size and total yield of tomato fruit continued to be adversely affected by the absence of supplementary carbon dioxide.

An outbreak of red spider mite also proved difficult to control and the situation was further compounded by the hot, sunny weather conditions in July. However, attempts to control the pest by using repeat introductions of the predatory mite Phytoseiulus persimilis, in conjunction with spot sprays of ‘Savona’ (potassium salts of fatty acids), helped to contain the outbreak.

The presence of Macrolophus pygmaeus predators helped to control general pest activity in the crop until the end of the trial.

August and September 2013

Cooler weather conditions in August and September encouraged more vegetative growth and the plants recovered from the heat stress caused by high daytime temperatures and lack of environmental control.

Red spider mite damage was visible in patches of the crop until the completion of the trial.

Final samples were taken from the crop on 01 October, including drainwater solution and substrates.

The input feed was stopped at the end of September and, as a result, substrate pH levels increased and both iron and manganese deficiency symptoms re-appeared on plant shoot re-growth.

3.0 Results and Discussion: Fruit Yield

The crop was harvested three times each week from week 16 to week 40 inclusive and the total marketable yields (in kg per square metre) for each substrate are summarised in Table 3.1 and Figure 3.1.

Data from the UK Tomato Working Party has been included, to provide a comparison with a commercial 'Dometica' crop. Weekly yields from two crops grown in older glasshouse structures in the NE of England on rockwool substrates were used to provide average data. It should be noted that the two commercial crops were produced in glasshouses fitted with modern computer-based systems for accurate control of the glasshouse environment and also the crop irrigation and hydroponic liquid feeding requirements.

Most importantly, the two commercial sites used supplementary carbon dioxide throughout the cropping period, to prevent glasshouse environmental depletion. The main yield differences between the commercial and trial crops is undoubtedly due to the absence of supplementary carbon dioxide enrichment of the glasshouse atmosphere and also the lack of accurate control over environmental and liquid feeding parameters.

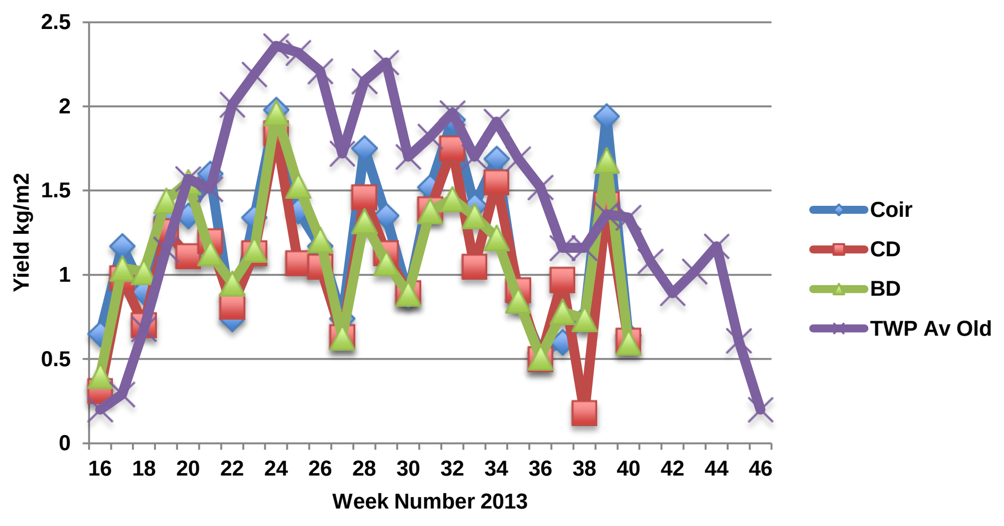
A further difference between the trial glasshouse and the commercial units is the cropping height from ground to gutter. Most commercial crops are cultivated in a vertical space of three to four metres, compared with approximately two metres working height in the trial structure. The additional height available in modern structures helps to ensure that the actively photosynthesizing leaves capture maximum light at the top and in the middle of the crop and that there is sufficient room to allow crop work and harvesting operations to continue without damaging the plants. Additional height also helps to complete plant de-leafing and layering tasks with maximum efficiency.

The coir slab total marketable yield at 30.19 kg per square metre was higher than the two digestate substrate mixtures. Furthermore, the bark and digestate substrate yielded 27.85 kg per square metre, compared with 25.89 kg per square metre from the coir and digestate plot. However, it is likely that positional effects of the substrate rows and the absence of replication in the trial glasshouse will have also influenced the plot yields.

Table 3.1 Substrate Yield Results

Week Number	Coir kg/m2	Coir and Digestate kg/m2	Bark and Digestate kg/m2	UK TWP Average (Old Glass) kg/m2
16	0.65	0.31	0.40	0.20
17	1.17	0.98	1.04	0.29
18	0.90	0.70	1.02	0.68
19	1.34	1.26	1.44	1.15
20	1.35	1.11	1.55	1.57
21	1.60	1.20	1.13	1.51
22	0.74	0.81	0.95	2.01
23	1.34	1.13	1.15	2.19
24	1.98	1.84	1.96	2.36
25	1.38	1.07	1.53	2.32
26	1.17	1.05	1.21	2.21
27	0.74	0.63	0.63	1.72
28	1.75	1.46	1.32	2.15
29	1.35	1.13	1.07	2.26
30	0.88	0.89	0.89	1.70
31	1.52	1.39	1.38	1.82
32	1.92	1.75	1.45	1.96
33	1.41	1.05	1.35	1.70
34	1.69	1.55	1.22	1.91
35	0.85	0.91	0.85	1.69
36	0.54	0.50	0.51	1.52
37	0.60	0.97	0.78	1.16
38	0.74	0.18	0.74	1.16
39	1.94	1.42	1.68	1.36
40	0.64	0.61	0.60	1.34
41				1.08
42				0.89
43				1.02
44				1.17
45				0.61
46				0.20
Total	30.19	25.89	27.85	44.91

Figure 3.1 Comparison of 'Dometica' Tomato Yield Data



4.0 Results and Discussion: Chemical Analysis of Hydroponic Solutions

4.1 Liquid Feed Analysis

Table 4.1 Liquid Feed Analysis Results

Parameter	Water 150213	Drip 150213	Drip 140313	Drip 120413	Drip 180413	Drip 300513	Drip 240613	Drip 260713	Drip 030913
pH	7.1	5.6	5.4	5.1	5.4	5.1	5.8	5.1	5.5
Conductivity µS/cm 20°C	84.6	3,010	2,910	2,980	2,470	3,000	1,100	2,360	2,350
Ammonium-N mg/litre	< 1	24.1	20.2	9.3	8.12	12.4	2.36	10.4	9.21
Nitrate-N mg/litre	48.6	281	321	219	181	275	66.7	190	193
Phosphorus mg/litre	2.07	68.5	47.4	95.9	81.3	63	24.2	35	58.8
Potassium mg/litre	< 1	219	154	519	437	449	178	330	377
Calcium mg/litre	8.14	426	429	170	142	258	56.9	225	168
Magnesium mg/litre	0.898	64.1	42.3	111	83.1	61.1	25.3	29.9	50.5
Sodium mg/litre	4.90	14.1	14	12.8	11	15.4	7.65	16.9	14
Chloride mg/litre	9.02	139	116	128	104	187	65.5	174	129
Sulphur mg/litre	< 10	86	55.3	165	115	81.6	41.5	45.6	78.2
Iron mg/litre	< 0.1	1.73	1.63	1.56	1.09	1.34	0.63	2.99	1.39
Manganese mg/litre	< 0.01	1.05	1.01	0.97	1.01	1.12	0.27	0.76	0.75
Boron mg/litre	< 0.1	0.62	0.47	0.41	1	0.93	0.36	0.42	0.79
Zinc mg/litre	0.10	0.78	0.65	1.05	0.87	0.68	0.45	0.43	0.78
Copper mg/litre	< 0.01	0.44	0.38	0.12	0.12	0.1	0.04	0.09	0.06
Molybdenum mg/litre	< 0.03	0.06	0.05	0.05	0.04	0.05	< 0.03	0.07	1.86
K:N ratio	N/A	0.72	0.45	2.27	2.31	1.56	2.58	1.65	0.04
K:Ca ratio	N/A	0.51	0.36	3.05	3.08	1.74	3.13	1.47	2.24
K:Mg ratio	N/A	3.42	3.64	4.68	5.26	7.35	7.04	11.04	7.47
K:Na ratio	N/A	16	11	41	40	29	23	20	27
K:Cl ratio	N/A	1.6	1.3	4.1	4.2	2.4	2.7	1.9	2.9

The use of proprietary liquid feeds resulted in high concentrations of ammonium-nitrogen in the drip sample results of 15 February and 14 March. More effective control over the concentration of nutrients and the overall balance between potassium and the other major elements (nitrate-nitrogen, calcium and magnesium) was obtained by the use of compound fertilisers in a calculated feed recipe.

There was good control over input pH and EC, with the exception of sample results obtained on 24 June. There was also good control over the main and trace element control (except 24 June).

It should also be noted that good concentrations of iron and manganese were maintained in the liquid feed throughout the trial.

4.2 Coir Drainwater Analysis

Table 4.2 Coir Drainwater Analysis Results

Parameter	**Drain 180413**	**Drain 300513**	**Drain 240613**	**Drain 260713**	**Drain 030913**	**Drain 011013**
pH	5.2	4.5	5.3	5.2	5.1	5.4
Conductivity µS/cm 20°C	3,030	3,730	4,120	3,340	4,270	4,450
Ammonium-N mg/litre	< 1	2.27	1.8	1.84	4.6	< 1
Nitrate-N mg/litre	181	315	226	264	352	240
Phosphorus mg/litre	156	76.4	77.5	74.5	90.3	199
Potassium mg/litre	588	489	570	493	593	601
Calcium mg/litre	139	345	375	290	373	337
Magnesium mg/litre	148	111	121	94.2	115	190
Sodium mg/litre	15.8	33.7	41.2	33.7	48	70.2
Chloride mg/litre	72.6	340	343	233	364	328
Sulphur mg/litre	220	125	138	112	125	252
Iron mg/litre	0.48	1.78	3.04	2.47	2.19	0.69
Manganese mg/litre	0.7	0.49	0.42	0.43	0.43	0.13
Boron mg/litre	1.79	1.49	1.53	1.29	1.63	2.65
Zinc mg/litre	0.84	1.11	0.90	0.83	0.86	0.69
Copper mg/litre	0.12	0.17	0.11	0.1	0.1	0.05
Molybdenum mg/litre	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03
K:N ratio	3.25	1.54	2.50	1.85	1.66	2.5
K:Ca ratio	4.23	1.42	1.52	1.70	1.59	1.78
K:Mg ratio	3.97	4.41	4.71	5.23	5.16	3.16
K:Na ratio	37	15	14	15	12	8.6
K:Cl ratio	8.1	1.4	1.7	2.1	1.6	1.8

The coir drainwater pH was in the range 4.5 to 5.4 (Figure 4.1).

Drainwater EC was generally steady between 3,030 and 4,450 µS per cm (Figure 4.2).

Concentrations of ammonium-nitrogen were low throughout, with a maximum result of 4.6 mg per litre in the drainwater sample of 03 September.

The measured nitrate-nitrogen concentration range was 181 to 352 mg per litre.

It was noticeable that the phosphorus drainwater concentration was above 70 mg per litre throughout the trial (Figure 4.3) and no deficiency symptoms were noticeable at any crop growth stage. In addition, the concentrations of potassium were above 480 mg per litre throughout the trial.

Drainwater sodium concentrations ranged between 15.8 to 70.2 mg per litre and chloride concentrations peaked at 364 mg per litre in the sample taken on 03 September.

Concentrations of iron and manganese present in the drainwater dropped below 1 mg per litre and 0.2 mg per litre on 18 April and 01 October, respectively (Figures 4.4 and 4.5).

Boron concentrations in excess of 1.2 mg per litre were consistently measured.

Drainwater zinc concentrations reached a maximum of 0.9 mg per litre on 24 June and remained above 0.5 mg per litre throughout the trial (Figure 4.6).

4.3 Coir and Digestate Drainwater Analysis

Table 4.3 Coir and Digestate Drainwater Analysis Results

Parameter	Drain 180413	Drain 300513	Drain 240613	Drain 260713	Drain 030913	Drain 011013
pH	6.2	5.8	5.8	5.8	5.9	5.8
Conductivity µS/cm 20°C	3,070	3,880	3,930	3,630	5,130	3,060
Ammonium-N mg/litre	< 1	< 1	2.98	1.51	1.88	< 1
Nitrate-N mg/litre	191	337	280	292	392	153
Phosphorus mg/litre	134	63.9	69.5	63.6	96.2	104
Potassium mg/litre	587	500	546	490	676	335
Calcium mg/litre	182	354	317	326	465	232
Magnesium mg/litre	129	119	124	113	160	146
Sodium mg/litre	16.7	32.6	42.6	39.9	64.5	65.1
Chloride mg/litre	79.3	301	330	292	480	315
Sulphur mg/litre	213	117	148	117	167	167
Iron mg/litre	0.35	1.18	2.43	2.13	1.96	0.9
Manganese mg/litre	0.27	0.59	0.51	0.38	0.3	0.27
Boron mg/litre	1.69	1.43	1.75	1.24	1.92	2.04
Zinc mg/litre	0.46	1.14	0.81	0.77	0.35	0.21
Copper mg/litre	0.11	0.22	0.22	0.16	0.1	0.06
Molybdenum mg/litre	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03
K:N ratio	3.07	1.48	1.93	1.67	1.72	2.19
K:Ca ratio	3.23	1.41	1.72	1.5	1.45	1.44
K:Mg ratio	4.55	4.2	4.4	4.34	4.23	2.29
K:Na ratio	35	15	13	12	10	5.1
K:Cl ratio	7.4	1.7	1.7	1.7	1.4	1.1

The drainwater pH results of 5.8 to 6.2 were consistently higher than in the coir drainwater (Figure 4.1). In addition, the EC was between 3,000 and 4,000 µS per cm, except in the sample taken on 03 September (Figure 4.2).

The phosphorus drainwater concentration was above 60 mg per litre throughout the trial (Figure 4.3).

Drainwater sodium concentrations ranged between 16.7 to 65.1 mg per litre and a maximum chloride concentration was measured at 480 mg per litre in the sample taken on 03 September.

Concentrations of iron dropped below 1 mg per litre on 18 April and 01 October, respectively (Figure 4.4). Manganese concentrations only dropped below 0.3 mg per litre on 18 April and 01 October (Figure 4.5).

Drainwater zinc concentrations reached a maximum of 1.14 mg per litre on 30 May and were below 0.4 mg per litre on 03 September and 01 October (Figure 4.6).

4.4 Bark and Digestate Drainwater Analysis

Table 4.4 Bark and Digestate Drainwater Analysis Results

Parameter	Drain 180413	Drain 300513	Drain 240613	Drain 260713	Drain 030913	Drain 011013
pH	6.1	5.9	6.0	6.1	5.8	6.5
Conductivity µS/cm 20°C	3,050	3,850	2,520	3,450	4,440	1,310
Ammonium-N mg/litre	< 1	< 1	1.49	1.6	1.58	< 1
Nitrate-N mg/litre	207	363	159	284	380	33.5
Phosphorus mg/litre	109	56.9	45.1	61.9	90.1	63.3
Potassium mg/litre	548	504	388	471	614	147
Calcium mg/litre	172	360	178	316	390	82.6
Magnesium mg/litre	132	100	71.9	97.2	122	56.3
Sodium mg/litre	17.7	31.5	27.2	34.4	45.7	39.1
Chloride mg/litre	121	345	211	255	335	104
Sulphur mg/litre	178	102	104	94.4	139	94.3
Iron mg/litre	0.67	1.38	2.08	2.21	1.54	0.41
Manganese mg/litre	0.67	0.57	0.35	0.27	0.18	0.02
Boron mg/litre	1.39	1.33	1	1.09	1.51	1.13
Zinc mg/litre	0.71	1.11	0.87	0.9	0.48	0.12
Copper mg/litre	0.17	0.21	0.19	0.15	0.08	0.06
Molybdenum mg/litre	0.03	< 0.03	< 0.03	< 0.03	< 0.03	0.05
K:N ratio	2.65	1.39	2.42	1.65	1.61	4.39
K:Ca ratio	3.19	1.4	2.18	1.49	1.57	1.78
K:Mg ratio	4.15	5.04	5.4	4.85	5.03	2.61
K:Na ratio	31	16	14	14	13	3.8
K:Cl ratio	4.5	1.5	1.8	1.8	1.8	1.4

The drainwater pH results of 5.8 to 6.5 were consistently higher than in the coir drainwater (Figure 4.1). In addition, the EC was measured below 3,000 µS per cm, in samples taken on 24 June and 01 October (Figure 4.2).

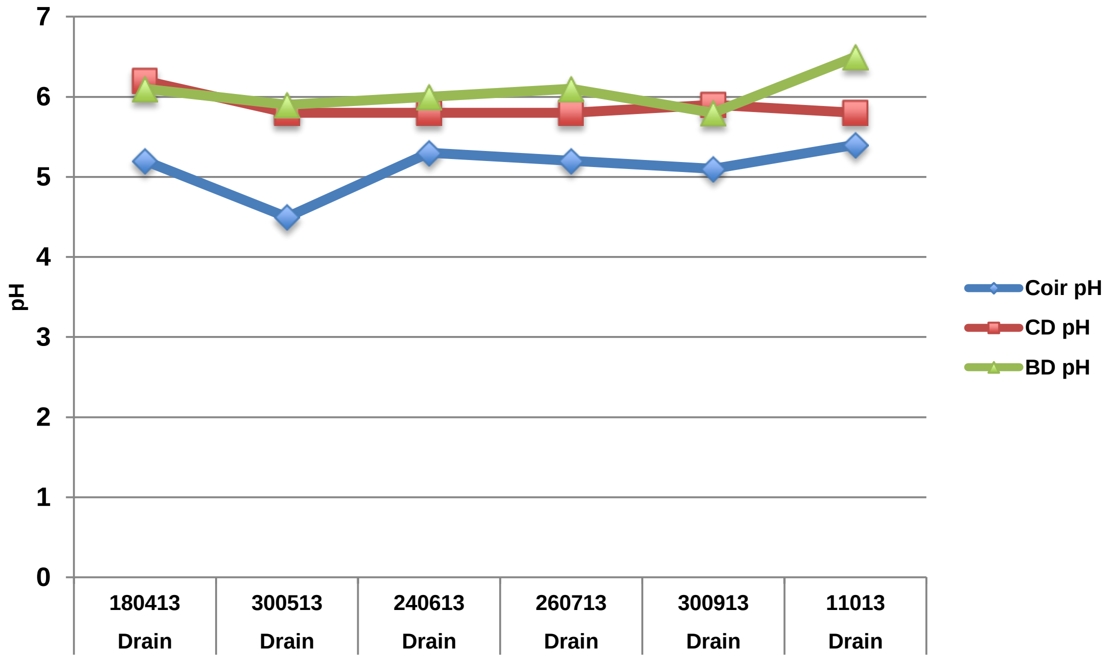
The phosphorus drainwater concentration was above 40 mg per litre throughout the trial (Figure 4.3).

Drainwater sodium concentrations ranged between 17.7 to 45.7 mg per litre and a maximum chloride concentration was measured at 345 mg per litre in the sample taken on 30 May.

Concentrations of iron dropped below 1 mg per litre on 18 April and 01 October, respectively (Figure 4.4). Manganese concentrations only dropped below 0.2 mg per litre on 03 September and 01 October (Figure 4.5).

Drainwater zinc concentrations reached a maximum of 1.11 mg per litre on 30 May and were below 0.5 mg per litre on 03 September and 01 October (Figure 4.6).

Figure 4.1 Drainwater pH levels for coir, coir mixed with digestate (CD) and bark mixed with digestate (BD)



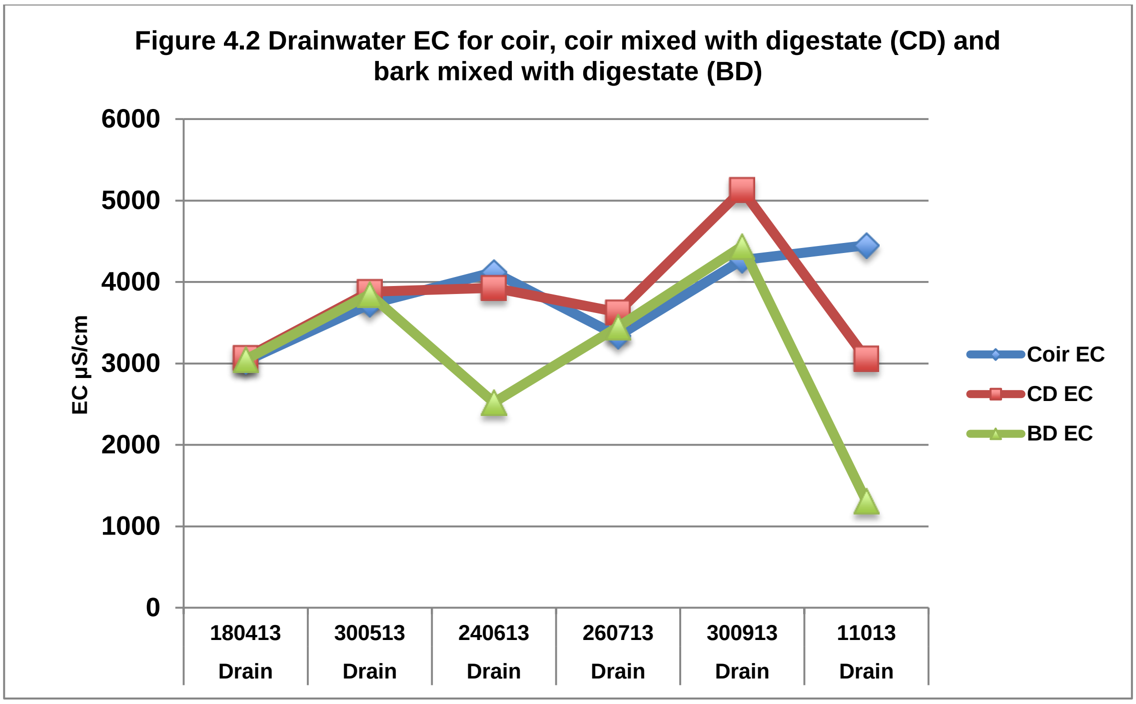


Figure 4.2 Drainwater EC for coir, coir mixed with digestate (CD) and bark mixed with digestate (BD)
6000
5000
4000
3000
2000
1000
0
EC µS/cm
180413 Drain
300513 Drain
240613 Drain
260713 Drain
300913 Drain
11013 Drain
Coir EC
CD EC
BD EC

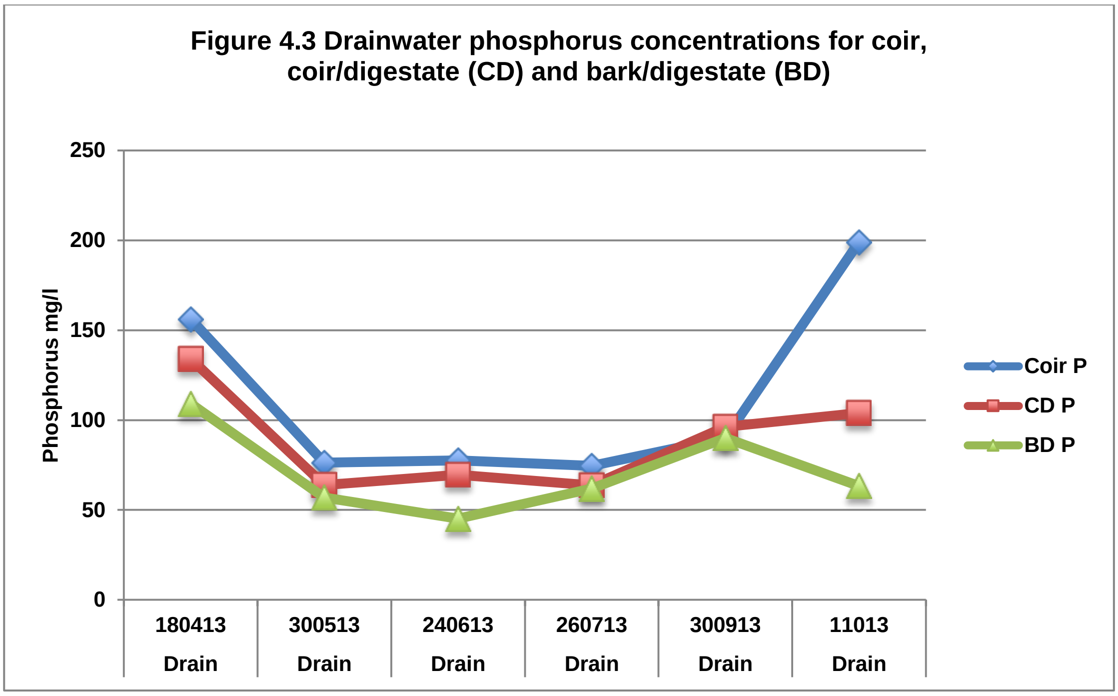


Figure 4.3 Drainwater phosphorus concentrations for coir, coir/digestate (CD) and bark/digestate (BD)
250
200
150
100
50
0
Phosphorus mg/l
180413 Drain
300513 Drain
240613 Drain
260713 Drain
300913 Drain
11013 Drain
Coir P
CD P
BD P

Figure 4.4 Drainwater iron concentrations for coir, coir/digestate (CD) and bark/digestate (BD)

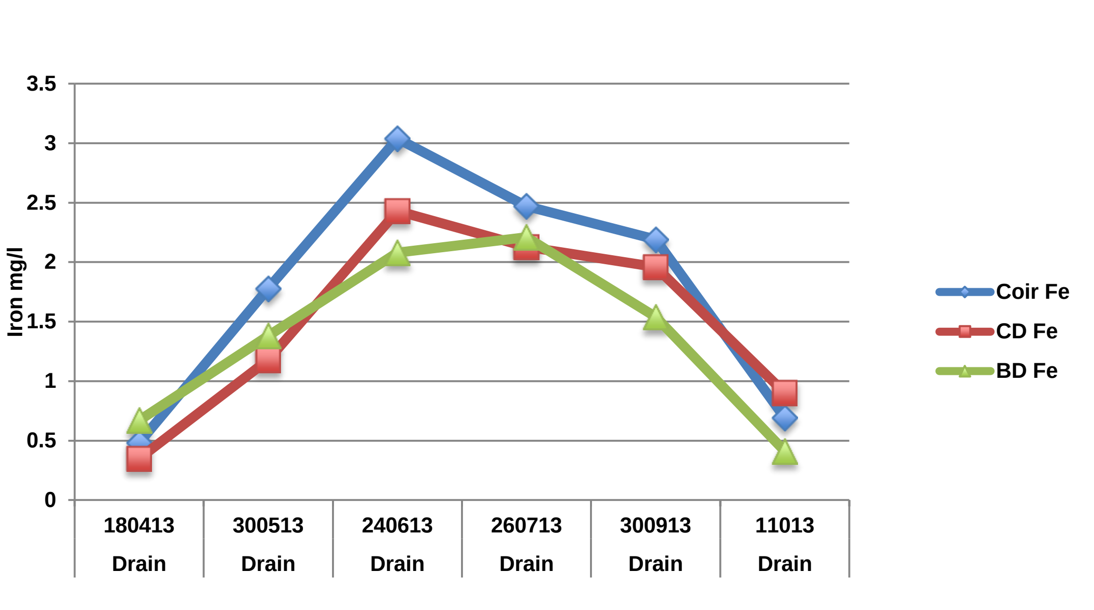


Figure 4.5 Drainwater manganese concentrations for coir, coir/digestate (CD) and bark/digestate (BD)

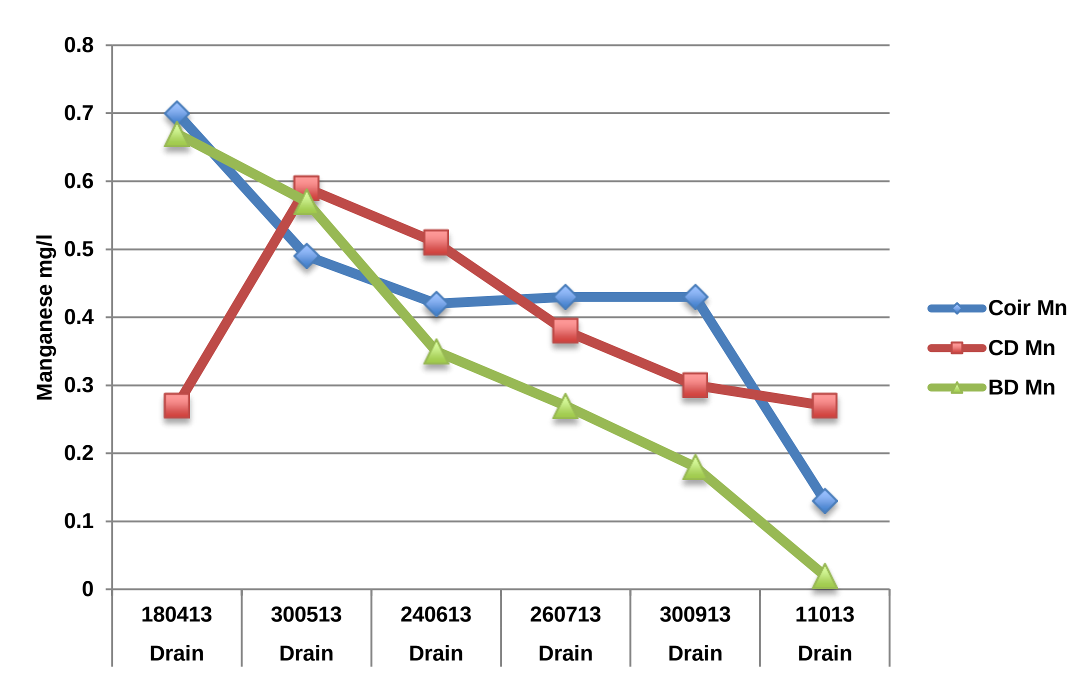
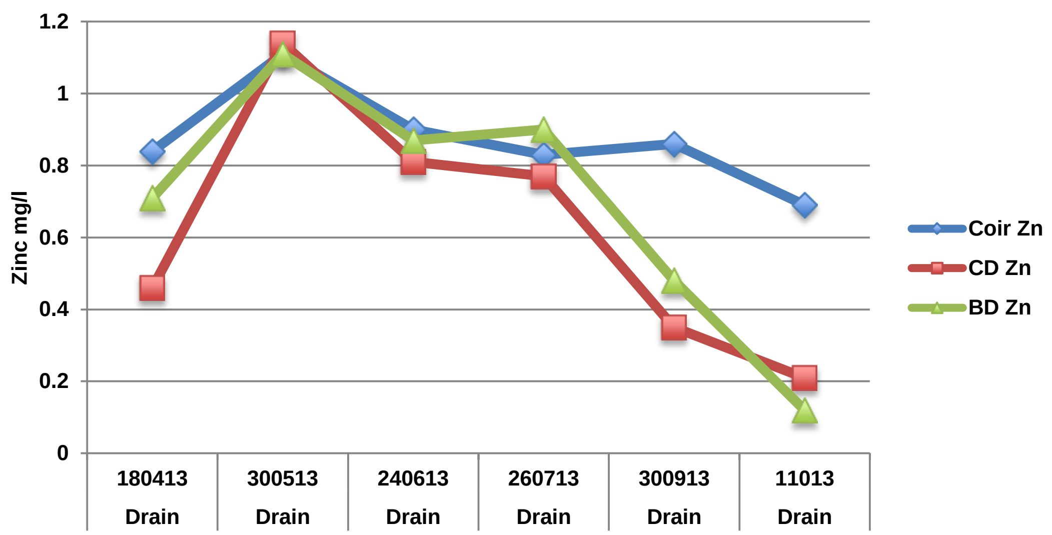


Figure 4.6 Drainwater zinc concentrations for coir, coir/digestate (CD) and bark/digestate (BD)



4.5 Optimum Nutrient Solution Concentrations (as provided by May Barn Consultancy Ltd)

A target specification sheet is attached (Table 4.5), to provide an indication of optimum nutrient concentrations and nutrient balances, using the glasshouse tomato as an example. The first column lists the most important elements to be measured in the analytical laboratory and also the ratio between the major nutrients.

EC is the electrical conductivity of the solution, which reflects the total concentration of ions in solution. The elements are further divided into major and trace, plus a reference to unwanted ions, for example sodium, chloride and sulphate. Although useful to control plant growth under low light or winter conditions, high concentrations of sodium and chloride will decrease the availability of water for plant uptake and may result in nutrient imbalances or in crop yield reduction.

The next three columns indicate the optimum nutrient concentration for production of long season tomato crops in hydroponic systems and concentration ranges are simply colour coded: red (problem), amber (warning) or green (acceptable).

The final column contains additional comments on important nutrient relationships.

Using potassium (K) as an example, the optimum concentration required for healthy plant growth and good quality fruit production in a commercial hydroponic system is 500 mg per litre. A concentration below 400 mg per litre in the substrate root-zone would limit potassium availability for the plant and is likely to result in fruit quality issues, such as blotchy ripening and poor flavour. A concentration above 1,000 mg per litre would be an excessive value but is unlikely to cause plant toxicity problems. However, such a high concentration may cause a reduced availability of other elements, such as calcium or magnesium.

With a potentially unwanted element such as sodium (Na), the root-zone optimum concentration is 200 mg per litre. A concentration above 400 mg per litre is likely to increase the plant uptake of sodium, which will substitute for potassium, calcium and magnesium. If this trend continues, plant growth, yield and fruit quality issues will result.

In the case of a trace element, such as zinc (Zn), the optimum concentration required for normal plant growth is 1 mg per litre. A concentration below 0.5 mg per litre is likely to increase the risk of zinc deficiency symptoms occurring.

The development of any plant nutrient deficiency will tend to reduce yield and fruit quality. As there is a complex link between phosphorus, manganese and zinc availability to plants, it is very important to ensure that the nutrient balance is as precise as possible.

The document is included as an example of the importance of nutrient balances in commercial hydroponic systems and the complexity of maintaining the nutritional balance in such a system, to provide optimum crop quality and yield.

Without the necessary understanding of such chemical relationships and plant interactions, the risk of system/crop failure is much increased.

Table 4.5 Optimum Nutrient Concentrations for Hydroponic Tomato Plants

Slab Sample	Minimum	Optimum	High	Comments
RAG Chart: Tomato	Red: Likely to result in plant damage	Amber: Likely to result in nutrient deficiency	Green: at or near the optimum concentration	RAG Chart: Tomato
pH	< 5.5	6.0	> 6.5	Target range: 5.8-6.2
EC µS / cm	< 2,500	4,000	> 6,000*	*Early season growth control
Major mg / litre				
NH4-N	0	2	> 10	As low as possible
NO3-N	150	250	> 300	
P	20	30-40	> 50**	**Induced Zn+Cu deficiency likely
K	< 400	500	1,000	Toxicity: rare
Ca	150	250	> 300	
Mg	< 65	80	> 100	High K inhibits Mg absorption
Na	< 100	200	> 400	High Na inhibits uptake of K, Ca, Mg
Cl	< 100	200	> 400*	*Early season growth control
SO4-S	< 50	100	> 200	
Trace mg / litre				
Fe	< 2.0	3.0-4.0	> 5.0	
Mn	< 0.4	0.5-0.6	> 1.0***	***Toxicity risk higher
B	< 0.3	0.4-0.6	> 1.0	

Slab Sample	Minimum	Optimum	High	Comments
Zn	< 0.5	1.0	> 1.5	Link with P and Mn
Cu	< 0.05	0.1	> 0.2	
Mo	< 0.03	0.05	> 0.1	
Ratios				
K:N	> 3.0	2.0	< 1.6	
K:Ca	> 3.0	2.0	< 1.6	
K:Mg	> 8.0	6.0	< 5.0	
K:Na	> 5.0	2.5	< 1.25	Important in recirc.
K:Cl	> 5.0	2.5	< 1.25	Important in recirc.

5.0 Results and Discussion: Chemical Analysis of Plant Leaf Samples

5.1 Coir Leaf Analysis

Table 5.1 Coir Leaf Analysis Results

Parameter	Leaf 130313	Leaf 180413	Leaf 300513	Leaf 240613	Leaf 260713	Leaf 030913
Total N g/100g dm	6.14	5.61	5.4	4.98	4.5	4.81
Total P g/100g dm	0.73	0.58	0.6	0.37	0.37	0.4
Total K g/100g dm	5.71	5.36	4.83	4.45	4.48	4.59
Total Ca g/100g dm	1.87	1.48	1.92	1.53	1.29	1.45
Total Mg g/100g dm	0.38	0.62	0.36	0.31	0.35	0.3
Total Na g/100g dm	0.03	0.04	0.04	0.04	0.03	0.05
Chloride g/100g dm	N/A	0.99	1.07	1.21	1.03	1.27
Total S g/100g dm	0.93	0.91	0.82	0.66	0.59	0.72
Total Fe mg/kg dm	141	124	140	75	111	109
Total Mn mg/kg dm	124	185	226	155	168	138
Total B mg/kg dm	33.2	34	35.7	41.3	43	47.2
Total Zn mg/kg dm	28.7	30.4	30.6	21.2	26.1	23.5
Total Cu mg/kg dm	21.9	18.3	16.4	11	12.4	11.7

With the exception of visible iron and manganese deficiency symptoms in the digestate substrate plots, there were no other signs of nutrient deficiency problems during the trial.

Leaf total nitrogen concentrations were consistently in the optimum range (Table 5.1), with the highest concentration of 6.14 mg per kg (dry matter) recorded in the sample taken on 13 March (Figure 5.1).

Total phosphorus, potassium, calcium and magnesium concentrations were within, or higher than, the optimum ranges in the samples taken from March to September (Figures 5.2, 5.3, 5.4, and 5.5).

The highest chloride concentrations were measured in the coir leaf samples (Figure 5.6). In addition, the total leaf iron concentrations were lower than optimum throughout the trial (Figure 5.7), whereas total manganese concentrations were consistently above the optimum (Figure 5.8).

Total zinc and boron were also lower than optimum throughout the trial (Figures 5.9 and 5.10). It is possible that inconsistent humidity control could have impeded both the plant uptake of boron and calcium. Although there were no visible signs of plant or fruit calcium deficiency problems, the total leaf calcium results were towards the lower end of the optimum range.

Total leaf copper concentrations followed similar trends in all three substrates (Figure 5.11).

5.2 Coir and Digestate Leaf Analysis

Table 5.2 Coir and Digestate Leaf Analysis Results

Parameter	Leaf 130313	Leaf 180413	Leaf 300513	Leaf 240613	Leaf 260713	Leaf 030913
Total N g/100g dm	6.06	5.5	6.04	4.7	4.57	4.34
Total P g/100g dm	0.69	0.61	0.58	0.35	0.36	0.44
Total K g/100g dm	5.54	5.11	5.18	5.05	4.38	4.23
Total Ca g/100g dm	1.74	1.41	1.95	1.65	1.22	1.57
Total Mg g/100g dm	0.33	0.56	0.41	0.35	0.38	0.36
Total Na g/100g dm	0.03	0.02	0.04	0.05	0.02	0.04
Chloride g/100g dm	N/A	1	0.89	1.17	0.96	1.13
Total S g/100g dm	0.78	0.87	0.79	0.73	0.58	0.78
Total Fe mg/kg dm	104	98.5	99.1	65	110	89.9
Total Mn mg/kg dm	125	176	249	146	150	117
Total B mg/kg dm	29.1	34.9	35.5	44.6	44.2	41.2
Total Zn mg/kg dm	26	22.3	35.3	23.2	27.1	27.1
Total Cu mg/kg dm	18	17.6	16.3	11.5	14.4	14.4

Leaf total nitrogen concentrations were consistently in the optimum range (Table 5.2), with the highest concentration of 6.06 mg per kg (dry matter) recorded in the sample taken on 13 March (Figure 5.1).

Total phosphorus, potassium, calcium and magnesium concentrations were within, or higher than, the optimum ranges in the samples taken from March to September (Figures 5.3, 5.4 and 5.5). However, total phosphorus concentrations were noticeably lower in samples taken on 24 June and 26 July (Figure 5.2).

In addition, the total leaf iron concentrations were lower than optimum throughout the trial (Figure 5.7), whereas total manganese concentrations were consistently above the optimum (Figure 5.8). Total zinc and boron were also lower than optimum throughout the trial (Figures 5.9 and 5.10).

5.3 Bark and Digestate Leaf Analysis

Table 5.3 Bark and Digestate Leaf Analysis Results

Parameter	Leaf 130313	Leaf 180413	Leaf 300513	Leaf 240613	Leaf 260713	Leaf 030913
Total N g/100g dm	6.08	5.8	5.62	4.7	5.29	4.34
Total P g/100g dm	0.7	0.62	0.54	0.37	0.39	0.45
Total K g/100g dm	5.74	5.28	4.5	4.32	4.45	3.45
Total Ca g/100g dm	1.87	1.44	1.95	1.78	1.2	1.52
Total Mg g/100g dm	0.37	0.64	0.44	0.4	0.37	0.37
Total Na g/100g dm	0.03	0.02	0.04	0.04	0.02	0.04
Chloride g/100g dm	N/A	1.01	1.03	1.12	0.9	1.17
Total S g/100g dm	0.78	0.88	0.77	0.77	0.57	0.79
Total Fe mg/kg dm	102	86.7	98.4	71.8	105	86.3
Total Mn mg/kg dm	111	165	217	160	133	134
Total B mg/kg dm	30	34.3	35	50	40.6	46.7
Total Zn mg/kg dm	28.3	22.8	36.3	26.7	27.7	29.5
Total Cu mg/kg dm	16.5	18.2	13.9	12	14.4	13.2

Leaf total nitrogen concentrations were consistently in the optimum range (Table 5.3), with the highest concentration of 6.08 mg per kg (dry matter) recorded in the sample taken on 13 March (Figure 5.1).

Total phosphorus, potassium, calcium and magnesium concentrations were within, or higher than, the optimum ranges in the samples taken from March to September (Figures 5.2, 5.3, 5.4 and 5.5).

In addition, the total leaf iron concentrations were lower than optimum throughout the trial (Figure 5.7), whereas total manganese concentrations were consistently above the optimum (Figure 5.8).

Total zinc and boron were also lower than optimum throughout the trial (Figures 5.9 and 5.10).

Figure 5.1 Tomato leaf total nitrogen concentrations for coir, coir mixed with digestate (CD) and bark mixed with digestate (BD)

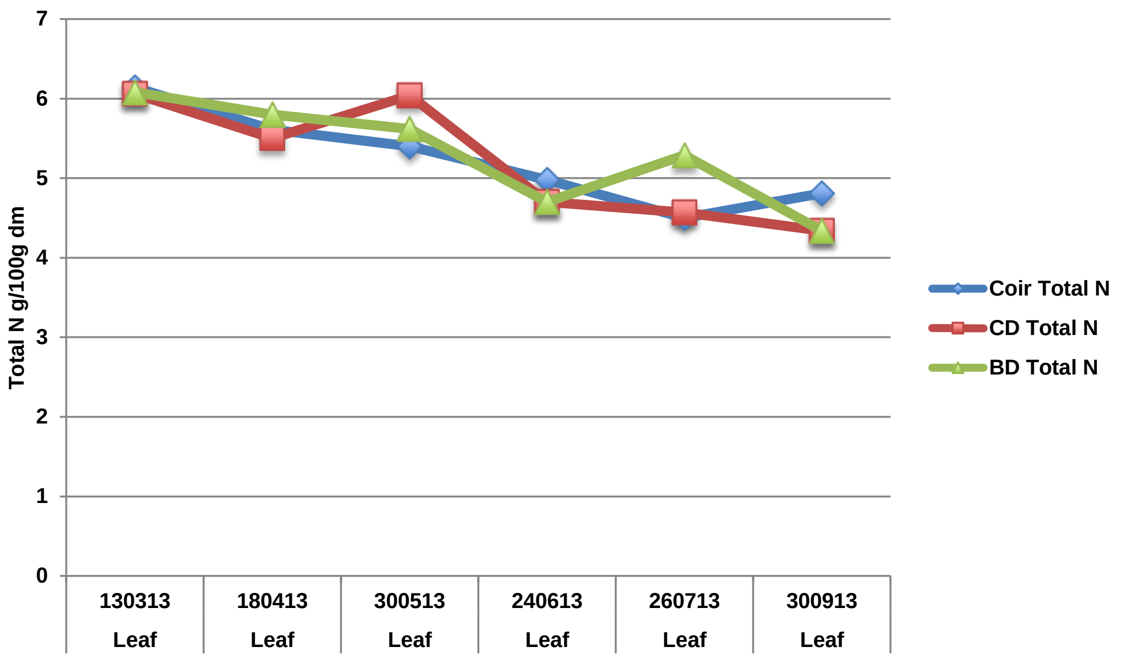
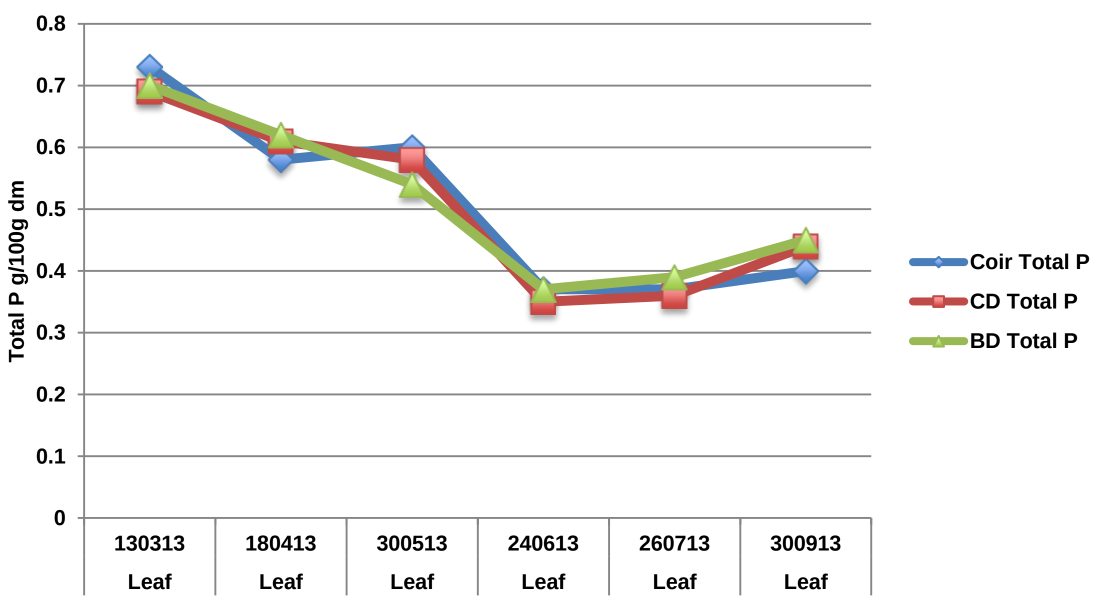


Figure 5.2 Tomato leaf total phosphorus concentrations for coir, coir mixed with digestate (CD) and bark mixed with digestate (BD)



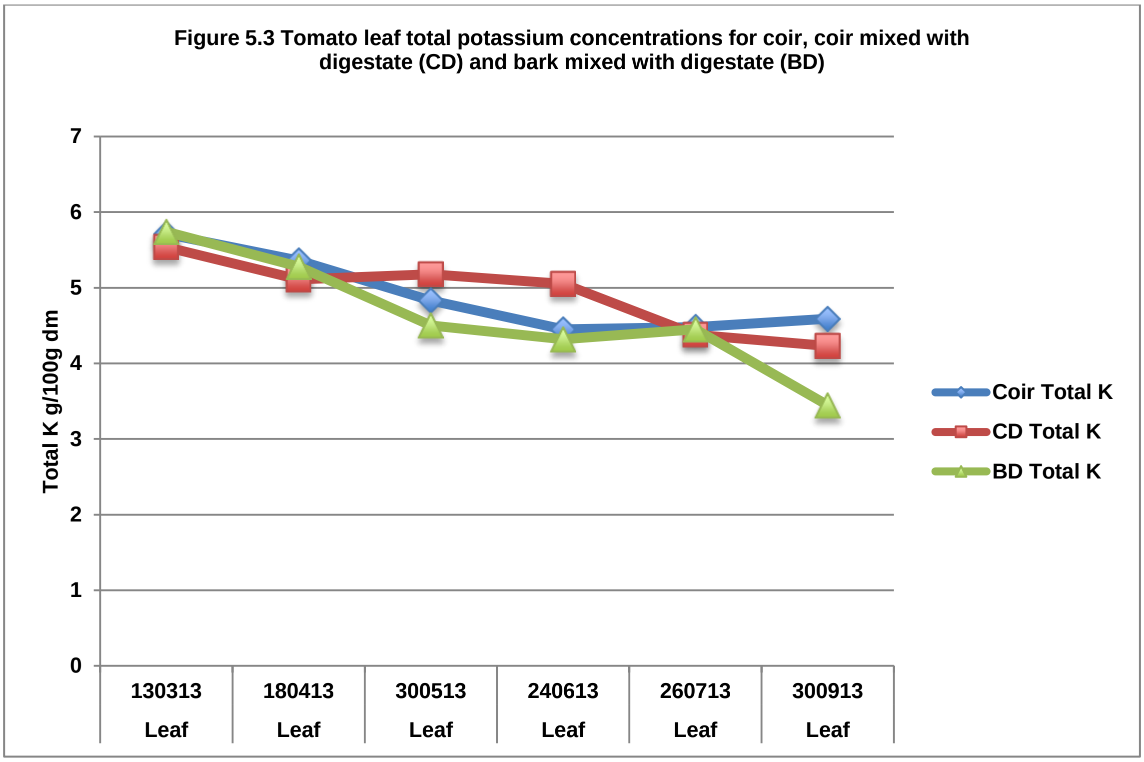


Figure 5.3 Tomato leaf total potassium concentrations for coir, coir mixed with digestate (CD) and bark mixed with digestate (BD)
Total K g/100g dm
7
6
5
4
3
2
1
0
130313 Leaf
180413 Leaf
300513 Leaf
240613 Leaf
260713 Leaf
300913 Leaf
Coir Total K
CD Total K
BD Total K

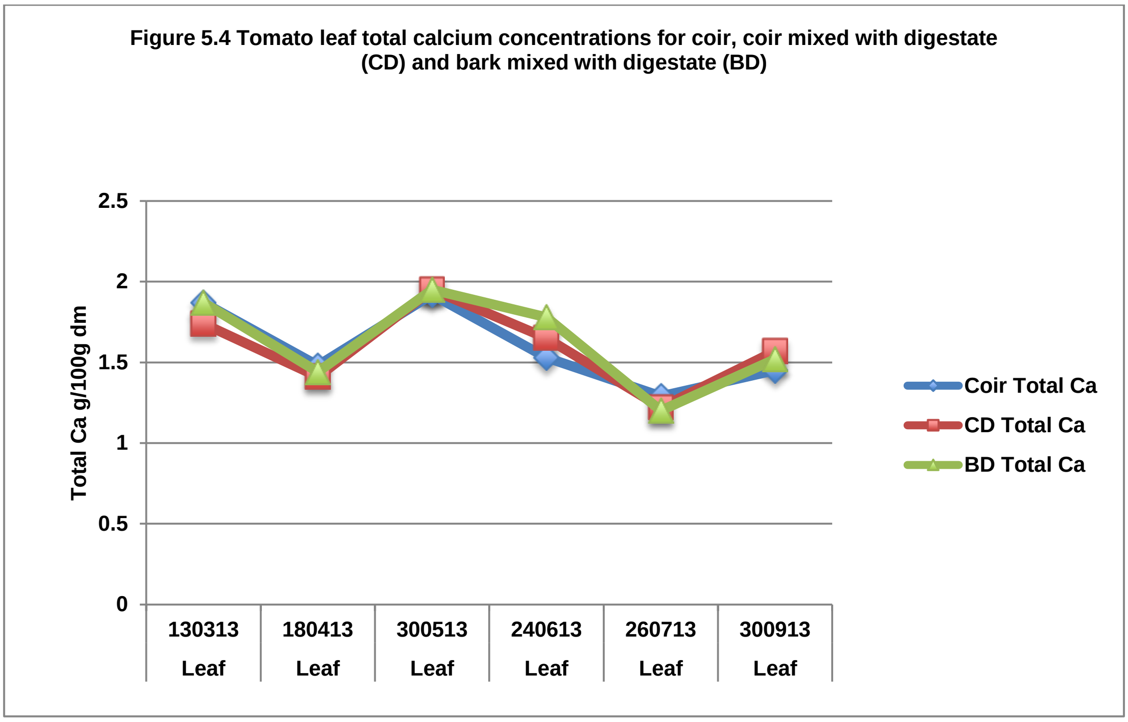


Figure 5.4 Tomato leaf total calcium concentrations for coir, coir mixed with digestate (CD) and bark mixed with digestate (BD)
Total Ca g/100g dm
2.5
2
1.5
1
0.5
0
130313 Leaf
180413 Leaf
300513 Leaf
240613 Leaf
260713 Leaf
300913 Leaf
Coir Total Ca
CD Total Ca
BD Total Ca

Figure 5.5 Tomato leaf total magnesium concentrations for coir, coir mixed with digestate (CD) and bark mixed with digestate (BD)

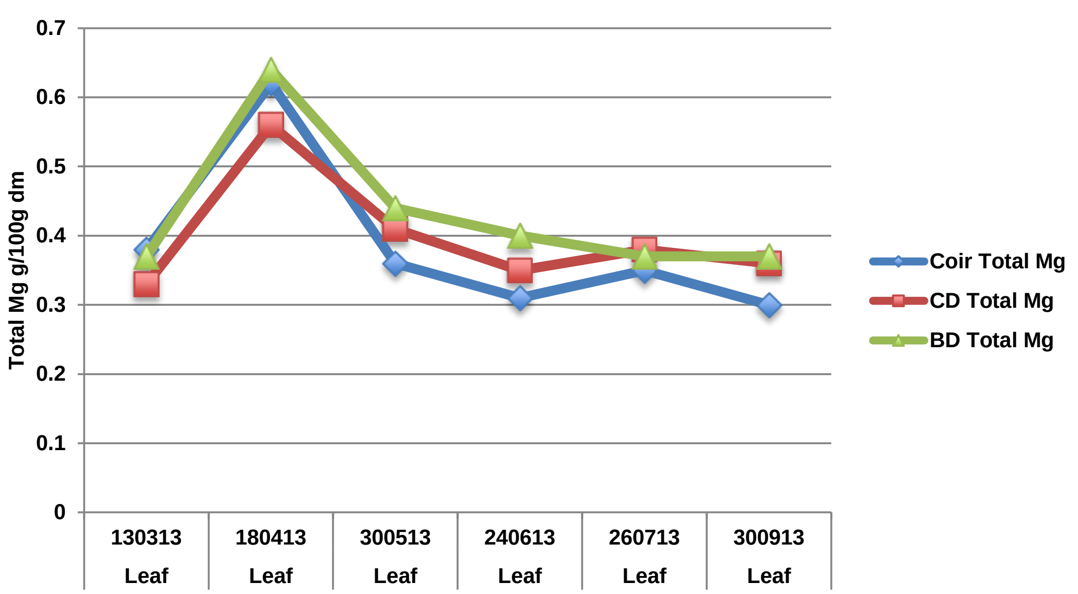
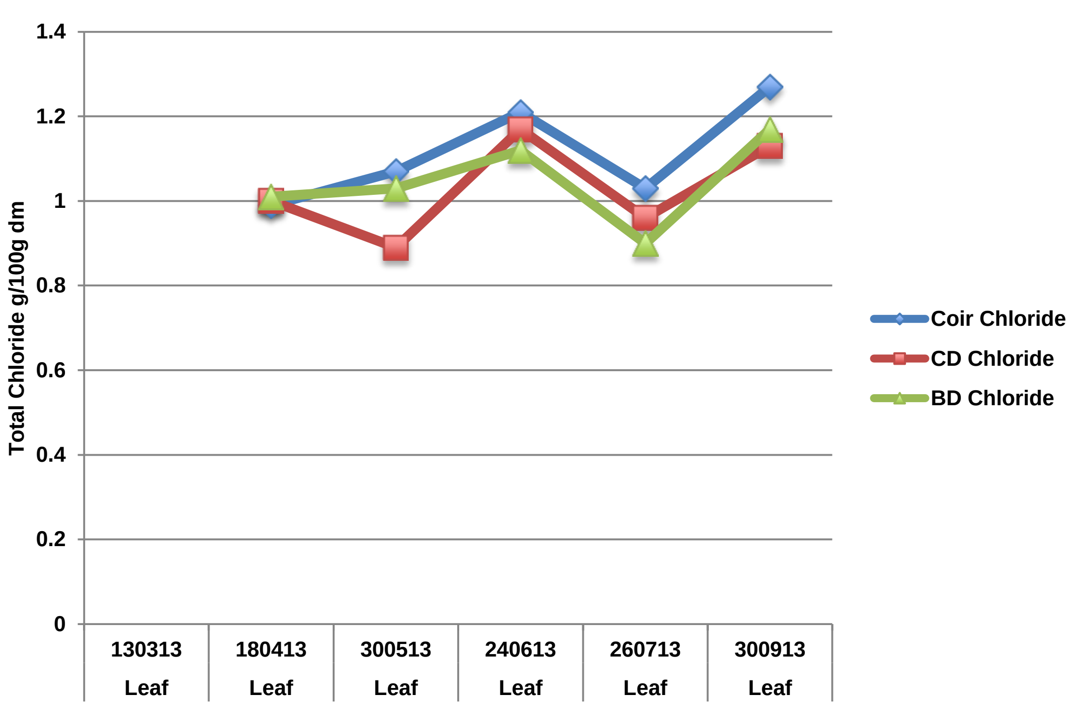


Figure 5.6 Tomato leaf total chloride concentrations for coir, coir mixed with digestate (CD) and bark mixed with digestate (BD)



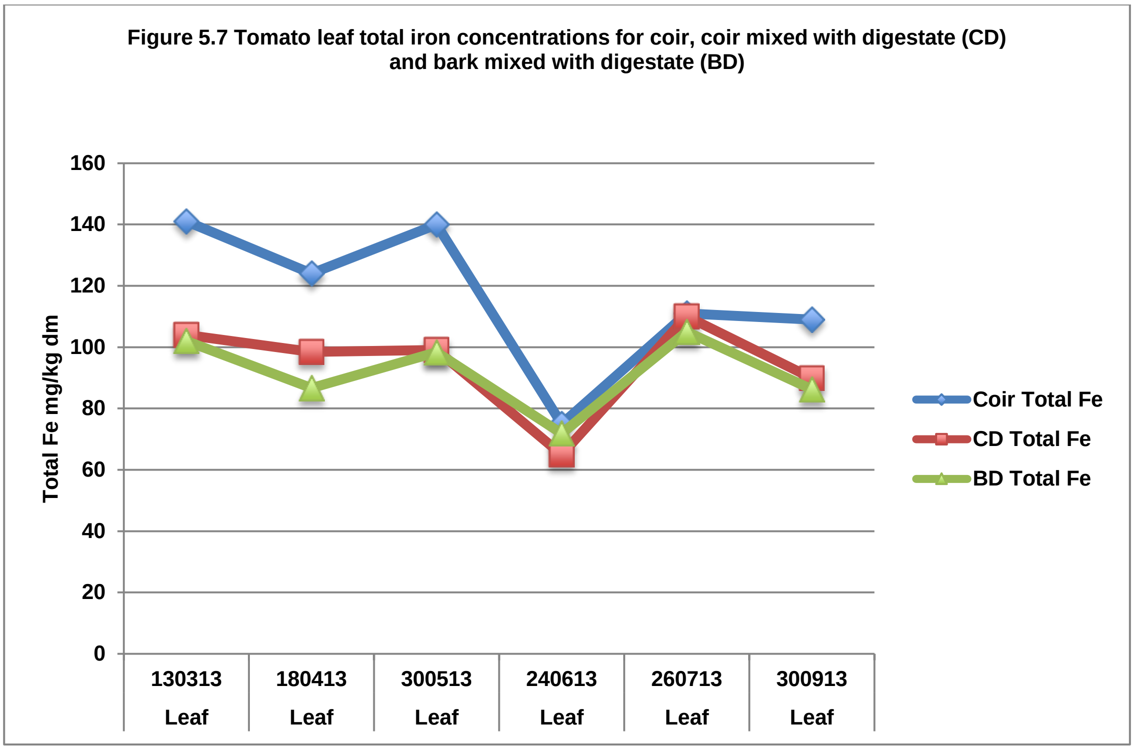


Figure 5.7 Tomato leaf total iron concentrations for coir, coir mixed with digestate (CD) and bark mixed with digestate (BD)
Total Fe mg/kg dm
160
140
120
100
80
60
40
20
0
130313 Leaf
180413 Leaf
300513 Leaf
240613 Leaf
260713 Leaf
300913 Leaf
Coir Total Fe
CD Total Fe
BD Total Fe

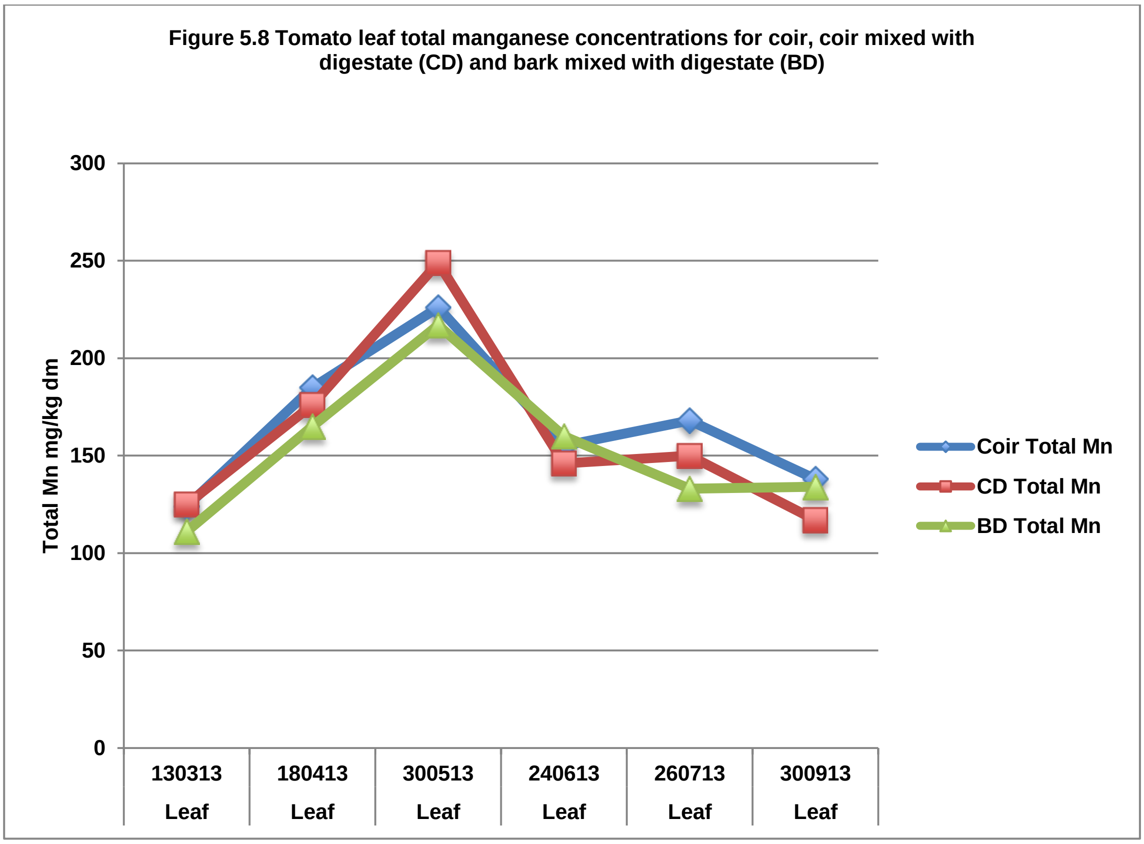


Figure 5.8 Tomato leaf total manganese concentrations for coir, coir mixed with digestate (CD) and bark mixed with digestate (BD)
Total Mn mg/kg dm
300
250
200
150
100
50
0
130313 Leaf
180413 Leaf
300513 Leaf
240613 Leaf
260713 Leaf
300913 Leaf
Coir Total Mn
CD Total Mn
BD Total Mn

Figure 5.9 Tomato leaf total zinc concentrations for coir, coir mixed with digestate (CD) and bark mixed with digestate (BD)

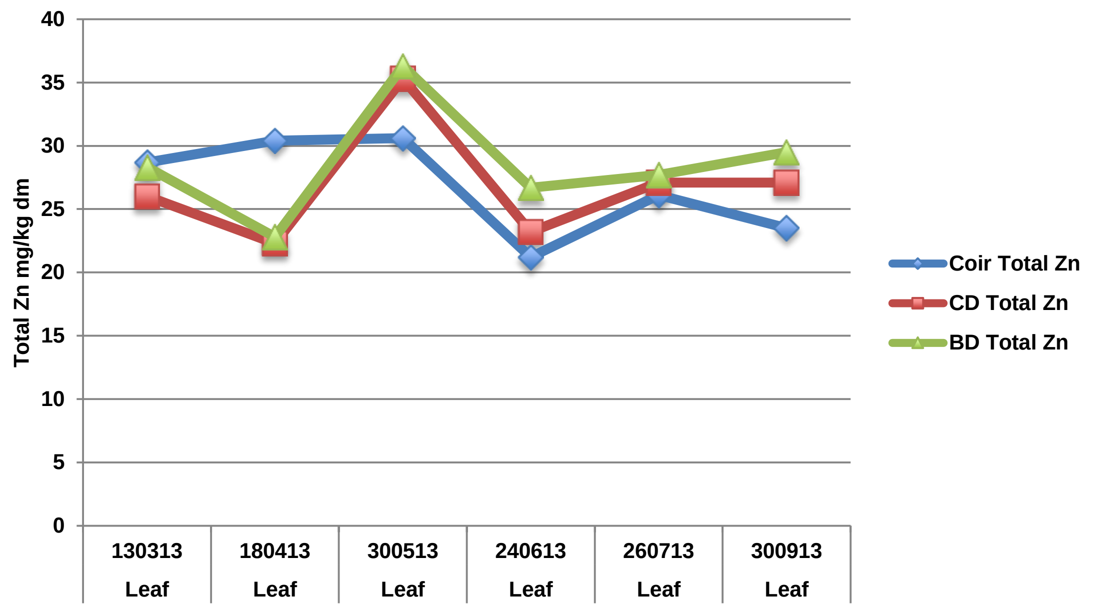
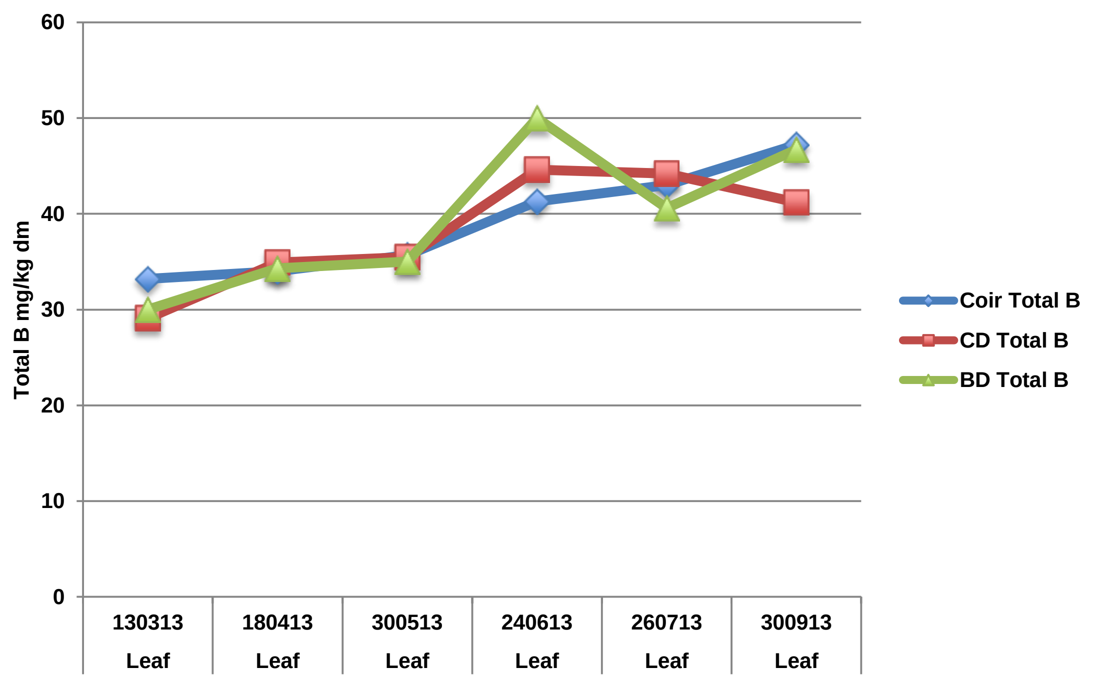


Figure 5.10 Tomato leaf total boron concentrations for coir, coir mixed with digestate (CD) and bark mixed with digestate (BD)



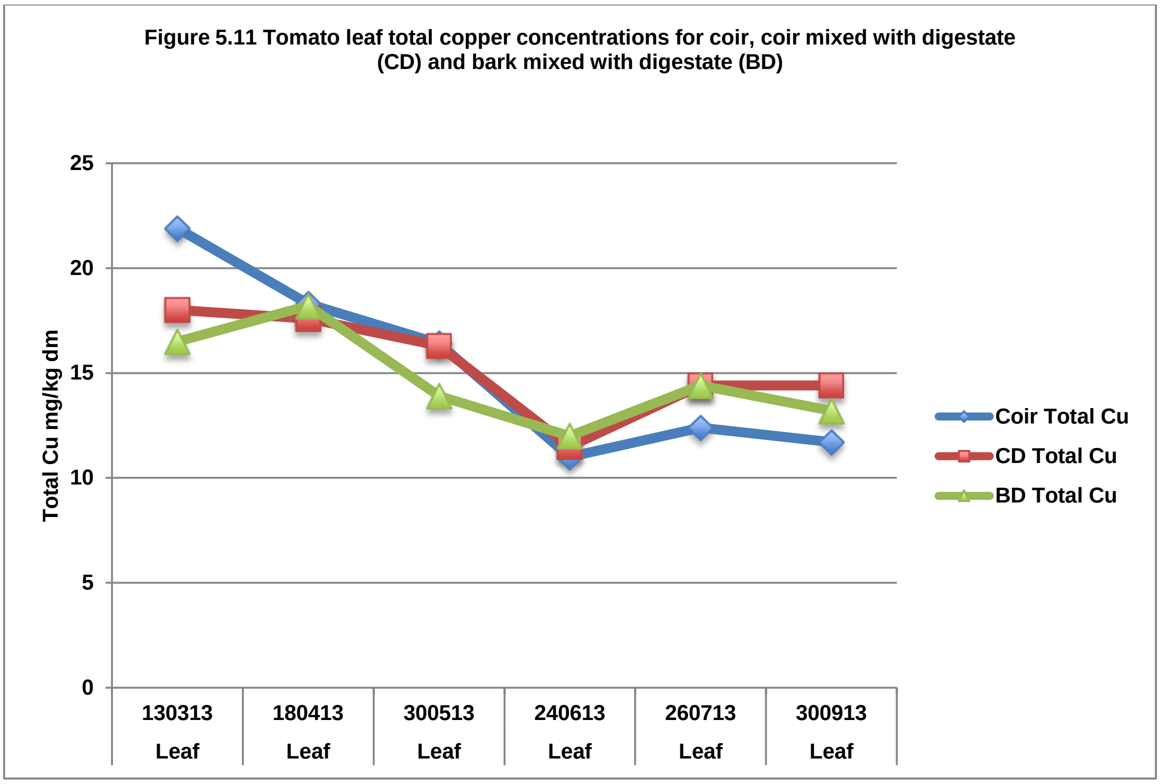


Figure 5.11 Tomato leaf total copper concentrations for coir, coir mixed with digestate (CD) and bark mixed with digestate (BD)
Total Cu mg/kg dm
25
20
15
10
5
0
130313 Leaf
180413 Leaf
300513 Leaf
240613 Leaf
260713 Leaf
300913 Leaf
Coir Total Cu
CD Total Cu
BD Total Cu

5.4 Optimum Leaf Nutrient Concentrations (as provided by May Barn Consultancy Ltd)

Table 5.4 Optimum Leaf Nutrient Concentrations

Plant Tissue Sample	Minimum	Optimum	High	Comments
RAG Chart: Tomato and other glasshouse crops	Red: Likely to result in plant damage	Amber: Likely to result in nutrient deficiency	Green: at or near the optimum concentration	RAG Chart: Tomato and other glasshouse crops
Major Element		% of dry wt		
N		2.0 - 5.0 %		Mobile element in the plant
P	0.2%*	0.3 - 0.5 %	> 1.0 %	
K		2.0 - 5.0 %		Toxicity: rare
Ca		0.1 - > 5.0 %		
Mg		0.15 - 0.35 %		High K inhibits Mg absorption
S		0.1 - 0.5 %		
		Suggested Optimum Concentrations		
Na	< 0.2 %	0.3 - 0.4 %	> 1.0 %	High Na inhibits uptake of K, Ca, Mg
Cl	0.25 mg/g dry matter*	1.5 - 2.0 %	> 30.0 mg/g dry matter*	> 5.0 % suggested as damaging to plants
Trace Element	Critical deficiency dry wt	Suggested Optimum Concentrations	Critical toxicity dry wt	
Fe	50 - 150 mg/kg	> 200 mg/kg	> 500 mg/kg	
Mn	10 - 20 mg/kg	> 100 mg/kg	1380 mg/kg	Critical toxicity value for sweet potato
B	20 - 70 mg/kg	> 100 mg/kg	> 200 mg/kg* 400 mg/kg	Toxicity value: tomato* Tox. value: cucumber
Zn	15 - 20 µg/g	50 µg/g	100 - 300 µg/g	Link with P and Mn
Cu	1 - 5 µg/g	10 µg/g	> 20 - 30 µg/g	
Mo	0.1 - 1.0 µg/g	> 2.0 µg/g	> 1,000 µg/g	

6.0 Results and Discussion: Chemical Analysis of Substrate Samples

6.1 Physical and Chemical Properties and Water Extractable Nutrients

Table 6.1 Physical/Chemical Properties/Water Extractable Nutrients (fresh samples)

Parameter	Unused Coir 150213	Unused Coir and Digestate 150213	Unused Bark and Digestate 150213	Used Coir 011013	Used Coir and Digestate 011013	Used Bark and Digestate 011013
pH	6.4	8.8	8.5	5.65	6.98	6.9
Conductivity µS/cm 20°C	267	413	381	1,130	1,150	926
Bulk Density g/l	412	423	468	354	446	535
Dry Matter % m/m	12.9	22	27.1	14.8	20.4	23.8
Moisture % m/m	87.1	78	72.9	85.2	79.6	76.2
Water Extractable				Water Extractable		
Ammonium-N mg/litre	< 1	< 1	< 1	2.54	< 1	< 1
Nitrate-N mg/litre	< 5	28.7	11.3	300	176	268
Phosphorus mg/litre	8.08	63.8	64.2	121	38.6	49.1
Potassium mg/litre	282	488	447	545	520	524
Calcium mg/litre	1.45	19.6	26.6	388	329	244
Magnesium mg/litre	< 1	12.6	18.7	220	280	183
Sodium mg/litre	80.6	106	85.5	98.3	126	85.9
Chloride mg/litre	334	195	141	538	591	402
Sulphur mg/litre	3.15	30.7	41.1	207	261	158
Iron mg/litre	< 0.5	0.875	0.569	0.988	< 0.5	< 0.5
Manganese mg/litre	< 0.1	< 0.1	< 0.1	0.14	< 0.1	< 0.1
Boron mg/litre	0.184	0.231	0.229	2.66	2.56	1.32
Zinc mg/litre	< 0.1	< 0.1	< 0.1	0.733	1.34	0.87
Copper mg/litre	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Molybdenum mg/litre	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1

The pH results for unused coir mixed with digestate and unused bark and digestate were 8.8 and 8.5, respectively. In comparison, the unused coir pH was much lower at 6.4.

On completion of the trial, pH measurements were lower, with both digestate mixtures at approximately 6.9, compared with coir at 5.65.

EC concentrations of the unused digestate substrate samples were higher than coir but measurements taken on the substrates at the completion of the trial were all higher than in the unused samples.

The water extractable nitrate-nitrogen concentration in the unused bark and digestate sample was lower than in the unused coir and digestate sample suggesting that there may be partial retention of nitrate-nitrogen by the bark fraction of the mixture.

6.2 Total Elements (fresh samples)

Table 6.2 Substrate Total Elements (fresh samples)

Parameter Totals	Unused Coir 150213	Unused Coir and Digestate 150213	Unused Bark and Digestate 150213	Used Coir 011013	Used Coir and Digestate 011013	Used Bark and Digestate 011013
Nitrogen mg/litre	209	1593	1898	505	2034	2561
Phosphorus mg/litre	50	380.7	579.8	157	501.3	806
Potassium mg/litre	590	828.9	962	520	635.4	860.6
Calcium mg/litre	265	1935	2613	840	3123	4082
Magnesium mg/litre	94.5	417.6	568.1	276.5	927	943.8
Sodium mg/litre	123.5	152.1	158.6	80	151.2	145.6
Sulphur mg/litre	55.5	344.7	512.2	213	728.1	799.5
Iron mg/litre	74.5	439.2	542.1	62	575.1	497.9
Manganese mg/litre	3.9	20.7	39.39	2.99	22.14	55.51
Boron mg/litre	1.17	2.69	3.32	4.38	6.9	8.91
Zinc mg/litre	2.41	21.24	32.89	2.26	32.31	35.75
Copper mg/litre	1.16	10.98	16.9	0.69	15.39	18.07
Molybdenum mg/litre	0.09	0.44	0.65	0.16	0.47	0.91

Total concentrations of the major and trace elements were all higher in both the digestate mixtures.

Total potassium, sodium, iron, manganese, zinc and copper concentrations were lower in the used coir sample, compared with the unused sample.

In contrast, only total potassium and sodium concentrations were lower in the used coir and digestate sample, compared with the unused sample.

Total potassium and sodium concentrations were lower in the used bark and digestate sample.

Total potassium, sodium and iron concentrations were lower in the used bark and digestate sample.

The highest total nitrogen, calcium, magnesium, sulphur, manganese, boron, zinc, copper and molybdenum concentrations were measured in the used bark and digestate sample.

The highest total iron concentration was measured in the used coir and digestate sample.

6.3 Total Elements (in dry matter)

Table 6.3 Substrate Total Elements (in dry matter)

Parameter **Totals**	**Unused Coir** **150213**	**Unused Coir and Digestate 150213**	**Unused Bark and Digestate 150213**	**Used Coir** **011013**	**Used Coir and Digestate 011013**	**Used Bark and Digestate 011013**
Nitrogen mg/kg	4170	17700	14600	10100	22600	19700
Phosphorus mg/kg	1000	4230	4460	3140	5570	6200
Potassium mg/kg	11800	9210	7400	10400	7060	6620
Calcium mg/kg	5300	21500	20100	16800	34700	31400
Magnesium mg/kg	1890	4640	4370	5530	10300	7260
Sodium mg/kg	2470	1690	1220	1600	1680	1120
Sulphur mg/kg	1110	3830	3940	4260	8090	6150
Iron mg/kg	1490	4880	4170	1240	6390	3830
Manganese mg/kg	78	230	303	59.7	246	427
Boron mg/kg	23.3	29.9	25.5	87.6	76.7	68.5
Zinc mg/kg	48.1	236	253	45.2	359	275
Copper mg/kg	23.1	122	130	13.7	171	139
Molybdenum mg/kg	1.89	4.94	4.98	3.14	5.24	6.98

The total concentration of each major and trace element was higher in the digestate mixtures, with the notable exception of potassium and sodium.

Both the unused and used coir samples contained higher concentrations of potassium than the digestate mixtures.

The used coir sample contained a higher concentration of sodium, compared with the digestate mixtures.

Total potassium, sodium, iron, manganese, zinc and copper concentrations were lower in the used coir sample compared with the unused sample.

Lower total potassium and sodium concentrations were recorded in the used coir and digestate sample.

In contrast, total potassium, sodium and iron concentrations were lower in the used bark and digestate sample.

Used coir had the highest total boron concentration.

Unused coir had the highest total potassium and sodium concentrations.

Used coir and digestate had the highest concentrations of total nitrogen, calcium, magnesium, sulphur, iron, zinc and copper.

Used bark and digestate had the highest total phosphorus, manganese and molybdenum.

6.4 Potentially Toxic Elements (fresh samples)

Table 6.4 PTE Results (fresh samples)

Parameter **PTE fresh**	**Unused Coir** **150213**	**Unused Coir and Digestate 150213**	**Unused Bark and Digestate 150213**	**Used Coir** **011013**	**Used Coir and Digestate 011013**	**Used Bark and Digestate 011013**
Cadmium mg/litre	0	0.01	0.06	0	0.04	0.07
Chromium mg/litre	1.29	10.08	16.12	1.36	12.33	14.43
Copper mg/litre	1.16	10.98	16.9	0.69	15.39	18.07
Lead mg/litre	0	2.21	2.85	0	2.11	3
Mercury mg/litre	0	0	0	0	0	0
Nickel mg/litre	0.69	6.08	10.04	0.43	10.71	9.31
Zinc mg/litre	2.41	21.24	32.89	2.26	32.31	35.75

Of the unused samples, the highest PTE concentrations were measured in the unused bark and digestate.

In contrast, the highest PTE concentrations were measured in the used bark and digestate sample (except nickel, which was higher in the used coir and digestate sample).

6.5 Potentially Toxic Elements (in dry matter)

Table 6.5 PTE Results (in dry matter)

Parameter PTE dry matter	**Unused Coir 150213**	**Unused Coir and Digestate 150213**	**Unused Bark and Digestate 150213**	**Used Coir 011013**	**Used Coir and Digestate 011013**	**Used Bark and Digestate 011013**	**PAS 100 Upper Limit mg/kg**
Cadmium mg/kg	< 0.1	0.151	0.468	< 0.1	0.490	0.544	1.5
Chromium mg/kg	25.8	112	124	27.1	137	111	100
Copper mg/kg	23.1	122	130	13.7	171	139	200
Lead mg/kg	< 5	24.55	21.93	< 5	23.45	23.10	200
Mercury mg/kg	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	1
Nickel mg/kg	13.7	67.5	77.2	8.53	119	71.6	50
Zinc mg/kg	48.1	236	253	45.2	359	275	400

High chromium and nickel concentrations were measured in both the unused and used digestate mixtures and were above the PAS 100 upper limit.

7.0 Final Discussion

7.1 Intensification of commercial hydroponic systems

Most of the systems referred to in the introduction (1.1) are now used in large-scale glasshouse cultivation of salad crops and an average nursery unit size of 10 hectares is not uncommon across the main glasshouse crop production areas in the world.

Achieved total yields and overall quality of crops produced in intensive hydroponic systems have both improved dramatically over the last 40 years. This reflects improvements made in plant varieties, crop growing structures, developments in environmental control systems, understanding of plant nutritional requirements and also the skill levels of the grower-producers.

Hydroponic systems allow plant growth characteristics to be very carefully controlled. For example, the establishment of the plant following contact with the substrate is essential to develop an extensive root system. This will allow the effective absorption of water and nutrients for the remainder of the production period. The encouragement of vegetative growth, in order to produce leaf growth for crop development, or for harvest, is more easily managed in hydroponic systems. The switch from vegetative to generative growth, in order to stimulate the production of flowers and fruit, is also more easily managed in intensive growing systems, when compared to field-scale operations.

Most of the major long-season salad crop plants - such as tomatoes, cucumbers and peppers - are now grown in hydroponic systems under glasshouses in the UK. Herb plants for final sale as growing plants in supermarkets are now grown in pots on benches, using hydroponic irrigation systems to provide water and nutrients.

Soft fruit crops, such as strawberries and raspberries, may also be grown in bags or modules under glass or in plastic tunnels, using hydroponic irrigation systems.

Investment in these more intensive crop production systems is expensive but the yield and quality of the plants is potentially optimised as a result.

There would appear to be opportunities for the use of digestate in these intensive hydroponic systems. However, the physical, chemical and biological characteristics of both the feedstocks and the digestate must be fully quantified before use. An understanding of the analytical profile of the digestate will help to avoid many of the potential nutritional difficulties and assist management decisions during the crop growth period.

8.0 Conclusions

- High initial concentrations of chromium and nickel in the digestate did not appear to be having an adverse effect on plant growth.
- However, short term storage of the digestate may have reduced the concentrations of available nutrients and potentially toxic elements, prior to use in the trial.
- There were no visible symptoms of plant damage caused by pesticides or herbicides, which may have been present in the digestate mixes.
- The high digestate pH was moderated by the lower pH of the coir and also in the bark mixture.
- Rootzone pH levels were also decreased by the applied liquid feed pH (5.2 to 5.4) and moderately high input concentrations of iron and manganese in the feedstock solution.
- Any root damage caused by irrigation equipment problems or natural growth changes at the onset of high fruit loading, for example, will have aggravated iron and manganese uptake by the plant.
- Liquid feed, drainwater and leaf analysis are all useful indicators of plant nutritional variations for the Grower.
- Digestate may act as an additional nutrient reservoir for the sustained growth and yield of crops, such as the tomato.
- Further research on potential crop contaminants and also the presence of human, animal and plant pathogens in the digestate will be required, especially prior to future use in intensive cropping.

As this initial information was based on an observation trial, any future work needs to focus on studies involving the performance of a range of crops, using the digestate in replicated trials and including statistical analysis of the results.

Once the new Reaseheath College horticultural unit is operational, it is suggested that further research on standard substrates such as coir, with digestates or digestate mixtures is undertaken.

Other crops such as strawberries, could then be monitored on substrates (including digestates) in a more carefully controlled environment, with the flexibility to include plot replication.

This potential work should be integrated with the WRAP studies on use of liquid and solid digestates.

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