VERMICOMPOST LEACHATE (VERMILIQWER) AS A LIQUID FERTILIZER FOR HYDROPONICALLY-GROWN PAK CHOI (Brassica chinensis L.) IN THE TROPICS

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MASTER OF APPLIED SCIENCE

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Vermicompost leachate (Vermiliquer) as a liquid fertilizer for hydroponically-grown pak choi (*Brassica chinensis* L.) in the tropics

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Abstract

Vermicompost leachate (vermiliquer) is the liquid obtained from frequent washing of worms, organic inputs and casts. It is rich in nutrients for plants. The aim of this study was to evaluate the potential of vermiliquer as an alternative to inorganic nutrient sources in hydroponics.

The research consisted of a series of separate experiments. It investigated plant response in terms of yield and nutrient content to such factors as pH, type of pH buffer, electrical conductivity (dilution) and solar radiation, with a comparison to conventional inorganic Boxsell fertilizer in each experiment.

The amount of nutrients in vermiliquer directly depends on the condition of the vermiliquer and source of organic waste used as food for earthworms. Vermiliquer was mainly obtained from vermicomposted paunch (organic waste of plant origin).

The experiments were carried out in two commercially-adopted hydroponic systems with recirculating nutrient solution: NFT (nutrient-film technique) and pot systems. Hydroponic units were operating either on ‘off-line’ batched aerated vermiliquer or ‘in-line’ vermiliquer directly linked to tanks containing recirculated ‘live’ vermiliquer through worm beds.

The results of the experiments carried out in different setups show that it is possible to successfully cultivate pak choi in a hydroponic system wholly based on vermiliquer and that management of such factors as pH, type of pH buffer, electrical conductivity (through dilution) and solar radiation (through shading), can positively influence plant yield and growth dynamics. The results also confirm that the source of organic material is an important factor which determines composition and properties (chemical, physical and biological) of vermiliquer and affects plant biomass production, nutrient accumulation and dry matter nutrient content.

This thesis discusses the various factors and the best management approaches to utilize vermiliquer as a hydroponic fertilizer.

Key words: hydroponics, vermiculture, integrated system, organic fertiliser, vermicomposting, vermicompost leachate, vermiliquer, pak choi, NFT-system
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1. General background

1. Introduction

Hydroponics, the technology of plant production without soil, is a highly productive modern artificial system of intensive farming, where nutrients are supplied to plants directly, dissolved within the nutrient solution. Hydroponically grown leafy vegetables generally out-yield those grown in soil (AVRDC, 1990). However, as in most intensive contemporary systems of plant production, hydroponics is based on high-quality and increasingly more expensive inorganic fertilisers. Both the high cost of hydroponic chemicals and the increasing awareness of their possible negative environmental impacts have stimulated a search for organic fertilisers. Over the past few years there has been a rapid rise in research on investigating ways of shifting from conventional hydroponics operated on inorganic fertilisers to techniques using organic substitutes, especially organic waste resources (Suthar, 2007). In the search for cheap and environmentally friendly alternatives to inorganic fertilisers I turned to the worm industry – vermiculture – to assess suitability of vermicompost leachate, a by-product in vermiculture, as a source of nutrients for hydroponic plant production. Hydroponics and vermiculture combined in one technology potentially opens up the horizons for intensive food production based on recycled organic wastes.

While hydroponics and vermiculture have been widely researched separately, there has been no published attempt to combine them into a system that is self-sufficient in terms of re-using organic wastes via vermiculture for hydroponics.

As far as I am aware, no similar research has been undertaken in Australia.
2. Aims/Objectives

The three most important things in design thinking are: perception, possibility and practicality (the three Ps).

Edward de Bono

The purpose of this research was to test the hypothesis that growth and yield of plants grown hydroponically on a nutrient source derived from vermiculture will be equal to or better than hydroponics based on an inorganic nutrient source. If so, the integration of hydroponic plant production and organic waste recycling through vermiculture is an attractive alternative to unsustainable conventional hydroponic fertilisers and waste disposal.

The major objective of the study was to develop and test such integrated systems and to evaluate management practices that might provide favourable outcomes, and specifically evaluate their suitability to Australian conditions.

With this in mind, two base models of integration were trialled: one operating on recirculating off-line (batched) vermiliquer and the other hydroponic system running on the in-line (direct hydroponic system linked to vermifarms) vermiliquer. Both models were tested with the commercially available nutrient film technique (NFT) setup, pot setup and with the combined NFT/pot setup. One of the primary objectives was to compare the performance of direct linkage with the off-line vermiliquer treatments, and the control.

Because vermiliquer is alkaline, one of the objectives was to reduce the pH of vermiliquer, employing orthophosphoric and nitric acids as buffers. Another was to reduce the amount of vermiliquer and pH buffer used to grow pak choi through dilution of vermiliquer. A series of experiments were carried out to assess plant yield, growth dynamics and nutrient content responses to such factors as pH, type of pH buffer, electrical conductivity (through dilution) and solar radiation (through shading), in comparison with a conventional inorganic fertilizer.
Another aim addressed in this study was to assess whether the source of organic material in vermiliquer affects the yield of the plants. Two sources of organic material (usually referred to as organic wastes) were tested: ‘paunch’ (waste from slaughterhouses: roughly-processed plant material contained in the first stomach of a cow) and kitchen food scraps.

Before addressing the main objectives, a number of minor trials were undertaken to improve management practices. As an example, during preparation for the research, several types of media were tested (data not included into this thesis). With the view of cutting costs of perlite, which was finally chosen for the experiments where medium was used, a technique of washing it for re-use in further experiments was developed.

### 3. Benefits and applications of the hydroponics-vermiculture integration system

*God does not create rubbish.*

(from an interview with a priest on the radio)

With the greater proportion of the global population now living in urban regions, there is a major disconnection between the supply, consumption and return of nutrients to the land. Food is, in the main, produced in rural regions and transported to urban centres, and the nutrients contained in wastes and excreta only rarely find their way back to rural areas.

With the growing demand for food, the pressure for economic land use is also growing. Marginal lands and other non-productive open spaces should be utilised for food production using intensive technologies of water and nutrient recirculation, such as hydroponics.

Organic wastes in cities are ideal substrates for vermiculture, and if integrated systems are developed that link *in situ* vermiculture and hydroponics (and even aquaculture if fish are fed with worms) in cities, numerous societal benefits may be achieved.

There will be benefits of reduced greenhouse gas emissions from land fill sites (although respiration rates and CO₂ emissions for vermiculture have still to be quantified), a lesser
demand on local government-managed land space for land fill sites and lesser transport emissions for haulage of organic wastes. Local governments will also benefit by extending the life of land-fills. Fresh produce available to a city (or isolated rural location) will reduce transport emissions, and produce will suffer less from loss of quality during transportation. The acceptance of hydroponic produce is now common in the marketplace, and the environmentally-friendly aspect of produce derived from organic (processed) wastes as a safe source of nutrients for plants, humans and the environment, and being freshly harvested to conserve quality attributes, should add to that. Therefore, urban consumers will be major beneficiaries. Local, yet non-consumer communities will also benefit from the added greenery introduced to bare roofs and vacant spaces, in terms of reduced heat islands, and in the aesthetic benefits of things green.

Commercial restaurants, and other food outlets will also gain; for if they adopt such systems they will be able to promote their businesses as being environmentally sensitive, minimising the production of true wastes, and adding value to the freshness aspect of local produce.

Potential consumers will include individuals, institutions, companies and businesses, including generators of food and other organic ‘wastes’ in general, managers of recycled organic wastes, worm growers, nurseries, orchard and greenhouse growers, horticulturalists, urban planners and landscapers focusing on environmental aspects, soil blenders, isolated rural communities such as mine sites, governmental structures and indigenous settlements. The list goes on.

As such, each of the above will be concerned with the generation and recycling of organic wastes, with the production of fresh food and with reduction in environmental footprints associated with the same.

The success of the integration will greatly depend on the quality of the food produced, the public environmental awareness of the associated benefits, and on rigorous applied research to underpin routine management practices that ensure commercial viability of future businesses.
4. Australian perspective

With our usual habits of analysis and judgement in the search for the truth, we believe that values are there 'to be discovered'. This is only partly true. Values also need inventing and designing.

Edward de Bono

Australia in general and Queensland in particular face a situation where enormous amounts of wastes are sent to landfills (Cameron et al., 1997). Authorities make an attempt to protect the environment by regulating waste disposal practices and promoting recycling of wastes and water. In Queensland, The Environmental Protection Act 1994, The Vegetation Management Act 1999, The Integrated Planning Act 1997, to name only a few, are examples of the Environmental Legislation which, through numerous regulations and policies, aim to reduce environmental impacts of traditional unsustainable practices. Many governments and local councils have tried to reduce dependency on landfilling by introducing new taxes on wastes, mandatory recycling laws, progressive banning of biodegradable wastes from landfills and increasing existing ‘dump’ fees (Carter, 2009; DEWA, 2003; Zero Waste, 2000).

In 1999 Australia ranked second, behind the USA, in terms of domestic waste generation per capita (Southern Waste Strategy Authority, 2009). In the most recent 2007 report ‘The state of waste and recycling in Queensland’ the Department of Environment and Resource Management documented the generation of 15.8 million tonnes of solid waste by Queensland households and businesses during the 2006-07 financial year (EPA, 2007). Only 38% (6 million tonnes) was recovered (diverted from landfills). It was estimated that on average, each Queensland resident generates 270 kg of household waste and 61 kg of recyclable paper and packaging materials per year. Councils have reported that the total amount of waste is increasing.

The 2006 report released by the Environmental Protection Agency states that in Queensland green and organic waste make more than a half of all wastes managed by the government and private sector (EPA, 2006). Even with relatively high rates of recovery (> 80%) enormous amounts of green and organic wastes are landfilled.
Of all resource streams, organic wastes and green wastes were two categories that had the highest rates of recycling (between 70%-80% in 2004-2005 years and 88%-94% in 2006-2007 years). Most of the organic and green wastes were recycled through composting (EPA, 2005, 2005, 2006, 2007). The main organic wastes were garden waste, biosolids, forestry wastes, manure, oils, grease and sludges; the main outputs were mulch, manufactured soil and soil conditioner (EPA, 2006).

Vermicompost and compost tea were only mentioned once in the 2005 report (Table 1.1). Out of eleven composters who participated in the survey only one used vermicomposting.

Table 1.1. Recovery of organic and green wastes in various materials (from EPA report, 2005).

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount recovered (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compost</td>
<td>60,029</td>
</tr>
<tr>
<td>Mulch</td>
<td>54,000</td>
</tr>
<tr>
<td>Soil mixes</td>
<td>9,000</td>
</tr>
<tr>
<td>Bark chips</td>
<td>4,000</td>
</tr>
<tr>
<td>Vermicompost</td>
<td>280</td>
</tr>
<tr>
<td>Compost tea</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>127,319</strong></td>
</tr>
</tbody>
</table>

These statistics clearly show that considerable quantities of nutrients are lost to landfills and that the use of vermicomposting, one of the cheapest and the most effective ways to recycle organic matter, is greatly undervalued.

Besides the need for recycling organic wastes, there are further issues associated with landfills such as methane production and other environmental hazards. With restricted access of moisture and oxygen to the organic wastes buried in landfills, they undergo anaerobic bacterial processes, which are slower than aerobic catabolism of organic material. This results in the formation of partially oxidised compounds many of which are phyto-toxic and contribute to the toxicity of the leachates. Products of anaerobic digestion are methane (CH₄), hydrogen sulphide (H₂S), phosphate (PO₄³⁻) and nitrogen gas (N₂). Methane as a gas is reported to be 21 times more potent than carbon dioxide in causing the so-called “greenhouse effect” that is implicated in global
warming and consequent climate change. Worldwide, emissions from landfills and open dumps have been estimated to contribute six per cent of total global methane emissions (Zero Waste, 2000).

Instead of increasing the rate of land fill growth and creating associated long-term methane emissions, urban food wastes and other organic wastes can and should be recycled into healthy fresh foods. An effective use of plant and animal waste resources might contribute to reducing net methane emissions.

Business opportunities in Australia to utilise organic wastes through integrated vermiculture-hydroponics system are better than anywhere else. Australia, ranked in the top 10 of world commercial hydroponic producers, already has a good basis for hydroponic production (RIRDC, 2001).

In colder climates hydroponic operations are restricted to greenhouses and can be an extremely energy-demanding industry because of the need to provide the plants with adequate amounts of light and heat for optimal growth. The climate in tropical parts of Australia provides a certain advantage for year-round food production – greenhouse heating is generally unnecessary (Garzoli, 1988) and more than half of all hydroponic crops are grown outdoors. The proportion of open hydroponic farms in Western Australia and Queensland is higher than in other states (RIRDC, 2001). In addition to the naturally reduced heating requirements, by world standards Australia has relatively low energy costs (RIRDC, 2001).

Vermiculture-hydroponics integration offers a way forward in the contemporary agronomics for sustainable food production, without damaging any eco-system. Besides transforming nutrients from organic wastes into valuable products, ‘on-site’ food production in close proximity to consumers could substantially cut transportation costs of food and provide the customer with top quality fresh produce. Presently fresh food consumed in cities is transported great distances. It has been estimated that the cost of transport of a $1 supermarket lettuce head ranges between 30 and 60 cents (Acharya et al., 2009; Sexton, 1995).

The integrated system can be operated in the most hostile urban environment. Concrete roofs are conductive to stormwater run-off; water that falls on the urban landscape often ends up
entering creeks, rivers, lakes and oceans (laden with urban pollutants), or enters sewage treatment plants, diluting the waste-stream and adding to the costs of water treatment. Water shortage has already been identified as a major problem for the agricultural industry in Australia and utilising Australian roof and wall space for water capture could provide part of the solution. Integrated vermiculture and hydroponics have the potential to provide comprehensive solutions to all of these issues and many more.

It will promote a healthy lifestyle, for eating more fresh vegetables and fruit in preference to manufactured foods with high fat, high starch or high sugar contents is one of the recommendations made by nutritionists trying to combat the “obesity epidemic”. The epidemic is well evidenced in Australia, especially among children.

As with any innovative approach, there are serious challenges and problems to be solved to ensure business certainty and public acceptance. Essentially comprising an organic system, the integrated system has yet to be accepted, developed and certified as such, because the plants are not grown in the soil.

Economic viability will be the main measure of success of the integrated system. Economic potential, together with long-term benefits of an environmental imperative, land conservation, and wise water-use benefits make the challenges worthwhile.

5. The Australian Asian leafy vegetables industry and hydroponic production of pak choi

You can analyse the past but you need to design the future. That is the difference between suffering the future and enjoying it.

Edward de Bono

Asian vegetables encompass leafy vegetables (e.g. pak choi, choy sum), leafy mustards (e.g. mizuna), legumes (e.g. yambean), water vegetables (e.g. Chinese water chestnut, lotus), herbs (e.g. shallots, basil, coriander) and root crops (e.g. ginger, daikon) and others (e.g. wasabi,
bamboo shoots). The domestic market accommodates more than 80 Asian vegetable types, but the major production volume is provided by a limited number of crops. These include leafy vegetables such as pak choi, kai laan, and choy sum (RIRDC, 2003).

Nearly a decade ago Moore et al. (1998) reported that Chinese vegetables comprised approximately 10% volume of the total Asian vegetable production in Australia. The Asian vegetable industry in Australia was valued at $136 million p.a., up from $50 million p.a., in 1993/1994, having more than doubled in production value and grower numbers since 1995 (RIRDC, 2003). Besides strong domestic demand for Asian vegetables, Australia currently exports 16% of Asian vegetable produce. Queensland and Western Australia dominate Australian export sales, which together account for 76% of export volume. Market surveys forecast that Western Australia will stagnate unless new and profitable export markets are identified, while export sales will grow in Queensland and the Northern Territory (RIRDC, 2003).

Market reports forecast massive growth in food demand by 2050, especially from countries such as China, India, Pakistan, Bangladesh and Malaysia (Beaumont, 2009). As a general trend, growth in ethnic populations contributes to demand for product diversity within the produce section (Cook, 1990) and food, previously considered ethnic or regional in nature is increasingly being consumed by a broader portion of the population (Palada and Crossman, 1999). Geographically close to Asian markets, Australian prospects for development of the Asian vegetables horticultural sector are bright (Midmore, 1997).

However, relatively high priced land, water, suitable labour, limited farm investment capabilities, costs of packaging and transport to markets have been reported as major weaknesses of the Australian Asian Vegetable Industry (RIRDC, 2003). However, the same report highlights hydroponic production among the main opportunities for industry development. Since the mid 1990s hydroponics has developed as a dynamic growing trend in the production of the Asian vegetables, especially of pak choi, choy sum and Asian herbs. Australia is recognised as the largest hydroponic lettuce grower in the world (RIRDC, 2001). Domestic hydroponic production is dominated by lettuce, tomatoes and cut-grown flowers.
Hydroponic culture of pak choi is well-proven. It falls into a stream of Asian vegetables that has a certain advantage in the market place. It relies on a commercial source of seed, including hybrid varieties, and production techniques supported by research studies, and marketing and logistics channels are well established. Geographic locations within tropical Australia can provide optimal growth conditions for pak choi all year round. In the summer months in temperate climates it takes as little as 2-3 weeks to hydroponically produce a crop of pak choi of a commercial standard. Pak choi is rich in vitamins A and C and folic acid. Glucosinolates, chemical substances found almost exclusively in the Brassica family (including pak choi), have been linked to reduced incidence of certain cancers (O’Hare et al., 2005; RIRDC, 2003). The high level of antioxidant (such as carotenoid) production in pak choi is considered to be beneficial for human dietary requirements (Oomen and Grubben, 1978).
2. Literature review

*We drive into the future with our eyes on the rear-view mirror.*

Marshall McLuhan*

(*cited by Edward de Bono)

**Part I. Hydroponics**

Hydroponics initially meant ‘growing plants in water’. In 1880 Julius Sachs, a German botanist, demonstrated for the first time that plants could be grown to maturity in defined nutrient solution without soil. Since then, with the rapid expansion in the hydroponics industry, ways to grow plants hydroponically have greatly improved. Hydroponic systems (i.e. NFT – nutrient film technique; aeroponics) have diversified and many substrates (i.e. perlite, rockwool, coco peat) have replaced soil. Therefore, the definition of hydroponics has been widened to ‘growing plants without soil’.

### 2.1 Why hydroponics?

Because it does not use soil, hydroponic plant production does not require fertile farmland and does not suffer from climatic variability such as droughts and floods. Hydroponics can be operated in cities, deserts, and even on spaceships. Hydroponics principles enhance water use efficiency. Recirculation systems allow for water re-use and minimise losses as evaporation and run-off. But the main advantages of hydroponics are in scheduled production of homogenous high-quality vegetables, a reduction in the incidence of diseases, and production throughout the entire year. Therefore, the soil-less plant production method supports rapid growth rates and greater control over the crop.

With efficient nutrient use, all elements required for growth are supplied directly to the roots. Plants in hydroponic systems normally out-yield soil-grown crops. For example, conventionally grown lettuces might produce 3-4 crops on the north coast of NSW, while hydroponics will produce between 7 and 14 (RIRDC, 2001), and so the greenhouse lettuce production cycle (35
days) is much shorter than the field production cycle (90-120 days) (Acharya et al., 2009). Hydroponics may also provide an earlier harvest of vegetable and flower crops.

However, as in all artificial systems, hydroponic methods need to be managed sustainably. Regardless of the type of system, hydroponics technology needs to be cost-effective. The expenses include start-up costs (including greenhouses, equipment, control systems) and operating costs that can be substantially greater than for conventional soil operations. Even though the high cost of hydroponics systems can be offset by their higher productivity, most problems associated with hydroponics originate from ‘how to become rich quick’ oversimplification of the technology and unrealistic expectations. Lack of management experience and basic scientific knowledge of gardening principles, together with a great dependence on technical support to keep the system functioning remain the major disadvantage of hydroponic ventures.

While soil provides the plant with some buffer capacity to resist nutrient stresses, hydroponically-grown plants lack that flexibility – there is very little room for errors and the system requires constant monitoring.

From the point of public awareness, some consumers still perceive hydroponics as an ‘unnatural’ chemical-reliant production system (Carruthers, 1993).

### 2.2 Types of hydroponics

Essentially, all hydroponic systems work on the same principle – to provide roots of plants with adequate water, oxygen and nutrients – but vary in design and engineering solutions.

There are two basic types of commercial hydroponic crop production systems: closed or open systems (Seymour, 1993). The first are designed to re-circulate the nutrient solution, while in the second the ‘worked out’ nutrient solution is discharged and totally replenished with the new one. The latter are also called ‘run to waste’ drainage systems.

Hydroponic systems are classed as media-based (in which different substances are used to support the plant, i.e. clay, perlite) or media-free (i.e. NFT – nutrient film technique).
Hydroponic systems can be further categorized in the way the plants are supplied with nutrients and oxygen. In drip-and-drain culture, nutrient solution is applied regularly, slowly drips from the top of the medium, or is sub-irrigated from the bottom. In aeroponics systems (which are rarely used commercially), roots are intermittently misted with a nutrient solution in a light-proof chamber.

Table 2.0.1. Types of production systems used by Australian growers (from RIRDC, 2001).

<table>
<thead>
<tr>
<th>System Type</th>
<th>Proportion of Commercial Producers using System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Closed (recirculating)</strong></td>
<td></td>
</tr>
<tr>
<td>Nutrient Film Technique (NFT)</td>
<td>38%</td>
</tr>
<tr>
<td>Media based</td>
<td>16%</td>
</tr>
<tr>
<td>Aeroponics</td>
<td>2%</td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td>56%</td>
</tr>
<tr>
<td><strong>Open (run-to-waste) Systems</strong></td>
<td></td>
</tr>
<tr>
<td>Rockwool (inorganic media)</td>
<td>13%</td>
</tr>
<tr>
<td>Other</td>
<td>30%</td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td>43%</td>
</tr>
</tbody>
</table>

Commercial production is run on a range of techniques. The Australian industry is primarily based on nutrient film techniques (NFT) and media-based systems (Table 2.0.1). NFT is a common choice for short-term leafy crops such as lettuce. Long term crops and flowers are usually grown in media-based systems (Donnan, 2009). More systems are moving towards recirculation.

NFT is the most popular commercially adopted hydroponics technique. It consists of a flat-bottomed sloped channel or gully with a recirculated thin film of nutrient solution flowing past plant roots (Mason, 2005). This NFT technique provides both nutrient uptake and good aeration of roots. The yield in the NFT has been reported to be higher than in other types of soil-less cultures, for example in sand culture (Zhai et al., 2009; El-Shinawy and Gawish, 2006).

With an array of available hydroponic designs, choice of hydroponic system depends on the crop, system reliability, life span, installation and maintenance costs, and skills of the grower.
2.3 Media used in hydroponics

A variety of substrates can be used in hydroponic culture. The main function of the media is to mechanically support the plant and to provide sufficient access to nutrients, water and oxygen by the roots. It is preferable to use physically and chemically inert (ideally “non-nutritive”) substrates free of contaminants, to avoid interference with the nutrients required by plants.

It is common to categorise media into organic (such as processed wood products, peat, coconut fibre, foam products) and inorganic (such as rockwool, perlite, pumice, clay, vermiculite). Media vary in water- and oxygen-holding capacity, as well as differing in structure, appearance and cost. Some of the materials can be washed of undesirable nutrients and contaminants and re-used. Perlite, vermiculite, rockwool, peat, clay pebbles and acid-washed quartz sand are some of most popular commercially-used substrates.

Some data on plants grown in different hydroponic media with nutrient solutions derived from either inorganic or organic salt-based fertiliser sources showed that there was only little variation in yield among media (Succop and Newman, 2004; Blom, 1999), but there is some evidence of better yields in perlite-based media compared with others (Gul et al., 2003; Maloupa et al., 1999).

Some differences among media may arise from their chemical characteristics. For example, coco-peat tends to be more acid than rockwool. Rockwool will usually have a slightly higher ammonium content and help control upwards pH drift, while coco-peat will usually have a slightly lower ammonium content and help control downwards pH drift (Donnan, 2009).

Stability of the growing media is important, particularly where the crops are grown over a long time. As a rule, organic media is broken down faster than inorganic media. The rate of breakdown depends on decomposition rate and particle size. For example, decomposition of fine peat was faster than coarse peat and wood fibres broke down even faster (Prasad and O’Shea, 1999). Anecdotal evidence of using such materials as sawdust as a hydroponic medium shows that after a short time the organic tissues start to decay and the media becomes acidic, loses its structure and then becomes anoxic.
Other differences among media have been attributed to their different characteristics. For example, different media also have different CEC (cation exchange capacity) and therefore differences in ability to bind nutrients. Initially the medium absorbs ions from nutrient solution to its maximum CEC, in a process known as ‘loading’. During this initial period care should be taken to ensure that, with nutrients tightly bound to the medium, plants do not suffer from nutrient deficiencies. To illustrate this, peat has a high CEC while perlite, polystyrene, rockwool and sand have almost no CEC (Argo and Fisher, 2008). To take advantage of the CEC, a high CEC peat would suit an ‘ebb and flow’ system, while rockwool would make a better choice in a constant flow system.

There have been several reports on how substrates may affect composition of the nutrient solution. Gul et al. (2003) report that some additions to the media (e.g. an increased clinoptilolite ratio in a tuff-based substrate) reduced the phosphorus content of the drained nutrient solution, but variation in clinoptilolite in the peat-based media did not significantly affect the phosphorus concentration of the drained solution. Blom (1999) reported on higher concentrations of micronutrients in roses grown in coco-peat media than in rockwool.

Structural differences should also be taken into consideration when choosing the medium. It has been reported that after irrigation rockwool is prone to a centre waterlogging, which diminishes its oxygen-holding capacity and, when regularly over-irrigated, may result in root rotting. This can be overcome by aerating the nutrient solution (Bhattarai et al., 2008).

Recently more publications are emerging on the subject of roof-top hydroponics (Elstein et al., 2008; Kidd, 2005; VanWoert et al., 2005; Wong et al., 2003). For roof-top hydroponics light-weight media are favoured for efficient use of construction materials and of roof space to avoid overloading and overcapitalisation.

Choice of media needs to take into account physical and chemical properties, price and anticipated use.
2.4 Requirements for hydroponic plant production and management practices to control specific environmental conditions

Greenhouse hydroponics is often associated with total environmental control for plant growth. Essentially, productivity of hydroponic systems reflects the farmer’s ability to provide plants with optimal conditions for growth. These include nutrients, water, oxygen, carbon dioxide, moisture, temperature and light. Hydroponics and greenhouse technology allow precise management of each of the factors.

2.4.1 Temperature – heating/cooling practices

Most plants are able to survive in a temperature range from 10-32 °C, but maximum growth rates are achieved when the plants are exposed to their optimal day and night temperatures. The rate of growth of plants is affected by temperature to such an extent that air temperature is still the dominant climatic parameter for greenhouse climate control (Garzoli, 1988). In temperate climates greenhouses are often heated to maintain the temperature within a desired range. For the same purpose in hot climates and on hot days in temperate climates, cooling systems are designed.

Agricultural crops are classified as cool-season (or cold resistant) and warm-season (or chilling sensitive) species. Cool-season species grow better in temperate climates and do poorly in the hot tropics, and vice versa for the warm-season species. Cabbage (*Brassica* spp.), barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), and spinach (*Spinacia oleracea*) are classed as cold-resistant crops. Conversely, species of tropical and sub-tropical origin such as cucumber (*Cucumis sativum*) and maize (*Zea mays*) are classed as chilling-sensitive species.

When dealing with production of plants, especially cool-season species in the Australian tropical environment, high temperatures and heat-stress are the most important issues. The costs to cool a greenhouse are three to five times higher than to heat one (RIRDC, 2001). In the tropics, growers implement diverse cooling practices to lower the temperature of the greenhouse and nutrient solution. To reduce solar heat load and dump excess heat energy, greenhouses have
effective ventilation systems and (flexible) shading. In conditions of relatively low humidity (under 60%), evaporation of water, fogging or misting, has a cooling effect. Such conditions are typical for northern inland regions of Australia, but evaporative cooling would not be so efficient in eastern ocean-side tropical areas. For example, the maximum amount of cooling obtainable with air at 30°C and 40% relative humidity is 8°C, while at an air temperature of 30°C and relative humidity 80% it is only 2.4°C (Connellan, 2009).

High temperatures initiate some biochemical and morphological changes in vegetables. In lettuce, for example, it causes development of loose heads (Dainello, 2003), reduces growth rate, increases bitterness and toughness of leaves, causes tip burn and, thus reduces commercial value of the product. In addition, plants tend to bolt at high temperatures.

It has been frequently reported that temperature in the root zone is even more important for plant growth than the surrounding ambient air temperature. For many plants adverse results occur with root temperatures below about 16°C and above about 25°C, probably because the uptake of nutrients and oxygen is impaired (Garzoli, 1988). Hydroponics has opened the way for controlling the temperature of the roots through heated or chilled nutrient solution. For example, experiments on heat-sensitive pak choi conducted in Singapore under hot equatorial conditions showed that plants growing in the nutrient solution chilled by a few degrees did significantly better than plants in the control solution (Leow and Wong, 2006).

### 2.4.2 Humidity – air movement control

Most plants grow best within a relatively narrow range of humidity values – 70-85% relative humidity for many species (Garzoli, 1988). With low humidity, moisture stress may occur even with an adequate water supply to the roots. High humidities depress the evaporative demand on the plant and impair the uptake of nutrients. Besides, with high humidities plants become vulnerable to pathogens and fungi developing in condensation droplets. Optimal humidity in greenhouses is maintained through an adequate air movement and altering temperature.

Experiments by CSIRO have shown that 0.5-1 m/sec is the ideal air speed through the plant canopy (Garzoli, 1988).
2.4.3 Light – solar radiation control

Light is essential for photobiological processes that take place in plants. In northern latitudes light is considered the most limiting factor for greenhouse vegetable production. Generally, a 1% decrease in light reduces yield by 1% (Jensen, 2002). In light-deficient conditions in temperate climates, especially in winter, artificial lighting, such as horticultural lamps, reflectors and light balancers help to maximize plant growth and yield.

In tropical climates, however, excessive solar radiation may cause heat stress and photo-shock. Too high a light intensity can cause scorching or bleaching of the leaves (Garzoli, 1988). Greenhouse covering and screens help to reduce solar heat load. Examples of improvements in greenhouse covering include those that reduce solar infrared radiation, incorporate colour pigments to improve the spectral balance (increase blue to red light ratio) and fluorescent agents to increase emission of red light, and selectively absorb ultraviolet to reduce the occurrence of plant pathogens (Giacomelli and Roberts, 1993). Thermal screens reflect light when it is excessive and retain heat when it is limiting, thus reducing accumulation or loss, respectively (Powerplants website). Seed germination of some species may be influenced by the absence or presence of light, showing a typical phytochrome-mediated response to red and far-red light.

Another aspect of light is its influence on flowering, known as photoperiodism. Plant species vary greatly in the light intensity required for a photoperiodic response. There are some techniques to stimulate or control growth processes by manipulating lighting such as blackout screens or supplementary lighting (Pinho et al., 2007; Garzoli, 1988).

2.4.4 Carbon dioxide

In the presence of light, photosynthesis converts carbon dioxide and water into sugars. There is normally 330-350 mg/L CO₂ in the atmosphere but locally it may vary between 300 to 600 mg/L CO₂. Some crops, such as vegetables and some flowers, show significant increases in yield when concentration of CO₂ is raised to 700-1000 mg/L (Garzoli, 1988). When using elevated levels of CO₂ the growth rate can be increased by as much as 100% to 200%. Most studies report increases in the 40% to 50% range (Biksa, 2008). Most plants can use 1500 mg/L
in optimum growing conditions. Thus, provided that water and light are sufficient, CO₂ enrichment can increase the growth rate (Mavrogianopoulos et al., 1999).

Carbon dioxide enrichment is employed routinely in the greenhouse industry. There are several ways to do this. The most common is to use CO₂ generators that burn either propane or natural gas. Another is to use bottled CO₂ gas and dry ice, although they are generally regarded as too expensive for commercial application (Garzoli, 1988).

The integrated hydroponics/vermiculture system discussed in the current study, besides other benefits, has a potential as an inexpensive natural CO₂ generator for a glasshouse application, since CO₂ is a normal bi-product of the vermicomposting process resulting from decomposition of organic matter.

2.5 Parameters of nutrient solutions

2.5.1 pH

The recommended range of pH in the root zone of most plants (the rhizosphere) is between 5 and 7 (Quilleré et al., 1993; Weir et al., 1986; Helyar, 1984; Hydroponic Growers’ website).

The direct effect of pH on root development is not great and plants have the potential to grow well in a wider pH range provided nutrients are available, but it is the availability of nutrients that is very pH-sensitive. Uptake of phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) decreases in acidic conditions below the optimal range. The solubility of phosphorus (P) and boron (B) increases as pH approaches neutrality (Jones, 1997). Availability of such elements as manganese (Mn), copper (Cu) and zinc (Zn) and especially iron (Fe) is greatly reduced in alkaline conditions.

It is recommended that nutrient availability for hydroponic culture is maximized at a pH between 5.5 and 6.5 (Jones, 1997). In other studies the optimal range of pH has been found to be between 5.5 and 5.8 (Bugbee, 2003). There are studies that show that the growth at pH 4.0 and pH 5.8 was not significantly different for wheat (Bugbee, 2003) and had little effect on
fresh yield of tomato plants (Huang and Tu, 1999), although it has been reported that low pH of 4.0-5.5 suppressed development of pathogens such as tomato bacterial canker (Huang and Tu, 1999). In hydroponic culture care should be taken when choosing a medium because low pH may dissolve some media, especially rockwool (Donnan, 2009).

Unfortunately, it is difficult to keep hydroponic solutions within the optimal pH range because they lack the natural buffer ability of soils. The major elemental uptake from the hydroponic solution and especially the form in which minerals are removed defines the pH shift. For example, alkalinity of the media is associated with the uptake of $\text{NO}_3^-$ and acidity of the media is associated with the uptake of $\text{NH}_4^+$ (Jones, 1997).

Buffers are used to stabilize pH (Bugbee and Salisbury, 1985). Phosphoric and nitric acids are traditionally used in hydroponics to lower the pH of the solution. Sulphuric acid is possible, but rarely used. Potassium bicarbonate or potassium hydroxide is used to elevate pH. Addition of ammonium ions into the system (in the form of ammonium nitrate, or contained as impurity within calcium nitrate) will result in a relative lowering of the pH, because ammonium ions are taken up by plants more quickly than other nutrients (Donnan, 2009). Where large amounts of buffer are required, care must be taken to prevent adverse effects, because of the risk of significant accumulation of the nutrient ions that come from the buffer. Bugbee (2003) reports that, for phosphoric acid, the amount of phosphorus required to stabilize pH is close to toxic concentration and also reports that when nitric acid is used for pH control, it makes up to a half of the total nitrogen required for the plant growth. High levels of ammonium can be toxic to plants, in particular causing root death (Donnan, 2009).

The usual practice is to provide the most pH-sensitive nutrients such as iron in a chelated form which provide a shell for the specific ion and degrade gradually, thus making the nutrient available to plants under any pH condition. This greatly offsets the necessity to adjust pH. Reports on tomato growth at pH levels between 8.0 and 8.5 with a chelating agent added to the solution to prevent the problems of solubility of nutrients show that the plants were not adversely affected by alkalinity of the solution (Quilleré et al., 1993; Watten and Busch, 1984).
2.5.2 Electrical conductivity

For conventional inorganic hydroponic fertilisers, electrical conductivity is an easy and accurate estimation of the total nutrient concentration in the solution. For organic fertilisers, EC of the nutrient solution is of limited use only, because it only detects inorganic constituents.

However, electrical conductivity does not necessarily estimate nutrient uptake or concentration of specific elements in the solution. Electrical conductivity may vary if plants take up more water than nutrients (an increase in solution EC as often happens in summer) or more nutrients than water (a decrease in solution EC as often happens in winter). It does not indicate nutrient balances and really only indicates the total amount of soluble nutrients contained in the solution in the form of negatively and positively charged ions. Bugbee (2003) notes that electrical conductivity mostly measures the calcium, magnesium and sulphate in solution and that the micronutrients contribute less than 0.1% to electrical conductivity.

Nutrient solution EC affects commercial characteristics of crops such as taste, plant and fruit firmness and shelf life. For normal plant growth, hydroponic nutrient solutions should be in the range 0.5 to 4.5 μS/cm (Carruthers, 1993), but some authors recommend electrical conductivity between 2.0 μS/cm and 4.0 μS/cm as optimal for static hydroponic systems, while for recirculating systems lower levels (circa 1.1 μS/cm) are recommended (Weir et al., 1986; Helyar, 1980; Hydroponic Growers website).

Leafy greens such as lettuce and most herbs require a low EC (0.7 to 1.5 μS/cm in winter and 1.5 to 1.8 μS/cm in summer). Cucumbers, melons, many ornamentals and some cabbage-related crops are recommended to be grown at medium EC (1.6-1.8 μS/cm in summer and 1.8-2.2 μS/cm in winter). Tomatoes, peppers and eggplants prefer a stronger EC (2.5 - 3.6 μS/cm in summer and 3.6 to 5.0 μS/cm in winter) (Sato et al., 2006; Carruthers, 1993; TPS website).

Low yield is a typical response of plants to low EC. As EC increases so does yield, up to a point where it increases no further and then decreases: eventually excessively high nutrient solution concentrations cause a crop failure. Tomatoes and carnations have been reported to be tolerant of high EC to above 10 μS/cm (Donnan, 2009).
High solution EC makes plants susceptible to calcium deficiency in periods of low transpiration or to high temperature that can lead to blossom end rot in tomatoes and tip burn in lettuce. High concentrations of some ions (sodium as an example) become toxic to many plants such as lettuce, capsicum, strawberries and roses (Donnan, 2009).

### 2.5.3 Water – quality control

An adequate supply of water is the most important priority in hydroponics. Insufficient supply of water, especially during peak demand hours on hot or unusually windy days, when the water demand is highest, may have an adverse effect on plant growth and cause crop failures.

Hydroponics provides far more efficient use of water than does conventional agriculture, but an adequate volume of nutrient solution is important in soil-less culture too. An adequate volume of nutrient solution ensures more stable nutrient balance, pH, EC and temperature stability.

Standards for water purity are usually higher for hydroponic systems than for soil application. Closed systems tend to accumulate substances dissolved in the water manifold. Residuals of pharmaceutical and industrial contaminants in water (heavy metals, pesticides and insecticides) may impact on growth and yield under soil-less culture but also threaten human health (Sánchez et al., 1999). In Australia, a high concentration of sodium chloride in water often causes problems (Donnan, 2009). For a sensitive crop like lettuce, the concentration of sodium should not be allowed to exceed 30 mg/L (Parks, 2009a).

To eliminate salts from water, de-salination, or reverse-osmosis treatment is required. Sterilization of water is also a common practice to reduce the risk of diseases.

### 2.5.4 Oxygen – aeration of hydroponic solution

The availability of oxygen to roots or aeration of the nutrient solution is an essential condition for hydroponic plant production. Microorganisms, mucilage and ultrastructure of roots are greatly enhanced by aeration of nutrient solution (Trollenier and Hect-Bucholz, 1984). Different plant species are known to have different aeration requirements. For example, those for cucumbers and gerberas are higher than for tomatoes and roses (Donnan, 2009).
The benefits of aeration of the root zone have been recognized for various crops under soil-less culture (Holtman et al., 2005; Urrestarazu and Mazuela, 2005; Asao et al., 1999; Thompson et al., 1998, Goto et al., 1996). For example, experiments on pak choi in hydroponic ‘fla’ bed showed that dry weight in aerated treatments was nearly double those in non-aerated ones (Anderson, 2001). Oxygation – delivery of aerated water into the growing medium by way of drip irrigation – greatly enhanced hydroponic production of pak choi in rockwool (Bhattarai et al., 2008). Research on the use of potassium peroxide (1 g/L) once a week as an oxygen generator in an oxygen-deficient rockwool substrate showed the increase in yield by 20% and 15% for sweet pepper and melon respectively (Urrestarazu and Mazuela, 2005). Holtman et al. (2005) reported an increase in the root biomass and leaf area in cucumber as a response to increased dissolved oxygen concentrations.

Because of the need to constantly supply oxygen to roots, the NFT (nutrient film technique) was designed to aerate the nutrient solution by providing a relatively large surface to volume ratio of the thin film of solution. The NFT enables quick replacement from the air of oxygen in solution as it is taken up by plants. The problems with the nutrient film technique have been discussed by several authors. Bugbee and Salisbury (1989) discussed the importance of flow rate and adequate root-zone oxygen levels. Slow flow rates in NFT may cause channeling of the solution and reduced flow to areas with dense roots, which may become anaerobic. Oxygen deficiency inhibits cell respiration, which prevents an adequate supply of metabolic energy for nutrient absorption (Taiz and Zeiger, 1991). This reduces nutrient uptake, increases nitrogen losses through denitrification, and makes roots susceptible to infection (Bugbee, 2003). To overcome the problem, some growers put the pumps on cycles, effectively flooding and draining the NFT system and some administer regular H₂O₂ at a very diluted ratio to the reservoirs containing nutrient solution (Winterborne, 2005).
2.6 Inputs to hydroponics: nutrients and nutrient balances

In hydroponics, all nutrients required for plant growth are fed to roots in solution (Resh, 1995) and for this reason the nutrient composition needs to include all required elements (Muckle, 1993). Plants require 17 essential elements (Hopkins and Huner, 2004), as macronutrients and micronutrients, the latter also known as trace elements. Macronutrients include hydrogen (H), oxygen (O), carbon (C), nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), magnesium (Mg) and are needed in large quantities. Micronutrients are needed in relatively small amounts (less than 10 mmol/kg of dry weight). They are iron (Fe), boron (B), copper (Cu), zinc (Zn), manganese (Mn), molybdenum (Mo), chlorine (Cl) and nickel (Ni). Actions of elements are specific, plants cannot complete their life cycle without them (Rorabaugh, 2002).

Nitrogen, phosphorus, potassium and manganese are readily taken up and redistributed in the plant. Nitrogen, potassium and phosphorous are the three major commercially-supplied essential elements. Understanding of the importance of providing the plant with the three major nutrients led to the concept of the N:P:K ratio, which dates back to the end of 18\textsuperscript{th} century, to the time when agricultural use of N:P:K fertilizers was established in Europe. N:P:K ratios for hydroponic cultures derive from formulae for soil-fertilizers, or are modifications of conventional hydroponic formulae, to provide sufficient amounts of required elements in the ratio for maximum plant growth.

Uptake of other elements – magnesium, sulphur, iron, zinc, copper, molybdenum and carbon – is slower than that of nitrogen, phosphorus and potassium. Calcium and boron are known for their passive mechanism of uptake and, consequently, slow removal from the nutrient solution. Deficiencies in trace elements may affect the ability of plants to assimilate macronutrients, especially nitrogen, phosphorus and potassium.

An appropriate composition of the nutrient solution helps to minimize both costs and environmental impacts. Hydroponic fertilizers need to be balanced and complete, and also free of contaminants, to fully meet requirements for plant growth (Adams, 1992; Heylar, 1984). There is no universal recipe for hydroponic nutrient solutions because different plant species
have different nutrient requirements, which also further depend on the ion source, phenological stage and environmental factors. Apart from ensuring that solutions contain all essential elements, the question of optimal nutrient composition still remains open.

There are guidelines on optimum concentrations of nutrients for particular plant species (e.g. Martin-Prevel et al., 1987; Reuter and Robinson, 1986), but the range of nutrient balance that is acceptable for plants is wide. In the majority of cases growers use commercially available brand formulae such as Manutec and Boxsell. Most hydroponic formulae are based on a composition originally developed by D.R. Hoagland (Hoagland and Arnon, 1950). Minor modifications in the composition of solutions are designed to meet specific needs.

The major problem with the composition is a selective uptake of elements and associated pH-shift. Ideally, nutrients should be added to the solution in the same ratios as they are taken up (Stanhill and Enoch, 1999). However, plants easily remove certain elements from solution, so maintaining high concentrations of nutrients in the solution, even when they are balanced, may result in excessive uptake (Bugbee and Nielsen, 1996; McKeehen et al., 1996). For example, there is evidence that hydroponically-grown plants contain more nitrate (Guadagnin et al., 2005), phosphorus and total nitrogen (McKeehen et al., 1996), but less of certain micronutrients than soil-grown plants as percentage of plant fresh weight.

To maintain nutrient balances in recirculating systems, many hydroponic growers monitor concentrations of individual nutrients in solution and regularly replenish the elements showing low concentration. However, depletion of some nutrients in solution can cause people to add toxic amounts of nutrients to the solution. Bugbee (2003) illustrates this with an example of adding phosphorous in the refill solution under conditions of high transpiration. Phosphorus was absorbed by the plant in a few hours resulting in a phosphorous nutrient concentration that was close to zero. An attempt to maintain the phosphorous at the original level resulted in the phosphorus concentration in plants being far higher than the optimum. High phosphorous level leads to iron and zinc deficiency (Chaney and Coulombe, 1982). Therefore, measuring and maintaining concentrations of nutrients in the solution at pre-set levels is of limited use only.
Bugbee (2003) suggests a model to develop nutrient solution recipes based on plant requirements rather than set-point concentrations in the solution.

Thus, composition and concentration are the most important factors in the formula of optimal nutrient solution. Costs associated with improved balance and increased quality of hydroponic fertilisers urge a search for alternative substitutes. The main focus is on sources containing major macroelements – nitrogen, phosphorus and potassium.

2.6.1 Nitrogen

Nitrogen (N) is one of the key elements in proteins. The most common sources of nitrogen for hydroponics are nitrate (NO$_3^-$) and ammonium (NH$_4^+$), which are the two major forms of nitrogen plants can take up (Mengel and Kirby, 1979), although recent reports give evidence for organic nitrogen uptake (Koga et al., 2001; Nilsholm et al., 2009). Nitrate and ammonium have different physiological effects on plant growth and performance, and so both concentration and ratio in the nutrient solution are of importance (Bar-Tal et al., 2001; Marschner, 1986; Goyal et al., 1982). The effects of NO$_3^-$/NH$_4^+$ ratios on plant growth vary among plant species (Chen et al., 2005; Stratton et al., 2001; Santamaria et al., 1999; Cao and Tibbitts, 1993; Alan, 1989).

Plants grown in hydroponics generally take up nitrogen in the form of nitrate and a strong relationship has been found between the concentration of nitrate in nutrient solution and in plant tissues (Hopkins and Huner, 2004). Studies on lettuce grown under hydroponics show that high concentrations of ammonium and nitrite can easily become toxic to plants (Hoque et al., 2008; Murshidul et al., 2008).

At the same time, however, it appears that many vegetables tend to excessively accumulate nitrate in tissues (EFSA, 2008; Bloom-Zandstra, 1989) and in hydroponic production nitrate level is higher than in soil culture (McKeehen et al., 1996). For example, leafy vegetables produced by different agricultural systems (conventional, organic and hydroponic) have been reported to have different nitrate content (Guadagnin et al., 2005). Nitrate level in crops of lettuce and aragula produced by the organic system was lower than in the conventional system which, in turn, was lower than the hydroponic system. For watercress, organic and hydroponic
samples had similar nitrate content, much higher than in conventionally cultivated samples. Lyons et al. (1993) reported that the median nitrate concentration measured in hydroponic lettuce (465 mg per kg dry weight nitrate-N) was more than twice that of field-grown lettuce.

Nitrate content in vegetables varies according to the species and cultivar, availability of nitrogen, and such environmental factors as light intensity and temperature (Santamaria, 2006; Yu et al., 2005). Some studies carried out in Europe have demonstrated that the nitrate levels in vegetables cultivated in winter are higher than in summer (MAFF, 1998, 2004; Petersen and Stoltze, 1999). In addition, the nitrate content depends on the harvest period in relation to maturation stage and the part of the plants (Ierna, 2008; Amr and Hadidi, 2001; McCall and Willumsen, 1998; Steingrover et al., 1993; Van der Boon et al., 1990, Maynard et al., 1976).

It has been shown that 72%–94% of the nitrate in the human body originates from vegetables (Ysart et al., 1999; Dich et al., 1996; Shen et al., 1982). As a rule, leafy vegetables have a higher nitrate content than any others (Walker, 1990) and Asian leafy vegetables generally have a higher nitrate concentration than any other leafy vegetables including lettuce, silverbeet and spinach (Parks, 2009b).

High nitrate content in food and drinking water is believed to have adverse effects on human health, but this is controversial. As a chemical, nitrate is considered to be of low toxicity, but it can be converted to nitrite which may cause subsequent reactions in the gastrointestinal tract that give rise to highly carcinogenic compounds (Tosun and Ustun, 2004; Weyer et al., 2001). Nitrite toxicity interferes with oxygen transport by haemoglobin and thousands of poisoning cases have been reported, especially in infants (Tosun and Ustun, 2004). Nitrate is suspected to cause certain cancers (Coss et al., 2004; Kim et al., 2002; Eichholzer and Gutzwiller, 1998). However, L’hirondel and L’hirondel (2002) suggest that nitrate from vegetables and tap water presents no danger to human health and may even have beneficial effects, particularly with respect to infectious digestive diseases, cardiovascular diseases, and cancer. Furthermore, it is generally agreed that diets rich in vegetables have been associated with reduction in the risk of cancer due to presence of antioxidants and other anticarcinogenic substances (O’Hare et al., 2005; WHO, 1996).
Despite this conflicting evidence, some countries have introduced regulations for nitrate content in vegetables and drinking water. In Europe, the European Union established for lettuce produced under cover and in the open air maximum levels of 4500 and 3500 mg/kg (fresh weight) for the winter and summer seasons respectively (EC, 2006). The United States Environmental Protection Agency set the limit of 10 mg/L NO₃⁻ for drinking water (US EPA, 1991). Australia presently does not have any regulations regarding the content of nitrate in vegetables. The guideline levels in drinking water in Australia and New Zealand are 50 mg/L for nitrate and 3 mg/L for nitrite (National Health and Medical Research Council and Agriculture and Resource Management Council of Australia and New Zealand, 1996; Ministry of Health, 2000).

Apart from effects on human health, an excess of nitrate taken up and accumulated in plants has been reported to increase the risk of bacterial soft rots and to reduce vegetable quality, including lower vitamin C concentrations (Parks, 2009b). The same author mentions that a high nitrate concentration reduces shelf life of vegetables.

Low-nitrate solutions have been recommended for hydroponics (El-Shinawy and Gawish, 2006; Ellis et al., 1993; Reinink, 1988). Santamaria et al. (1998, 2001) suggested using nutrient solutions with NO₃-N and NH₄-N rather than nitrate nitrogen only, and removing part or eliminating all of the nitrate nitrogen from the nutrient solution a few days before harvesting as strategies of reducing nitrate content in hydroponically-grown rocket salad. Another suggestion to reduce nitrate concentration and increase mineral nutrient concentration in shoots without significant reduction of crop yields was to substitute up to 20% of the nitrate, traditionally used as a source of nitrogen, with glutamin (Gln-N) (Huajing et al., 2008) and other amino-acids (Gunes et al., 1996; Inal and Tarackcioglu, 2001; Chen et al., 2004). Supplying chloride (Cl⁻) and sulphate (SO₄²⁻) in nutrient solutions has been shown to reduce nitrate concentration in vegetables (Inal et al., 1998; Van der Boon et al., 1990).

### 2.6.2 Phosphorus

The key role of phosphorus in plant metabolism is in cell energy transfer. Phosphorus, rather than nitrogen, is most commonly the limiting element in natural ecosystems (Hopkins and
Huner, 2004). Low phosphorus content is characteristic of Australian soils. Plant species and cultivars adopt different metabolic strategies to enhance phosphorus solubilisation and acquisition from phosphorus-deficient nutrient solutions.

Research shows that different Brassica cultivars may exhibit substantial growth difference in terms of crop yield and phosphorus accumulation and utilisation in tissues under phosphorus-deficient conditions. Utilisation of phosphate from extracellular sparingly-soluble phosphorus sources may be promoted by exudation of certain organic acids and root-mediated pH changes. Higher phosphorus acquisition was shown to be related to higher calcium uptake, and so particular cultivars with efficient Ca accumulation ability could acquire higher amounts of phosphorus from phosphorus-deficient sources and better adapt to low-phosphorus conditions (Shabaz et al., 2006).

2.6.3 Potassium

Potassium participates in osmoregulation. For example, in some plants a third of the osmotic potential change can be accounted for by the movement of potassium ions. Therefore, its major function in the plant is through osmotic stomata control in facilitating photosynthesis and transpiration. It also acts as a catalyst in many enzymatic processes. This is the most abundant cellular cation and is required in large amounts, but unlike other macronutrients it is not structurally bound in the plant (Hopkins and Huner, 2004). Potassium deficiency has a dramatic effect on plant ability to survive stresses such as low/high temperatures and resistance to pests. Under alkaline conditions, increased levels of other cations such as calcium, magnesium and sodium can affect the availability of potassium to the plant.

Usually potassium deficiencies are not easily recognised, especially unless true direct potassium deficiency occurs. Developing symptoms of potassium deficiency include yellowing of older leaves, followed by dieback of the leaf tips and scorching of leaf margins (Wallace, 1943).
2.7 Organic materials as inputs to hydroponics

Conventional inorganic fertilizers made of purified mineral salts are basically non-living media, containing pre-determined chemical elements in soluble form. They contain few organic compounds or microorganisms. When used hydroponically, total organic carbon in solution, which consists of microbial biomass and root exudates, does not exceed 15 mg per litre of solution even after two months (Bugbee, 2003).

The concept of adapting commercial hydroponic systems to retrieve nutrients from unconventional sources is not new. A number of experimental designs have been used to utilize nutrients directly from organic matter to produce vegetables for human consumption.

For example, in 1995 a pilot study was conducted at the University of South Wales on production of hydroponically grown lettuce using wastewater (Boyden and Rababah, 1995). They found that lettuce removed over 80% of the nitrogen and 77% of phosphorus from the wastewater, but the growth rate and harvest parameters were lower than in the control crops grown on commercial hydroponic nutrients. Similar results for plants grown hydroponically on domestic wastewater were reported by Norstrom (2005), who found 72% of N and 47% of phosphorus removal from the solution, but, in contrast to the previous authors, this was mainly attributed to precipitation, bacteria and algae. Values for harvested biomass did not support significant recycling of nitrogen and phosphorus through plant uptake.

Anderson and Schmidt (2001) found that the water-soluble materials derived from algae had little value as an organic fertilizer for lettuce. Dry weight of lettuce grown with these materials was only 10-18% of those grown in inorganic fertilizer, depending on the cultivar.

Most reports concur that when using organic nutrient solutions under soil-less culture, yields, fresh shoot weight and chlorophyll content are lower than in inorganic (control) solution (El-Shinawy et al., 2006; Abd-Elmoniem et al., 2001).

Attempts to integrate an aquaculture/hydroponics system serve as another example to capitalize on organic waste from fish production for hydroponic plant production (Losordo et al., 1998;
Rakocy et al., 1992; Rakocy, 1989; Zweig, 1986; Naegel, 1977). In such an integrated system fish effluent becomes a source of nutrients for hydroponics.

A comparison of nutrient content of fish effluent and a standard hydroponic lettuce formulation shows that concentrations of some nutrients in the fish effluent exceed standard hydroponic values, while for others it was less (Rakocy et al., 2007). To estimate the potential of hydroponic plants to cleanse the effluent from aquaculture operations, Quilleré et al. (1993, 1995) carried out studies on a combined system with tilapia (Oreochromis niloticus), tomatoes (Lycopersicon esculentum) and various lettuce cultivars. To promote plant growth, the fish effluent was augmented with extra minerals, including potassium, phosphorus and magnesium. Fresh weight in tomatoes grown on the solution was approximately 70% of the yield from soil-grown culture, while that for lettuce varied between 60% and 112% of the yield produced in a conventional recycling hydroponic system. The plants were only 35% efficient at removing nitrogenous wastes from the effluent, but the authors confirmed that a hydroponics system or integrated recirculation system has the ability to utilize nutrients from the fish effluent.

Jungersen (1997) used wastewater from eel production to cultivate tomatoes in an NFT system. The used wastewater solution had nutrient concentrations of 100 mg N/L and 10-15 mg P/L.

The rates of nitrogen and phosphorus removal for tomato plants were 338-429 mg N/m²/d and 52-70 mg P/m²/d. The annual yield of tomatoes was around 30 kg/m².

The most obvious logistic complication when designing an integrated aquaponics-hydroponics system is to balance the respective sizes of the hydroponic and aquaculture units for satisfactory nutrient supply to the former.

There have been numerous reports that materials derived from organic sources may need to be amended through dilution, supplementation and desalination in order to be used as hydroponic fertilizer.

Ikeda and Tan (1998) grew tomatoes on solutions containing nitrogen (N) derived from inorganic, organic and combined sources. They used different concentrations of urea, nitrate and ammonium to evaluate the role of urea as an organic N source compared to that of nitrate and ammonium as inorganic N sources. Their experiments showed N deficiency and excess...
symptoms in the urea-fed plants at lower (28 mg N/L) and higher (336, 504 mg N/L) N concentrations, respectively. When plants were cultured with the solution containing 168 mg N/L, the total dry weight of the plants which received urea+nitrate was significantly higher than that of plants that were urea-fed only and almost equal to the plants that received nitrate or nitrate+ammonium. These experiments show that both absorption and utilization of N in the plants fed with urea decreased compared with plants fed with inorganic nitrate/ammonium N. Consequently they recommended applying urea+nitrate as a combined source of N for adequate plant growth and sufficient N utilization.

Abd-Eminiem et al. (2001) report on experiments where lettuce was hydroponically-grown in water culture with somewhat unconventional nutrient sources composed of different mixes of pigeon and chicken manure, alluvial soils and inorganic fertilizers. Chlorophyll content did not differ significantly among treatments, with the exception of the pigeon manure+inorganic fertilizer treatment where it was significantly lower compared to the control. Mineral composition of lettuce plants varied significantly depending on the treatment. The highest potassium (K) content was found in pigeon+chicken+inorganic treatment, while chicken+pigeon treatment showed higher phosphorus (P) level and lower levels of Ca, Mg and Fe than the other treatments. The soil extract resulted in the lowest levels of NO₃⁻, N, P, K, Zn and Cu and the highest level of Mg in the dry plant matter. From these findings, the authors suggest that chicken+pigeon manures could be used to supplement conventional inorganic nutrient solutions for hydroponically-grown lettuce.

Other authors (Gul et al., 2003) propose the use of organic manure mixed with different substrates (perlite, clinoptilolite and tuff) as a complete nutrient source for lettuce cultivars. From these experiments, the head weight did not differ significantly between organic and inorganic control treatments, though the analysis of the nutrient solution indicated that NO₃⁻, Ca and K concentrations were lower and the number of non-consumable leaves were higher in plants grown on organic nutrient solution compared to the inorganic control treatment. Later trials to compare the effects of organic manure and conventional inorganic nutrient solution in perlite-based media for growing cucumbers showed that organic manuring decreased the total
yield by 22.4% in comparison with the inorganic nutrient solution. The authors concluded that solid manure application was not adequate for crops with high nutrient demand and a relatively long growing period, and attributed the reduced yield to the lower availability and slower release of nutrients from organic sources (Gul et al., 2007).

Some organic nutrient sources with improved nutrient content through supplementation with salt-based fertilizers show promising results. For example, hydroponic crops of tomatoes grown in combinations of composts obtained from yard wastes, swine manure and spent mushroom substrate, supplemented with liquid sources of organic potassium (K), calcium (Ca), magnesium (Mg), sulphate (SO₄), nitrogen (N) and phosphorus produced yields comparable to that of conventional inorganic hydroponic fertilizer (Zhai et al., 2009). Mushroom compost supplemented with a low concentration of plant-based organic fertilizer was found the most productive organic treatment in these experiments. The organic tomatoes also had a lower postharvest decay index (and therefore a longer shelf life). These treatments showed the highest gross microbial activity, but community physiological profiles of the bacterial populations did not differ between organic and conventional inorganic treatments.

Conditioning of organic nutrient solution may include manipulating its pH and salinity. Capulin-Grande et al. (2005) report on experiments where the liquid fraction of cattle manure, supplemented with calcium nitrate, potassium sulfate and Fe-EDTA, was used as a nutrient solution for hydroponically grown tomatoes. A comparison of citric and phosphoric acids used in their experiments to reduce pH of the solution showed the superiority of phosphoric acid as a buffer. Further trials on nitric and phosphoric acids and mixtures of these, did not reveal any significant difference between the acidulants for plant height, number of fruits or weight per fruit, but better yield and fruit diameter were evident for plants grown on a mixture of nitric and phosphoric (2:1 ratio) acids.

Recycling compost run-off leachates by incorporating them into hydroponics culture is another way of using nutrients that would otherwise go to waste, but little is known about the use of compost-derived products in hydroponic culture.
Jarecki et al. (2005) report on experiments with tomato seedlings (*Lycopersicon esculentum* Mill.) on leachates from spent mushroom compost and pond-collected runoff from a commercial composting operation, including enrichment of these leachates with extra nitrogen and phosphorus. The leachates had low N and P content, and the plants showed N and P deficiency symptoms and restricted growth (e.g. more shoots than roots). At the same time the leachate was rich in potassium (K), magnesium (Mg), calcium (Ca), sodium (Na) and various microelements. The presence of nutritional disorders indicated a need to balance a composition of leachates before recycling in the hydroponic system, because any organic material added to a hydroponic system will only reflect the content of the organic sources. There are also concerns that when applied to hydroponics for food production, all unwanted constituents will be excessively accumulated in plants. For example, plants grown on primary treated effluents tend to accumulate high concentrations of metals (Rababah and Ashbolt, 2000). Organic sources may contain pharmaceuticals, a great variety of household chemicals and substances discharged from trade and industry (Kroiss, 2004). Other concerns are that organic sources may carry or promote plant and human pathogens (bacteria, protozoa and viruses). Zhai et al. (2009) report on Fusarium crown and root rot diseases induced with organic sources of nutrients. In experiments with hydroponic lettuce, uptake of virus-sized particles has been demonstrated (Rababah and Ashbolt, 2000) and so uptake and growth of pathogenic agents is not to be forgotten.
Part II. Vermiculture

In 1881, one year before his death, Charles Darwin wrote in his book 'The Actions Of Worms':

'worms have played a more important part in the history of the world than that most persons would at first suppose'.

Charles Darwin was the first scientist to recognise the key role of the earthworms in the history of the world. He wrote further: 'In the year 1869, Mr. Fish rejected my conclusions with respect to the part which worms have played in the formation of vegetable mould, merely on account of their assumed incapacity to do so much work. He remarks that 'considering their weakness and their size, the work they are represented to have accomplished is stupendous'. Here we have an instance of that inability to sum up the effects of a continually recurrent cause, which has often retarded the progress of science, as formerly in the case of geology, and more recently in that of the principle of evolution.' (Darwin, 1881).

Today the beneficial role of worms in organic matter decomposition processes is widely accepted. Vermiculture has on numerous occasions been reported as an efficient and cost-effective way to dispose of organic wastes (Turnell et al., 2007). Seeding with worms is one of the simplest and cheapest ways of improving soil. Worm-digested nutrients become readily available to micro-organisms and plants while soil aeration and moisture infiltration improve.

2.8 Why vermiculture?

The market growth of the worm industry reflects its commercial potential for use in fishing, composting and production of worm castings and 'worm liquid' (Hansen 2001; Cullinan, 1997). Presently Australia is one of the leaders in the world's vermiculture technology (Vermicrobe Manual, 2008; Hansen, 2001). Commercial-sized vermicomposting plants are operating presently in Australia and other countries (Guerrero, 2005; RELN web-site). In Australia, pilot programs to utilize earthworms in order to reduce the quantities of organic waste sent to landfills were reported on more than a decade ago (Rajiv et al., 2002; Ndegwa and Thompson,
2001; Cullinan, 1997). Industrial applications include the use of earthworms to digest sewage sludge (Edwards and Neuhauser, 1988) and in wastewater treatment facilities for nutrient and pathogen reduction.

### 2.9 Requirements and management practices in vermiculture

Requirements for worm farming naturally depend on the scale of the business and its focus. The principle of a basic vermifarm includes earthworm populations in a bed filled with composted wastes and bedding materials. Vermicomposts and vermicasts (the latter classed as vermicomposts with finer structure) are direct products of worm activity. Basically, they are worm faeces. To maintain humidity in the worm beds, castings are regularly watered and to prevent saturation, the beds are fitted with drainage and collection systems. Collected vermicomposting leachate, or ‘worm tea’, contains large amounts of plant nutrients, as discussed later.

There is a large literature base on vermiculture, but much of the information has been gathered and developed by practitioners, often without scientific peer review. Under conditions of strong market competition, further research and development is very dependent on governmental bodies (Hood, 1999).

#### 2.9.1 Worm species

Earthworms can be divided into two broad categories: earthworkers and composters (Handreck and Lee, 1986; Handreck, 1978). Earthworkers live in soil, while composters are not normally found in soil – to survive they need a moist warm environment with large amounts of compostable organic matter and therefore occur naturally in leaf litter. There are about 350 species of earthworms in Australia (Rutherford and Lamonda, 1996), but all main commercial species suitable for vermicomposting – best decomposers – are introduced composters: the tiger worm, also called the brandling or manure worm (*Eisenia fetida*), and the red worm or red wiggler (*Lumbricus rubellus*) are both species of European origin, while the blue worm (*Perionyx excavatus*) is of Asian origin (Vermicrobe, 2008). These species have higher reproductive rates than native species.
Edwards et al. (1984) evaluated the suitability of six different species for decomposing agricultural waste and sludge: *Eisenia fetida, Dendrobaena veneta, Dendrobaena subrubicunda, Lumbricus rubellus, Eudrilus eugeniae,* and *Perionyx excavatus.* They found that while *Dendrobaena veneta* showed rapid growth and attained a greater weight at maturity than *Eisenia fetida,* its cocoons produced fewer hatchlings.

The choice of species for use in vermicomposting largely depends on temperature (McClintock, 2004). As a rule, within the temperature range between 15°C and 25°C, there is little variation in worm growth rates, while higher temperatures between 30°C and 35°C reduce growth and even caused mortality in earthworms originating from temperate regions (Neuhauser et al., 1988). A few species are usually grown together.

Under Australian conditions *Eisenia fetida* has been reported to be the most suitable species for intensive bulk worm production. It is tolerant to temperatures ranging from 0°C to 35°C (Edwards and Neuhauser, 1988) and can rapidly colonise a wide range of organic matter (Hollow, 2002).

In tropical regions, *Eudrilus eugeniae,* the African night crawler, is widely used as a composting worm and as a source of protein meal (Kumar, 1994; Kale, 1993). Along with *Eisenia fetida* and *Eudrilus eugeniae,* *Perionyx excavatus* and *P. sansibaricus* are well suited to cooler tropics where summer temperatures are lower than in the hot tropics (Kumar, 1994), although productivity of *E. eugeniae* per unit volume from cow manure has been reported to be far higher than that of *P. excavatus.* (Gajalakshmi et al., 2001).

### 2.9.2 Population dynamics

The population in a well-maintained worm farm has been reported to double every two to three months.

Worm growth patterns vary according to species, source of organic wastes, environmental conditions and initial stocking density. Aston (1988), for example, compared productivity of *Eisenia fetida* and *Perionyx excavatus* and found that, while *Perionyx excavatus* produced more
cocoons over the 20-day reproductive cycle, hatching rates for this species were low and the highest rate of live worms was in *Eisenia fetida*.

Earthworm population dynamics after a worm bed (pit) re-setting, i.e. starting afresh with worms, wastes and some amendments, fits a bell curve (Vermicrobe, 2008)). Initial increase in worm biomass is accompanied by a maximum processing rate of organic material. Eventually, the worm population reaches its peak. By that time most of the organic matter is decomposed. After that the number of worms decreases. Worm cycles last about 21 days (Vermicrobe, 2008).

This is supported by findings by Suthar (2007) that reproduction rate (cocoon/worm/week) in populations of *Perionyx excavatus* and *P.sansibaricus* in cattle waste solids increased progressively and attained a peak in the 15th-16th week. The following decrease in cocoon production after 23rd-24th week was attributed to quality of substrate and stabilisation of waste. Alternation in reproduction performance was reported to correlate with aging and environmental conditions (Domínguez et al., 2001; Reinecke and Venter, 1985, 1987).

Correctly chosen initial stock density ensures fastest increase in worm population over time.

Supra- or sub-optimal stocking densities usually result in reductions either in worm weight or number (Domínguez et al., 2001, 1999; Domínguez, 1999; Domínguez and Edwards, 1997; Frederickson et al. 1997). Gajalakshmi et al. (2001) found that stocking and feed rate of 950 g cow manure and paper waste for 250 *Eudrilus eugeniae* worms per 3 L container produced 6.5 times more castings per unit reactor volume compared to 75 g feed for 20 worms per 4 L container. Figures for optimal stocking density vary greatly from author to author. Optimal stocking density for *E. fetida* was found to be 1.60 kg/m² (Ndegwa et al., 2000). Recommended initial stocking density for commercial operations is about 5 kg/m² (Sherman-Huntoon, 2000).

Higher commercial stocking density standards aim to get ‘the best of two worlds’ – worm biomass and vermicast production. Juvenile earthworms have been reported to consume more food than mature earthworms and so juvenile predominance in earthworm population is desirable for a higher rate of vermicomposting processes. Gunadi and Edwards (2003) reported that some *E. fetida* could survive without any new substrate addition up to 60 weeks. Multiple organic waste addition and periodic worm ‘harvesting’ allows continuous earthworm cultures.
2.9.3 Waste input

Worms have been described as ‘one of the nature’s ultimate recyclers’ – they can apparently eat anything that once was alive (Vermicrobe, 2008). An enormous variety of organic matter can be vermicomposted.

There are three major categories of organic wastes suitable for vermicomposting: animal wastes, plant wastes and urban wastes (Gunadi and Edwards, 2003). Some practitioners (Vermicrobe, 2008) believe that horse, cow and pig manure are the most palatable of all feedstocks (McClintock, 2004) and the best choice for a commercial vermicomposting business to produce marketable uniform vermicompost.

Each type of manure has its benefits and limitations. Pig manure has the highest nutrient levels of any feedstock, but solids must be separated from the liquid fraction before vermicomposting to lower moisture content to acceptable levels (Edwards, 1998; Phillips, 1988; Edwards et al., 1984). Solids have to be stabilized to prevent overheating prior to vermicomposting. Cow manure is acceptable to *E. fetida* within a few days after separation from a slurry form and is considered the ‘easiest’ waste for vermicomposting (Edwards, 1998; Edwards et al., 1984). Gajalakshmi et al. (2001) tested cow manure + paper waste mixes of 4:1, 5:1 and 6:1. They concluded that while a higher proportion of manure increased production of worm castings the difference was too small to be economically justified.

Earthworms are selective to consumption of different types of substrates and many types of organic matter are unattractive to them (Singh et al., 2005). Numerous literature sources and web-sites recommend avoiding vermicomposting of organic materials that take too long to be decomposed or that are not compatible with worm living requirements such as bones, large branches and prunings (unless shredded), highly acidic foods (citruses and onion peels), fat and oil, materials that may affect drainage and aeration in the worm pit (large quantities of powdery waste from coal fires) and substrates that may contain toxic constituents (salty products, magazines or sawdust from treated timbers, or excessive concentrations of heavy metals in feedstocks).
Some organic matter should be vermicomposted with care. Poultry litter is a problematic feedstock for vermicomposting due to its high content of ammonia and soluble salts (Edwards, 1998). Mitchell (1997) reported that worms were unable to survive in manure in its initial condition with pH of 9.5 and electrical conductivity of 5.0 μS/cm. Nitrate content greater than 1 g/kg can result in rapid increases in mortality, with 100% morality occurring between 3 and 4 g/kg. Soluble salt levels above 5 g/kg can also be toxic (Edwards, 1988). The concentrations of salt and NH₃ in fresh manure may be reduced by leaching, pre-composting or stockpiling. Most commercial vermicomposters use pre-composted material, although the preliminary treatment reduces nutritional value for worms.

Practical recommendations for household vermicomposting are to use about 20 parts of waste rich in carbon (dry leaves, twiggy prunings, sawdust, paper, straw and dry grass, wood ash) to 1 part rich in nitrogen (vegetable scraps, fruit peelings, fresh lawn clippings, farm manure, garden weeds, seaweed) as an ideal mix for vermicomposting (Managing Waste in your Community – Education Kit, 2001). All feedstock should be milled to increase surface area. The organic loading of 17.6 kg/m² at 75% moisture is recommended as the optimum, and maximum degradation of organic matter occurs in the first two weeks with stabilization following after a month (Singh et al., 2005). Practitioners strongly recommend against overfeeding, which may lead to worm losses more than does insufficient feeding or bedding (Vermicrobe, 2008).

2.9.4 Environmental conditions

Worm management practices developed by scientists and practitioners (Handreck and Lee, 1986; Appelhof, 1982) aim to keep temperature, moisture, aeration and feedstock within a range acceptable for worms (Edwards, 1998) and to exclude excessive light exposure and constituents that might be toxic or harmful for earthworms, such as herbicides, pesticides, insecticides, or salty substrates.

2.9.4.1 Temperature

Precaution should be taken to prevent temperatures in feedstocks that may initiate thermophilic decomposition, which may kill worms (Subler, 2002). In cooler climates, too low ambient
Temperature may cause worm death too. Temperatures between 20°C and 25°C are considered to be optimal for most worm species with optimal cocoon production temperature of 25°C (Neuhauser et al., 1988). As indicated earlier, higher temperatures from 25 to 33°C can be lethal for earthworms from temperate species and 34 to 38°C – for sub-tropical species (Aston, 1988). The optimal temperatures for cocoon production are often lower than those for rapid growth: *Eisenia fetida* was the only species capable of producing cocoons at 15°C, and only *Perionyx excavatus* at 30°C (Aston, 1988).

2.9.4.2 Moisture

Although earthworms can survive in drought conditions, prolonged suboptimal moisture levels may cause considerable mortality. Similarly, too much water in the worm bed will create an anoxic environment.

According to the majority of publications, optimal moisture content in vermicomposting lies between 70 and 90% (Edwards, 1998; Neuhauser et al., 1988; Reinecke and Venter, 1987), although physical and chemical differences in feedstocks may cause slight variations (McClintock, 2005).

Dominguez and Edwards (1997) examined growth of *Eisenia andrei* in a mixture of pig manure and maple leaves at moisture content of 65, 70, 76, 80, 85, and 90%. Results indicated a direct relationship between moisture content and growth rate, with maximum growth occurring at 85%.

2.9.4.3 Aeration

As discussed earlier, oxygen is essential for the process of aerobic decomposition. Without proper aeration, decomposition of organic matter will be incomplete and slow. Aeration (i.e. loosening of the substrate) enhances microbiota population and helps stabilise the temperature in the worm bed. The recommended aeration depth of applied material is 0.5 to 1.0 m (Phillips, 1988), with a recommended frequency of aeration (by loosening) of at least once a week.
Earthworms are very pH-sensitive. The majority of publications agree that a neutral, or slightly alkaline, environment is most suitable (Vermicrobe 2008; Singh et al., 2005), although the actual range of pH over which worms can survive is wider: from pH 5.0 to pH 9.0 (Edwards, 1998). Outside this range pH is lethal for worms. Edwards (1998) reported on mortality of worms when pH exceeded 9.5. Substrates having strong acidic initial pH were found to be less suitable for vermicomposting (Singh et al., 2005). Practitioners recommend lime or rock powders to stabilise pH in the worm pit.

2.10 Vermicomposting and vermicomposts

Composting is a well-recognised sequence of events in the natural breakdown of organic material in the soil through the actions of natural agents such as bacteria and fungi. Earthworms enhance the humification, fragmentation and mineralisation of the organic matter, transforming it into plant-available forms (Edwards, 1998). Where earthworms are applied, the composts are commonly referred to as vermicomposts (Atiyeh et al., 1999, 2000d; Elvira et al., 1997, 1998). The digestive system of the earthworm provides ideal environmental conditions of temperature, pH and oxygen concentration for speedy growth of useful aerobic bacteria, thus resulting in high microbial populations (Vermicrobe, 2008). Earthworms have been described as ‘compost bacteria multipliers with some remarkable other features’ because they are effective natural tubular bioreactors and mills in which the consumed organic waste is ground into uniform particles with a finer structure which increases surface area (Frederickson et al., 2007; Singh et al., 2005; Benitez et al., 1999; Subler et al., 1998). Clay-humic complexes and other cementing agents, which are formed with the help of enzymatic secretions (amylase, cellulase, protease, lipase, chitinase, and lichenase) and certain actinomycetes (Senapati, 1993), stabilize the organic matter into a loosely aggregated, granular material. Its stability depends on the source of organic matter, moisture concentrations and bacterial and fungal polysaccharide structures (Kale, 1993).
Essentially, vermicomposts are amalgamated humified earthworm faeces and organic matter. They can be described as products of mesophilic, aerobic biodegradation and stabilization of organic materials, produced through interactions between earthworms and micro-organisms. The nutrient composition of vermicompost naturally depends on the source of organic matter (Hervas et al., 1989). During vermicomposting some nutrient losses may happen due to volatilization, leaching, or denitrification (Frederickson et al., 2007; Buchanan et al., 1988), but they are usually balanced by a reduction in volume.

Vermicomposting can be successfully operated on any scale: from a large commercial worm farm to a small individual household. Vermicomposting has been successful using different types of organic wastes, including municipal and industrial sludges, animal wastes and crop residues (Arancon et al. 2005; Elvira et al., 1998; Edwards and Bohlen, 1996). In recent years, production of vermicomposts has increased tremendously (Edwards, 1998; Dominguez and Edwards, 1997; Van Gestel et al., 1992; Haimi, 1990; Edwards and Neuhauser, 1988; Reinecke and Venter, 1985). Three main vermicomposting systems are in commercial use: windrows, single-batch reactors, and continuous flow systems (Sherman-Huntoon, 2000; Edwards, 1998).

Vermicomposts are widely used as organic amendments, conditioners and media for soil-grown plants (Edwards and Arancon, 2005; McClintock, 2004; Wan and Lin, 2002; Edwards 1998; Edwards and Neuhauser, 1988). Being peat-like materials with high porosity, good aeration, drainage and water-holding capacity, they improve soil properties and structure (Kahsnitz, 1992). Very high microbial activity provides for a greater availability of mineral nutrients to plants (Gilot, 1997) and biologically-active metabolites that work as plant growth regulators such as auxins, gibberellin-like substances and humic acids (Arancon et al., 2003; Tomati et al., 1998; Casenave de Sanfilippo et al., 1990).

Exact reasons are not known, but such factors as improvement of the physical structure of the potting medium, increases in populations of beneficial organisms and availability of plant growth-influencing substances could contribute to the enhanced seed germination, plant growth and flowering which has been observed (Gutierrez-Miceli et al., 2007; Zaller, 2007; Arancon et
Humic materials produced in the faeces of earthworms have been reported to exhibit auxin-, gibberellin-, and cytokinin-like activities (Nardi et al. 1994, 1996, 2002; Dell’Agnola and Nardi, 1987). Treating carrots cells with the humic materials increased their growth and induced morphological changes similar to those produced by auxins (Muscolo et al., 1999).

Vermicomposts from cattle manure, food waste and paper waste have been shown to somewhat promote the germination, growth, and yields of plants (Arancon et al., 2004, 2008; Atieh et al., 2000a, 2000b, 2001; Buckerfield et al., 1999). Atiyeh et al. (2002) and Arancon et al. (2005) suggested that the major contribution of vermicompost is in plant growth regulators adsorbed onto the humic acids. Humic acids are molecules that regulate many processes of plant development including macro- and micronutrient absorption (Atiyeh et al., 2002). Another possible explanation is involvement in the mechanism of nutrient uptake and plant development. For example, humic acids increase the number of roots (Alvarez and Grigera, 2005) and promote their elongation (Mylonas and McCants, 1980).

It is recognised that plant response to humic acids varies according to species, source of the vermicompost and concentration (Vadiraj et al., 1998). For example, Atiyeh et al. (2002) report that plant growth tended to be increased by treatments of cucumber and tomato seedlings with 50–500 mg/kg humic acids, but often decreased significantly when the concentrations of humic acids in the container medium exceeded 500–1000 mg/kg. Plant bioassays also indicated that 40- to 60-d old compost inhibited plant growth (Atiyeh et al., 2002). There is some evidence that vermicomposts suppress plant diseases such as Phytophthora and Fusarium (Szczech and Smolinska, 2001; Szczech, 1999, Nakamura, 1996; Szczech et al., 1993).

2.11 Vermiliquer – vermicompost leachate – ‘worm tea’

Vermileachate is nutrient-enriched water, drained through worm-beds containing vermicomposted wastes, bedding materials and worm populations. Vermicomposted leachate,
also called ‘worm tea’ (Warburton and Pillai-McGarry, 2002) or vermiliquer, presently has little economic application although it is regarded as a beneficial liquid soil enhancer. Its effects are even less extensively investigated than that of vermicast, with relatively little work having been done on nutritional quality of vermiliquer and its effect on plant growth.

Literature on this subject indicates that vermiliquer, a vermiculture by-product, is rich in nutrients for plants and could potentially provide an alternative option to conventional organic fertilizers, if used with care (Garcia-Gomez et al., 2008; Tejada et al., 2007; Ingham, 2005).

Besides an abundance of organic and inorganic material dissolved in water, vermiliquer contains complex micro-biota.

The role of vermiliquer, with a focus on its chemical and biological characteristics, on plant growth and development is not clear, however, research on the role of amendments such as phytohormones, organic matter, fulvic and humic acids, rhizobacteria and so on, on root development and plant growth merits attention (Midmore, 2008a).

Vermiliquer applied to plants as foliar sprays and to soil as enhancers has been reported to improve yield and mineral composition of plants (Singh et al., 2010; Carpenter-Boggs, 2005; Scheuerell and Mahaffee, 2002) and to suppress some plant diseases such as grey mould (Botrytis cinerea) on green beans, strawberries, grapes and geraniums, leaf spot on tomatoes, bacterial speck in Arabidopsis and powder mildew on apples (Haggag and Saber, 2007; Scheuerell and Mahaffee 2004, 2006; Al-Dahmani et al., 2003; Diver, 2001; Zhang et al., 1998; Hoitink et al., 1997; Cronin et al., 1996; Elad and Shtienber, 1994; Weltzein, 1991; Weltzein and Ketterer, 1986).

Recent reports confirm that vermiliquer influences growth, mineral nutrients, phytonutrients and antioxidant activity in pak choi (Pant et al., 2009).

2.11.1 Vermiliquer as a fertilizer in hydroponics

An array of recently published material on vermiliquer indicates that its physical characteristics and nutrient content suit the requirements of a hydroponic fertilizer (Pant et al., 2009; Rincon et
Nutrient composition of vermilique naturally depends on the composition of vermicomposted wastes.

Besides nutrients present in inorganic form, vermilique contains organic substances such as humic acids that act as plant growth-regulators. Fulvic acid and humic acid concentrations in the above-mentioned studies (Gutierrez-Miceli et al., 2008) were 1.5% and 2.4% of the total C content of the vermilique. In certain concentrations humic substances stimulate plant growth, while in higher concentrations they have been reported to suppress it (Garcia-Gomez et al., 2008). For example, vermilique has been found to inhibit seed germination and growth to some degree (Garcia-Gomez et al., 2008; Savage and Tyrrel, 1996). And there are other publications suggesting that vermilique would need to be diluted to ensure minimal plant damage, especially for sensitive plants (Gutierrez-Miceli et al., 2008). However, the dilution would also decrease the N:P:K concentration necessary for plant nutrition. It has been reported that vermilique contains high concentrations of nitrate and phosphorus – suggesting that it could have good fertiliser properties if used undiluted (Garcia-Gomez et al., 2008).

Garcia-Gomez et al. (2008) undertook research on how dilution of vermilique combined with different concentrations of N:P:K fertiliser can affect efficiency of fertiliser uptake by maize plants. The study confirmed that vermilique diluted to 50% stimulated plant development, but supplementary fertilization with N:P:K was required for maximum growth. Gutierrez-Miceli et al. (2008) carried out similar research on sorghum to investigate how dilution of vermilique combined with different concentrations of an N:P:K fertilizer would affect plant development. Vermilique stimulated plant development and could be used as liquid fertiliser for the cultivation of sorghum without dilution, but amending it with an extra N:P:K fertiliser provided maximum growth. Results of their experiments showed that vermilique had a significant effect on sorghum growth and the total macronutrient content of the plant (i.e. N:P:K uptake).
2.12 Constraints of the hydroponics-vermiculture integrated system

Problems attract thinking attention.

Edward de Bono

Under pressure of increased costs of chemicals, energy and labour the need for farming innovations grows. A focus on fertilisers generated from organic wastes, and on energy and water-saving technologies, can only be seen as favourable by consumers. The task is both appealing and urgent.

The idea behind integration of vermiculture and hydroponics is simple, amounting to the application of the natural cycle where earthworms and plants coexist side by side, having interacted with each other over millions of years. Major inputs to the integrated system are the water and the worm food. Major outputs are the live worms, vermicast, vermiliquer and plants.

However, with both components being physically, chemically and biologically complex systems in their own right, an integrated system will require proper management and maintenance (Masser et al., 1999; Redding et al., 1997; Watten and Busch, 1984). The major concern with using organic wastes for plant production is in a possible accumulation in the system of any unwanted substances and pathogens. More research is urgently required to develop knowledge of how vermiliquer affects plants to ensure that its application in hydroponics is safe.

Various contaminants such as herbicides and pesticides used in crop production for animals, commercial feeds and drugs used in animal production processes, environmental pollutants and metal salts derived from traffic and mining industry operations could accumulate in the close-loop system and might eventually harm worms, plants or, at later stages, humans. To illustrate this point, it is common practice that commercial feedstuffs for animals are frequently enriched with the essential elements copper, manganese, iron, zinc, cobalt, molybdenum and selenium to promote optimum nutrient supply for optimum animal growth rate. Sager (2007) reports that in intense pig farming, the amount of copper eliminated through the animal faeces corresponds to 72-80% of the amount ingested, and this proportion can be as high as 92-96% for zinc (Mantovi
et al., 2003). For example, manures from Germany contained more copper and zinc than all types of mineral fertilisers. In particular, pig manures contained extraordinary amounts of nickel (Ni). Similarly, in sewage sludges and composts, the mean concentrations of lead, copper, chromium, nickel and zinc were higher than in mineral fertilisers (Sager, 2007). In Northern Italy, 10-15 years of fertilization with manures from intense pig or cattle farming led to significant enrichments of copper and zinc in arable soils (Mantovi et al., 2003). Therefore, if commercial cattle feedstocks continue to be artificially enriched, their use in hydroponic systems could result in the build-up of toxic concentrations.

One of the potential issues to be addressed when using vermiliquer from vermicomposted organic wastes is the possibility that they may contain plant and human pathogens. Phytotoxic compounds may also be present. However, reports on microbial assays for faecal coliforms (Escherichia coli), Salmonella sp. and Shigella spp. indicated that vermiliquer is free of these pathogenic organisms (Garcia-Gomez et al., 2008). This suggests that microbial activity in worm beds and vermiliquer acts as a biofilter, reducing pathogens from the wastes (Frederickson, 1998). Pierre et al. (1982) relate the reduction of pathogens in the vermicomposts to the release of coelomic fluids by the earthworms, which have antibacterial properties and kill pathogens. Microbial studies in the integrated system must deserve a special focus of research, but are not included herein.
3. Materials and Methods

*Design makes use of 'standard known elements'.
Design is a matter of putting together current knowledge to deliver new value...*

Edward de Bono.

3.1 Location and climatic conditions

All research was conducted at the main CQUniversity Campus in Rockhampton, which is situated on the Tropic of Capricorn, 40 km from the coast: latitude: 23-23°S, longitude: 150-28°E, elevation: 10 m. Experiments were conducted all year round and therefore plants experienced all seasons (Figure 3.1 and Figure 3.2).

Figure 3.3 and Figure 3.4 show monthly average of the minimum and maximum daily temperatures and precipitation in Rockhampton for the past 70 years. Weather station: Rockhampton Airport: latitude: 23.38°S, longitude: 150.48°E, elevation: 10 m.

![Figure 3.1. Mean maximum monthly temperature (°C) during the period of experiments.](image1)

![Figure 3.2 Mean monthly precipitation (mm) during the period of experiments.](image2)
3.2 Infrastructure

Two major pieces of infrastructure were employed: vermicomposting and hydroponics. Both vermicomposting and hydroponic components of the integrated system for our research were identical to commercial systems with minor adaptation, using NFT (nutrient film technique) and pot systems (perlite medium), with commercial inorganic nutrient or batch or in-line nutrient supplied from vermiliquer nutrient supplies.

3.2.1 Vermicomposting

The farms were donated by Vermicrobe International Pty Ltd. They comprised nine individual and purpose-built worm beds (subsequently the design was retailed to individual parties) to replicate commercial systems. Each individual worm bed was a Vermicrobe® mini pit (Figure 3.5). The pits were 1000 mm x 1500 mm boxes, 400 mm deep and elevated 750 mm. A drainage line from each pit was linked to a Reln 380L tank set 300 mm sunken in the ground to provide adequate fall through gravity to feed the vermiliquer into the tanks (Figure 3.6). The recirculating system for irrigation of the pits was provided by a 40 L/min peripheral vane turbine pump (Mitron QB-60). This provided approximately 80% moisture content in the worm beds. The pits were set out in a 3 x 3 self-contained replication (each tank was linked to a specific worm pit and so three different irrigation and feeding cycles were possible).
Each worm bed was filled with composted material (paunch – roughly processed plant material contained in the first stomach of a cow – for most experiments and food waste in a few) and some bedding material, containing earthworm populations (three commercial species *Eisenia fetida*, *Lumbricus rubellus* and *Perionyx excavatus* but predominately *Eisenia fetida*).

Following the feeding cycle, vermicompost leachate (vermiliquer) reached ‘maturity’ approximately 8-10 weeks after the worm pit re-setting. Vermiliquer was collected and stored in the vermiliquer tanks, which were constantly aerated by Hiblow Hp80-type air pumps each supplying bs-1000 silicone aerators with each aerator aerating three tanks through 250 mm silicone diaphragm diffusers.

On occasion a separate 1475 L reservoir was used for holding batched vermiliquer for the experiments in hydroponics. It was kept aerated by 2 x 65 mm air stones per tank, supplied by air from an aquaculture system at 3.7 cubic foot per minute (approximately 1 cubic metre per minute) constant vane air blower.

### 3.2.2 Hydroponics

The hydroponic systems comprised 6 m long six channel (at 26 cm centre to centre channel spacing) commercial Ell-Gro® systems manufactured by Boxsell Hydroponics. Commercial Ell-Gro® NFT-channels (Figure 3.7 and Figure 3.8) were easily converted into a pot system (Figure 3.8) and vice versa. Plant and pot numbers varied according to experiment.
The nutrient film technique (NFT), commonly used in hydroponics, is well understood and simple to operate, but nutrient solutions heat up excessively during the summer. Assuming that pot culture withstands and mitigates high solution temperatures better than NFT, the pot system (Figure 3.9 and Figure 3.10) was, therefore, used as an option to address the issues of high mid-summer temperatures in Central Queensland (Figure 3.3). In cooler winter months it was converted back to NFT (Figure 3.11), or used in combination with it (Figure 3.12). Changing the NFT system to the pot system was essentially converting the NFT into a low pressure drip irrigation system, where each pot was individually fed using an open-ended 400 mm length, 4 mm internal diameter dripper pipe.
Hydroponic NFT-channels were modified to isolate and link each channel to an individual 100 L tank for batch vermiliquer treatments (Figure 3.13) and directly to the collecting 300 L tank with vermiliquer in the in-line treatments. Recirculation was provided by a 1200 L/hr Aqua-world magnetic impeller pump feeding each NFT channel through a 13 mm feed line with a 4 mm outlet to each channel. Constant aeration to all nutrient tanks was provided to maintain an
aerobic environment within the system, unless a non-aerated treatment was included in the experiment.

![Figure 3.13. Hydroponic setup: reservoirs with nutrient solution linked to the NFT-channels.](image)

During experiments nutrient solution in the 100 L reservoirs was supplemented with a pH buffer when necessary, but was not topped up.

### 3.2.3 Media

With the hydroponic pot system perlite was used (Figure 3.14) which was an excellent medium for hydroponically-grown plants because it supported enough water buffer to allow the pumps to work in alternating equally timed (30 min) on/off modes, thus operating in energy-saving mode.

To reduce the cost of growing medium, in experiments 5 to 12 perlite was recycled from the previous experiments after being leached, sterilized with 1% chlorine solution, rinsed and refilled into the pots immediately before the commencement of the next experiment. Perlite used in the control treatment in a previous experiment, was allocated to the control treatment in the next experiment, and the perlite, previously used in vermiliquer treatments, was allocated to the vermiliquer treatments in the next experiments. To compensate for the natural losses of the perlite from the previous experiments, the pots were evenly topped up with new perlite.
3.2.4 Plant material

The hydroponic system is suitable for many vegetable species. The Asian vegetable species *Brassica chinensis* subsp. *chinensis* cv. Shanghai, commonly known as ‘pak choi’ was chosen as an ideal trial plant for the experiments for its high rate of turnover within a practical setting.

Pak choi, also known as pak choy, or bok choy, is a fast-growing Asian leafy vegetable from the *Brassica* family. The botanical name has undergone several revisions and synonyms exists: *Brassica rapa* L cv. Group Pak Choi; *B. sinensis*; *B. campestris* ssp. *chinensis* (RIRDC, 2005).

There are many pak choi cultivars. There are over a dozen pak choi cultivars that are popularly grown in China at present. The common Shanghai cultivar, used in this study, has been reported to have a low nitrate accumulation (Luo *et al*., 2006). Optimal temperatures are thought to be between 15°C and 20°C with warmer climate varieties available (Moore *et al*., 1998). Some publications report optimal temperature conditions being 5-7 degrees higher than that – at 27°C (Frantz *et al*., 2004).

In summer months in the tropics it takes as little as 2-3 weeks to hydroponically produce a crop of a commercial size from transplants. To collect extensive data on production performance during all vegetative phases, experiments were run for 3-4 weeks resulting in plants that overgrew commercial standards. Therefore, within as short a time span as one year (2008-2009) twelve experiments were run in the same hydroponic system.
In all experiments I used seeds of non-hybrid pak choi (*Brassica chinensis* cv. *Shanghai*) purchased from ‘Searles Seeds’ (J.C. & A.T. Searle Pty Ltd, Australia) (Figure 3.15). Trials with preparation of seedlings showed that using vermiculite in deep trays with cells 4 cm x 4 cm x 10 cm (Figure 3.16) provided high germination, reliable seedling growth and a well-developed seedling root system. One seed was sown per cube/cell in trays with vermiculite, at the depth of c. 1-2 mm. The seeds germinated in 3 days, with germination rate more than 95%.

**Figure 3.15.** ‘Searles Seeds’ pak choi.

**Figure 3.16.** Filling trays with vermiculite.

**Figure 3.17.** Seedlings ready for transplanting into the hydroponic system.

All precautions were taken to protect the plants from heat and possible soil-borne diseases – seedling trays were kept outdoors in a shed under a tiled roof out of direct sunlight and remained moist at all times. Seedlings were kept moist with deionised - reverse osmosis (RO) -
water until the appearance of the second true leaf. When they attained a height of about 2–3 cm (usually with four leaves: two cotyledons and two foliage leaves), they were fed with 10% commercial Boxsell inorganic nutrient solution and maintained on that until one week before their transplanting into the hydroponic system. For the final week before transplanting they were watered with RO water only.

Before transplanting the seedlings were judged to be sufficiently uniform (in terms of their size and number of leaves) to be used for transplanting into the experimental systems (Figure 3.17).

On the commencement date of each experiment seedlings were manually transplanted into the hydroponic system: one seedling per orifice in the NFT system and two (three in some experiments) seedlings per pot in the pot system. Pots were randomly arranged to different hydroponic units to provide initial uniformity of all treatments. Randomizing seedlings from different trays and their randomised transplanting into different channels and orifices of the system until complete filling of the whole system was performed to ensure initial uniformity across all the NFT-channels and treatments (Figure 3.18).

![Figure 3.18. Combined NFT/pot setup in experiment 10. The plants had just been transplanted into the system.](image)

### 3.3 Vermicast and vermilquirer used in the study

In this research, vermiliquer was primarily obtained from vermicomposted ‘paunch’, chosen for its stability in terms of nutrient content and physical properties. In experiments 2 to 10 vermiliquer was produced from composted ‘paunch’ sourced from Australian Meat Holdings and composted by a local Meatworks contractor, Rob Land of Broad Meadows.
The final experiments 11 and 12 used vermiliquer obtained from different sources: of plant origin and from food waste. The food waste was semi-composted kitchen waste from the Capricornia Residential College at the Rockhampton CQUniversity Campus.

To obtain vermiliquer the following technique was used. All the pits were fed the same feed source (amount and timing) to provide a consistent vermiliquer supply for the hydroponic system. Every 7 to 10 days 20 L of compost was added to each pit as the food source became depleted. Physical aeration of each pit accompanied each feeding. The placement of food in the pit was to a depth of 25 mm and an air gap was maintained approximately 100 mm around the edge of the pit to maintain air flow through the pit, and to avoid the build-up of noxious gases. Nutrient solutions in the vermiliquer reservoirs connected to the worm pits, and tanks with batch vermiliquer for the hydroponic system were kept aerated at all times. Aeration aimed to maintain conditions in the batch vermiliquer used in these experiments similar to those in the collectors of leachate from vermifarms with the view to further integration of vermiculture and hydroponics. Previous experiments and publications (Midmore, 2008a) and results from experiment 2 (as described in Chapter 5) also demonstrated that aeration of inorganic nutrient solutions leads to considerably greater plant yields.

On average, for every 100 kg of composted faunal material, 115 L of vermiliquer and 94 kg of worm casts (fresh weight, at c. 68% moisture content) were produced. Illustrative compositions of the vermicast at the ends of vermiculture cycles and vermiliquer at the beginning of various hydroponic runs are presented in Table 3.1 and Table 3.2 respectively. It should be noted that Table 3.2 gives total concentrations of elements in vermiliquer. ‘Bioavailability’ of the nutrients to plants is not known.

Application rates and dilution of vermiliquer for hydroponic plant production was not specifically matched to the plant needs. Nutrient content of vermiliquer in the beginning and the end of most experiments was analysed at CSBP Ltd., an accredited soil and plant analysis laboratory in Western Australia. All data were finally calculated with respect to concentrations on a dry weight basis.
Table 3.1. Summary of nutrient composition of vermicast from ‘paunch’ material sampled at different times during a year.

<table>
<thead>
<tr>
<th>Element</th>
<th>Unit</th>
<th>October 2008</th>
<th>January 2009</th>
<th>May 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (N)</td>
<td>%</td>
<td>2.69</td>
<td>2.59</td>
<td>2.60</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>%</td>
<td>0.79</td>
<td>1.035</td>
<td>1.154</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>%</td>
<td>0.171</td>
<td>0.141</td>
<td>0.105</td>
</tr>
<tr>
<td>Sulphur (S)</td>
<td>%</td>
<td>0.301</td>
<td>0.270</td>
<td>0.276</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>%</td>
<td>0.250</td>
<td>0.291</td>
<td>0.344</td>
</tr>
<tr>
<td>Calcium (Ca)</td>
<td>%</td>
<td>1.933</td>
<td>2.686</td>
<td>2.754</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>%</td>
<td>0.202</td>
<td>0.202</td>
<td>0.209</td>
</tr>
<tr>
<td>Chlorine (Cl)</td>
<td>%</td>
<td>0.126</td>
<td>0.093</td>
<td>0.086</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>mg/kg</td>
<td>45.98</td>
<td>107.00</td>
<td>39.61</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>mg/kg</td>
<td>114.81</td>
<td>169.73</td>
<td>129.90</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>mg/kg</td>
<td>205.8</td>
<td>215.2</td>
<td>226.7</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>mg/kg</td>
<td>5709</td>
<td>5826</td>
<td>6553</td>
</tr>
<tr>
<td>Nitrate (NO₃⁻)</td>
<td>mg/kg</td>
<td>2286</td>
<td>1174</td>
<td>305</td>
</tr>
<tr>
<td>Boron (B)</td>
<td>mg/kg</td>
<td>6.72</td>
<td>7.8</td>
<td>7.54</td>
</tr>
</tbody>
</table>

¹Total nitrogen (N), nitrate nitrogen (NO₃⁻) and Cl were measured colorimetrically in segmented flow analyser; total P, S, K, Ca, Mg, Na, Cu, Zn, Mn, Fe and B were measured using ICP AES (inductively coupled plasma, argon emission spectrometer).

Table 3.2. Summarised nutrient composition of vermiliquer used in hydroponics experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Total Nitrogen (mg/L)</th>
<th>Total Phosphorus (mg/L)</th>
<th>Calcium (by AAS) (mg/L)</th>
<th>Magnesium (by AAS) (mg/L)</th>
<th>Potassium (by AAS) (mg/L)</th>
<th>Sodium (by AAS) (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method³</td>
<td>4500-N B</td>
<td>4500-P F</td>
<td>3500-Ca B</td>
<td>3500-Ma B</td>
<td>3500-K B</td>
<td>3500-Na B</td>
</tr>
<tr>
<td>Exp 3 - start</td>
<td>134</td>
<td>40</td>
<td>54</td>
<td>26</td>
<td>236</td>
<td>504</td>
</tr>
<tr>
<td>Exp 4 - start</td>
<td>227</td>
<td>52</td>
<td>82</td>
<td>26</td>
<td>154</td>
<td>523</td>
</tr>
<tr>
<td>Exp 5 - start</td>
<td>124</td>
<td>36</td>
<td>40</td>
<td>10</td>
<td>51</td>
<td>317</td>
</tr>
<tr>
<td>Exp 6 In-line-1</td>
<td>157</td>
<td>67</td>
<td>48</td>
<td>12</td>
<td>60</td>
<td>380</td>
</tr>
<tr>
<td>Exp 6 In-line-2</td>
<td>105</td>
<td>46</td>
<td>52</td>
<td>12</td>
<td>58</td>
<td>422</td>
</tr>
<tr>
<td>Exp 6 In-line-3</td>
<td>172</td>
<td>44</td>
<td>85</td>
<td>19</td>
<td>102</td>
<td>560</td>
</tr>
<tr>
<td>Exp 7 - start</td>
<td>128</td>
<td>40</td>
<td>56</td>
<td>15</td>
<td>68</td>
<td>387</td>
</tr>
<tr>
<td>Exp 8 - start</td>
<td>141</td>
<td>47</td>
<td>62</td>
<td>16</td>
<td>81</td>
<td>425</td>
</tr>
<tr>
<td>Exp 9 - start</td>
<td>107</td>
<td>32</td>
<td>52</td>
<td>17</td>
<td>63</td>
<td>455</td>
</tr>
<tr>
<td>Exp 10 - start</td>
<td>464</td>
<td>87</td>
<td>129</td>
<td>36</td>
<td>2</td>
<td>1080</td>
</tr>
<tr>
<td>Exp 10 - post harvest</td>
<td>182</td>
<td>29</td>
<td>37</td>
<td>12</td>
<td>&lt;1</td>
<td>398</td>
</tr>
</tbody>
</table>

³Nitrogen was determined colorimetrically by the salicylate-hypochlorite method of Baethgen and Alley (1989), and phosphorus by an adaptation of Murphy and Riley’s (1967) single solution method (Anderson and Ingram, 1989). Na, K, Ca, Mg were determined by atomic absorption spectrophotometry.
3.4 Control nutrient solution

The first trial (experiment 1) was conducted to compare two inorganic fertilisers: Manutec and Boxsell. Manutec Hydroponics nutrient was composed of part A: 7.6:3.1:18.2% N:P:K ratio and 4.5% S, 3.5% Mg, 0.34% Fe, 0.08% Mn, 0.04% Zn, 0.03% Cu, 0.003% B, 0.001% Mo; and part B: 19:15.5% Ca:N ratio. The ratio of parts A:B was maintained at 0.6:0.4.

Boxsell Hydroponic inorganic nutrient (N:P:K ratio 5.8 : 1: 9.11 %) comprised of part A (g/L): 20.49 Ca, 16.90 N ratio, 0.74 Fe and part B (g/L): 18.39 N, 6.06 P, 55.32 K, 5.69 Mg, 7.55 S, 0.027 B, 0.045 Zn, 0.0058 Mn, 0.009 Cu, 0.004 Mo. The application ratio was 3.4 L of part A and 3.4 L of part B per 1,000 L of water.

The pH in the nutrient solution was maintained close to pH 6.5 through the use of pH buffers (10% orthophosphoric acid in experiments 1 and 2, and 10% nitric acid in all further experiments).

In all further experiments the Boxsell mix was chosen as the control treatment for three reasons. Firstly, experiment 1 did not show a significant difference in yield between the two control treatments. Secondly, electrical conductivity of the recommended hydroponic solution (approx. 1.2-1.7 μS/cm) in the Boxsell was closer to that in vermiliquer. Thirdly, Boxsell Hydroponics acted as a sponsor for this project and provided a good supply of the fertiliser for this research. Therefore, in all experiments where vermiliquer treatments were compared to the control, the control unless stated otherwise refers to Boxsell hydroponic inorganic mix.

3.5 Experimental design

Twelve experiments were carried out during 2008-2009. Aims and goals of each experiment are presented in Table 3.3. A summary of the experiments is presented in Table 3.4. The general layout of experiments is presented in Figure 3.19.

All experiments were carried out under natural light conditions. In experiments 9, 10 and 11 one block of treatments (six NFT channels) was shaded with a polyethylene cover clad over iron half moon supports.
<table>
<thead>
<tr>
<th>Exp.</th>
<th>Trials</th>
<th>Treatments</th>
<th>Objective</th>
</tr>
</thead>
</table>
| 1    | Different conventional inorganic fertilisers; NFT setup | Manutec  
Boxsell | 1. Gain experience with hydroponics system  
2. Compare yield using different conventional inorganic fertilisers  
3. Choose the control for further experiments |
| 2    | Off-line (batch) vermiliquer; Orthophosphoric acid as pH-buffer | Vermiliquer treatment  
Control treatment  
Filtration and Aeration for the NFT setup  
Separate pot and NFT setup | 1. Test off-line (batch) vermiliquer  
2. Compare yield with the control inorganic fertiliser  
3. Quantify differences between the NFT and pot setup  
4. Investigate whether sand filter and aeration of the nutrient solution provide better yield than does non-filtered and non-aerated vermiliquer |
| 3    | Different pH; Pot setup | Vermiliquer maintained at pH 7.0  
Vermiliquer maintained at pH 5.5  
Control maintained at pH 5.5 | 1. Investigate the effect of pH of the solution on plant yield  
2. Reduce the amount of pH buffer required to grow pak choi  
3. Compare the yield at different pH with the control |
| 4    | Different buffer sources; Pot setup | Vermiliquer buffered with orthophosphoric acid  
Vermiliquer buffered with nitric acid  
Control | 1. Compare yield using different buffer sources  
2. Reduce the amount of pH buffer required to grow pak choi  
3. Determine if low production in vermiliquer treatments in experiment 2 was due to buffering with orthophosphoric acid |
<table>
<thead>
<tr>
<th>Exp.</th>
<th>Trials</th>
<th>Treatments</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Dilutions of vermilique; Nitric acid as pH-buffer; Pot setup</td>
<td>100% vermilique</td>
<td>1. Investigate the effect of dilution (EC) on plant yield</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50% vermilique</td>
<td>2. Reduce the amount of vermilique used to grow pak choi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>3. Reduce the amount of pH buffer required to grow pak choi</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4. Reduce the nitrate concentration in plants at harvest</td>
</tr>
<tr>
<td>6</td>
<td>Direct linkage; Pot setup</td>
<td>In-line vermilique</td>
<td>1. Test direct linkage setup</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>2. Compare the yield with the control inorganic fertiliser</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3. Compare controls in synchronous experiments 5 and 6 to identify whether the systems can be used as experimental blocks for further experiments</td>
</tr>
<tr>
<td>7</td>
<td>Dilutions of vermilique; Nitric acid as pH-buffer; Pot setup</td>
<td>100% vermilique</td>
<td>1. Repeat experiment 5, investigate the effect of dilution (EC) on plant yield</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50% diluted vermilique</td>
<td>2. Reduce the amount of vermilique used to grow pak choi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>3. Reduce the amount of pH buffer required to grow pak choi</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4. Reduce the nitrate concentration in plants at harvest</td>
</tr>
<tr>
<td>8</td>
<td>Direct linkage versus off-line (batch) trials; Buffered versus unbuffered off-line vermilique Pot setup</td>
<td>In-line vermilique</td>
<td>1. Compare yield between in-line and off-line vermilique</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unbuffered off-line vermilique</td>
<td>2. Compare yield on vermilique at different pH levels</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Buffered off-line vermilique</td>
<td>3. Reduce the amount of pH buffer required in off-line treatments</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4. Compare buffered off-line vermilique treatments in synchronous experiments 7 and 8 to identify whether the systems can be used as experimental blocks</td>
</tr>
<tr>
<td>Exp.</td>
<td>Trials</td>
<td>Treatments</td>
<td>Objective</td>
</tr>
<tr>
<td>------</td>
<td>--------</td>
<td>------------</td>
<td>-----------</td>
</tr>
<tr>
<td>9</td>
<td>Dilutions of vermiliquer; Nitric acid as pH-buffer; NFT setup</td>
<td>100%- vermiliquer 50%- diluted vermiliquer Control Shading in one block</td>
<td>1. Develop better management practices, repeating experiments 5 and 7 with the NFT 2. Investigate the effect of dilution (EC) on plant yield 3. Reduce cost of the growing medium 4. Quantify differences in growth, yield, photosynthesis in the open and in the shade in order to develop better management practices for further commercial application</td>
</tr>
<tr>
<td>10</td>
<td>Dilutions; Nitric acid as pH-buffer; Combined NFT (no media) and pot setup;</td>
<td>100%- vermiliquer 50%- diluted vermiliquer Control NFT and pot setup Shading in one block</td>
<td>1. To compare yield and growth between the NFT and pot setup, supplied with the same nutrient solution 2. To reduce the cost of growing medium 3. To investigate whether pot culture withstands and mitigates high solution temperatures better than NFT 4. To compare the yield in vermiliquer treatments with the control 5. To investigate growth dynamics by way of sequential harvest 6. To reduce the amount of vermiliquer used to grow pak choi 7. To reduce the nitrate concentration in plants at harvest 8. Quantify differences in growth, yield, photosynthesis in the open and in the shade</td>
</tr>
<tr>
<td>Exp.</td>
<td>Trials</td>
<td>Treatments</td>
<td>Objective</td>
</tr>
<tr>
<td>------</td>
<td>--------</td>
<td>------------</td>
<td>-----------</td>
</tr>
<tr>
<td>11</td>
<td>Off-line (batch) vermiliquer obtained from different sources of organic waste; Nitric acid as pH buffer; NFT-setup;</td>
<td>Batch vermiliquer from paunch Batch vermiliquer from kitchen waste Control Shading in one block</td>
<td>1. Broaden application of the integrated system using organic waste with different origins 2. Compare yield with vermiliquer obtained from different organic sources 3. Investigate pH buffer capacity of vermiliquer sourced from different organic waste to reduce the amount of pH buffer required to grow pak choi 4. To reduce cost of the medium 5. Quantify differences in growth, yield, photosynthesis in the open and in the shade</td>
</tr>
<tr>
<td>12</td>
<td>Direct linkage; Different sources of vermiliquer NFT-setup</td>
<td>In-line vermiliquer from paunch In-line vermiliquer from kitchen waste</td>
<td>1. Compare yield with vermiliquer obtained from different organic sources 2. Compare the yield with that in experiment 11, which involved the same vermiliquer in the off-line buffered treatments 3. To reduce cost of medium</td>
</tr>
</tbody>
</table>
Table 3.4. Summary of experiments on hydroponics.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Date of sowing</th>
<th>Date of transplant</th>
<th>Date of harvest</th>
<th>Days from sow/ transplant to harvest</th>
<th>Treatments</th>
<th>Origin of Vermiliquuer</th>
<th>Issues / notes/ comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15/05/08</td>
<td>07/06/08</td>
<td>16/07/08</td>
<td>63/39</td>
<td>Control (Manutec) (2 reps) Control (Boxsell) (2 reps)</td>
<td>n/a</td>
<td>30.06 – pump failure resulted in severe damage in one NFT-channel</td>
</tr>
<tr>
<td>2</td>
<td>06/07/08</td>
<td>08/08/08</td>
<td>05/09/08</td>
<td>65/29</td>
<td>NFT-100% vermiliquuer (3 reps) NFT-Control (3 reps) Pot-100% vermiliquuer (2 reps) Pot-control (2 reps) All treatments were buffered with orthophosphoric acid</td>
<td>Combined from tanks 1, 2, 3 Identical for experiments 2, 3, 4, 5</td>
<td>To quantify effectiveness of other factors for further experiments, replicates of each NFT-treatment were modified as follows: 1 channel was operated on quartz as filter; 1 channel was aerated at all times; 1 channel was non-filtered and non-aerated</td>
</tr>
<tr>
<td>3</td>
<td>10/09/08</td>
<td>31/10/08</td>
<td>25-26/11/08</td>
<td>77/26</td>
<td>Pot-100% vermiliquuer, buff. to pH 7.0 (4 reps) Pot-vermiliquuer, buffered to pH 5.5 (4 reps) Pot-control (4 reps) All treatments were buffered with nitric acid</td>
<td>ditto</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>11/11/08</td>
<td>05/12/08</td>
<td>03/01/09</td>
<td>55/29</td>
<td>Pot-100% vermiliquuer, buffered with nitric acid (4 reps) Pot-100% vermiliquuer, buffered with orthophosphoric acid (4 reps) Pot-control (4 reps) All treatments were buffered to pH 5.5</td>
<td>ditto</td>
<td></td>
</tr>
</tbody>
</table>

Origin of Vermiliquuer

N/a

All treatments were buffered with orthophosphoric acid

All treatments were buffered with nitric acid
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Date of sowing</th>
<th>Date of transplant</th>
<th>Date of harvest</th>
<th>Days from sow/trans plant to harvest</th>
<th>Treatments</th>
<th>Origin of Vermiq uer</th>
<th>Issues / notes/ comments</th>
</tr>
</thead>
</table>
| 5          | 27/12/08      | 02/02/09           | 05-06/03/09     | 70/32                              | • Pot-100% vermiliquer (4 reps)  
• Pot-50% vermiliquer (4 reps)  
• Pot-control (4 reps)  
All treatments were buffered to pH 5.5 with nitric acid | ditto | Due to unusually wet January, the experiment was effectively running on a half-dilution, resulting in 50%-vermiliquer, 25%-vermiliquer and 50%-control treatments |
| 6          | 27/12/08      | 02/02/09           | 05-06/03/09     | 70/32                              | • Pot-100% in-line vermiliquer (3 reps)  
• Pot-control (3 reps)  
No Buffering | Tanks 7, 8, 9 | Due to unusually wet January, the experiment was effectively running on a half-dilution, resulting in less than 100% (but not quantified)-vermiliquer and 50%-control treatments. No spraying against pests |
| 7          | 03/03/09      | 26/03/09           | 27/04/09        | 59/33                              | • Pot-100% vermiliquer (4 reps)  
• Pot-50% vermiliquer (4 reps)  
• Pot-control (4 reps)  
All treatments were buffered to pH 5.5 with nitric acid | Combined tanks 7,8,9 | Aimed to repeat the previous experiment 5 without 'natural' dilution |
| 8          | 03/03/09      | 26/03/09           | 27/04/09        | 59/33                              | • Pot-100% in-line vermiliquer (2 reps)  
• Pot-100%-batch unbuffered vermiliquer (2 reps)  
Pot-100%-batch vermiliquer buffered to pH 5.5 with nitric acid (2 reps) | Tanks 8, 9 | No spraying against pests (that might potentially affect live worms) |
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Date of sowing</th>
<th>Date of transplant</th>
<th>Date of harvest</th>
<th>Days from sow/transplant to harvest</th>
<th>Treatments</th>
<th>Origin of Vermiliqueur</th>
<th>Issues / notes/ comments</th>
</tr>
</thead>
</table>
| 9          | 15/04/09       | 15/05/09           | 11-12/06/09    | 59/28                             | • NFT-100% vermiliqueur (4 reps)  
• NFT-50% vermiliqueur (4 reps)  
• NFT-control (4 reps)  
All treatments were buffered to pH 5.5 with nitric acid | Combined tanks 3, 4, 5, 6 | Treatments as per exp.7 in the NFT in two blocks: shaded polyhouse (approx. 35% light reduction) versus full sun |
| 10         | 29/05/09       | 29/06/09           | 31/07/09       | 66/33                             | • Pot/NFT-100% vermiliqueur (4 reps)  
• Pot/NFT-50% vermiliqueur (4 reps)  
• Pot/NFT-control (4 reps)  
All treatments were buffered to pH 5.5 with nitric acid | Combined tanks 3, 4, 5, 6 (as for the previous exp-1) | Pot and NFT setup within the same hydroponics unit  
Treatments as per exp.7 and 9 to compare pot and NFT systems in two blocks: shaded polyhouse (approx. 30% light reduction) versus full sun. Sequential harvest |
| 11         | 14/07/09       | 22/08/09           | 20/09/09       | 68/30                             | • NFT- paunch vermiliqueur (4 reps)  
• NFT- food waste vermiliqueur (4 reps)  
• NFT-control (4 reps)  
All treatments buffered to pH 5.5 with nitric acid | Combined tanks 4-6 (food/w) and 7-9 (paunch) respectively | Experiment on batch vermiliqueur from different sources of organic material in NFT systems in shade and full sun |
| 12         | 14/07/09       | 22/08/09           | 20/09/09       | 68/30                             | • NFT-100% in-line vermiliqueur from precomposted paunch (3 reps)  
• NFT-100% in-line vermiliqueur from kitchen food waste (3 reps)  
No Buffering | Tanks 4-6 with food/w, tanks 7-9 – with paunch | Experiment on in vivo vermiliqueur from different sources of organic material: precomposted paunch and kitchen food waste |
In-line system:
(3 replicates of 2 treatments,
or 2 replicates of 3 treatments):

- Treatment 1
- Treatment 2

Batch system:
- Treatment 1
- Treatment 2
- Treatment 3

**Figure 3.19. General layout of experimental design**

In most experiments the batch system was employed. The in-line hydroponic system with different disposition (perpendicular to the batch system and so differently sun-oriented, and separated from it by approximately 30 metres) was established next to the vermifarm collecting tanks and was engaged for in-line experiments (experiments 6, 8 and 12).

The experimental setup for a batch system comprised a two-block design, each block containing two plots with randomised replicates of three treatments. Each replicate was a separate hydroponic unit, containing six pots with two (or three in some experiments) plants in each pot for the pot system, or 10-16 plants in the NFT system. Thus, the batch system comprised: 2 blocks, 4 plots, 4 replicates of each treatment, 12 hydroponic units, 6 pots in each replicate (for the pot system), 12-16 plants in each replicate (for the NFT-system).

Due to technical limitations, the in-line experiments were conducted in one block with two replicates of three treatments, or with three replicates of two treatments. Thus, the in-line system comprised: 1 block, 2 replicates of 3 treatments (or 3 replicates of 2 treatments), 6 hydroponic units, 6 pots in each replicate (for the pot system), 12-16 plants in each unit (for the NFT-system), each replicate linked (where the treatment dictated) to a different Vermicrobe worm pit and collecting tank.
3.6 Methods and equipment

Information on data collection, periodicity and the equipment used during the studies are presented in Table 3.5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Periodicity</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH in nutrient solution</td>
<td>Daily</td>
<td>TPS FL-90 meter</td>
</tr>
<tr>
<td>EC in nutrient solution</td>
<td>Daily</td>
<td>TPS FL-90 meter</td>
</tr>
<tr>
<td>Temperature in nutrient solution</td>
<td>Daily</td>
<td>TPS FL-90 meter</td>
</tr>
<tr>
<td>Dissolved oxygen in nutrient solution</td>
<td>Daily</td>
<td>TPS FL-90 meter</td>
</tr>
<tr>
<td>Ammonium in nutrient solution</td>
<td>Daily</td>
<td>TPS WP-90 meter</td>
</tr>
<tr>
<td>Nitrate in nutrient solution</td>
<td>Every 5 days</td>
<td>Horiba Cardy c-141 NO3⁻ meter</td>
</tr>
<tr>
<td>Potassium in nutrient solution</td>
<td>Every 5 days</td>
<td>Horiba Cardy c-131 K⁺ meter</td>
</tr>
<tr>
<td>Combined leaf chlorophyll content</td>
<td>Weekly</td>
<td>Konica Minolta SPAD-502</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>Weekly</td>
<td>Quantum/radiometer/photometer LICOR, Model LI-250 John Morris Scientific Pty Ltd Light Meter CAN 001 768 396, Made in USA).</td>
</tr>
<tr>
<td>Nitrate in sap</td>
<td>Weekly</td>
<td>Horiba Cardy c-141 K⁺ meter</td>
</tr>
<tr>
<td>Potassium in sap</td>
<td>Weekly</td>
<td>Horiba Cardy c-131 K⁺ meter</td>
</tr>
<tr>
<td>Sugar in sap</td>
<td>Weekly</td>
<td>BS+ refractometer DR-103</td>
</tr>
<tr>
<td>Parameter</td>
<td>Frequency</td>
<td>Instrument/Software</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>-------------------------------</td>
<td>-----------------------------------------------------------</td>
</tr>
<tr>
<td>Leaf area</td>
<td>Weekly</td>
<td>Scanner/Delta-Scan software</td>
</tr>
<tr>
<td>Specific leaf area (SLA)</td>
<td>Weekly</td>
<td>Calculator</td>
</tr>
<tr>
<td>PAR</td>
<td>On 3\textsuperscript{rd} and 4\textsuperscript{th} week of the experiment</td>
<td>LCA-4 (ACD, Hoddesdon, UK)</td>
</tr>
<tr>
<td>Photosynthetic activity</td>
<td>On 3\textsuperscript{rd} and 4\textsuperscript{th} week of the experiment</td>
<td>LCA-4 (ACD, Hoddesdon, UK)</td>
</tr>
<tr>
<td>Leaf surface temperature</td>
<td>On 3\textsuperscript{rd} and 4\textsuperscript{th} week of the experiment</td>
<td>LCA-4 (ACD, Hoddesdon, UK)</td>
</tr>
<tr>
<td>Stomatal conductance</td>
<td>On 3\textsuperscript{rd} and 4\textsuperscript{th} week of the experiment</td>
<td>LCA-4 (ACD, Hoddesdon, UK)</td>
</tr>
<tr>
<td>Transpiration rate</td>
<td>On 3\textsuperscript{rd} and 4\textsuperscript{th} week of the experiment</td>
<td>LCA-4 (ACD, Hoddesdon, UK)</td>
</tr>
<tr>
<td>Fresh weight of shoots</td>
<td>Harvest</td>
<td>Sartorium scales</td>
</tr>
<tr>
<td>Fresh weight of roots</td>
<td>Harvest</td>
<td>Sartorium scales</td>
</tr>
<tr>
<td>Total fresh weight</td>
<td>Harvest</td>
<td>Sartorium scales /calculator</td>
</tr>
<tr>
<td>Dry weight of shoots</td>
<td>Harvest</td>
<td>Drier OM1500 ME, Clayson Laboratory Apparatus Pty. Ltd, Brisbane, Australia</td>
</tr>
<tr>
<td>Dry weight of roots</td>
<td>Harvest</td>
<td>Top pan balance PB303, Metler Toledo, Switzerland</td>
</tr>
<tr>
<td>Total dry weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry shoot/root ratio</td>
<td>Harvest</td>
<td>Calculator</td>
</tr>
<tr>
<td>Ambient temperature and humidity in each block (in the shade and the open)</td>
<td>Every hour</td>
<td>Tinytag Ultra sensors</td>
</tr>
</tbody>
</table>
3.6.1 Measurement procedures

a) Nitrate measurements

In the absence of the perfect method (Cometti, 2002), I chose the Horiba-ion-meter to measure nitrate in both nutrient solution and sap of plants. Preliminary comparison of nitrate measurements carried out with a RQflex Merck reflectometer (E.Merck, D-64271 Darmstadt, Germany) and a Horiba-ion meter did not differ significantly from each other. For that, nitrate was measured across a series of plant sap samples (approximately 50) diluted to the ratio 1:50 (within the reflectometer's acceptable range of relatively low concentrations of NO$_3^-$). The reflectometer was calibrated with a factory strip. The Horiba-ion meter was calibrated to 150 mg/L NO$_3^-$ solution. The results showed that at this degree of dilution the differences in readings made with the meters were within 3-4%. Difference for repeated measurements on the same sample was in the same range of values, 3-4%. Comparison between the measurements of undiluted sap by the Horiba-ion-meter calibrated to 2000 mg/L NO$_3^-$ solution with the value calculated from reflectometer's reading in 1:50 diluted sap and multiplied by the proportion of dilution gave up to a 30% difference. Accuracy of dilution might also have contributed to the error. Therefore, the Horiba calibrated to 150 mg/L NO$_3^-$ appeared to be a simple to use and a cost-effective option to produce fast and direct results within a wide range of readings, while the reflectometer required exact dilution for reading within a relatively narrow range of values. The nitrate strips would be expensive to use for the number of samples required throughout the experiments.

Thus, to measure nitrate concentration in nutrient solution, I used a Horiba-ion-meter calibrated to the standard NO$_3^-$ solution of 150 mg/L. To measure nitrate concentration in sap of plants, we used a Horiba-ion-meter calibrated to the standard NO$_3^-$ solution of 2000 mg/L. To ensure the consistency of measurements, the sample material was obtained from a petiole of the youngest fully expanded leaf. The value was calculated as the mean of three (in some experiments five) randomly chosen plants from each hydroponic unit (NFT-channel). Calibration of the Horiba-ion-meter was repeated and corrected if necessary every 10-15 measurements. Measurements of
nitrate in the nutrient solution and sap were taken on fresh samples within minutes for nutrient solution and within seconds after extracting sap with a garlic press.

b) Potassium measurements in nutrient solution

Potassium can be measured with an ion specific electrode meter or a reflectometer (colorimetric method). With the numerous samples carried out during this study, colorimetric test strips (single test costing approximately $1.0) appeared to be a costly method. In addition, the colorimetric methods would require an accurate dilution to bring the potassium concentration within a relatively narrow reading range of the test.

To measure potassium content in nutrient solution, I used the Horiba-ion-meter calibrated to the standard $K^+$ solution of 150 mg/L. Potassium concentration in plant sap was measured with the Horiba-ion-meter calibrated to standard $K^+$ solution of 2000 mg/L. To ensure the consistency of measurements, the sample material was as obtained for nitrate samples.

c) Biological parameters

Such biological parameters as photosynthetic activity, transpiration rate and stomatal conductance were measured with IRGA (Canopy gas exchange meter) once or twice during most experiments. To increase consistency of results, readings were taken in cloudless weather near midday across all hydroponic units starting from one or the other end of the experiment over a number of times (say, starting from unit 12, then 11 etc. to unit 1, then in the opposite order from unit 1 to 12 etc.). This order for taking measurements was applied in order to spread the effect of time-related factors (flow stabilization for each reading takes approximately 3-5 minutes) over all treatments and replicates.

d) Chlorophyll estimation (arbitrary SPAD values)

A surrogate of chlorophyll concentration (relative leaf chlorophyll, or RLC) was measured on a weekly basis using a Minolta Co. Ltd Japan - Chlorophyll-meter SPAD-502. Measurements were taken twice a week for all plants in each unit to obtain an average chlorophyll value in the youngest fully expanded leaf for each hydroponic unit (replicate), treatment and block.
e) Leaf area

The area of the leaf for which petiole sap was measured was measured a few times during each experiment. Average leaf area was determined as an average of three laminas of the youngest fully expanded leaves from three randomly chosen plants for each treatment replicate (Figure 3.20). In experiment 10 total leaf area was measured from three randomly chosen plants for each replicate on a weekly basis.

Figure 3.20. Leaf area was measured for the lamina detached from the petiole.

f) Harvest procedure

Above- and below-ground parts of plants were separated. Shoots, when necessary to remove visual contaminants, were rinsed with deionised (reverse-osmosis) water. Roots were washed with tap water of the remaining perlite (in the pot system) and vermiculite (which was used for the preparation of seedlings). For the NFT-plants roots were separated and weighed on a per plant basis. A procedure of washing the roots in the pot setup involving a system of baths filled with RO water was established to roughly free the plants of the perlite and fine wash the roots. Perlite was collected, washed off, sterilized in 1% chlorine bleach to be re-used in the following experiments. A dense net of roots was interwoven on the cloth in the bottom of the pot (the cloth was to prevent pump blockage from the perlite getting into the recirculating system) and was collected for weighing. It was impossible to separate roots of different plants in a single pot. So, while above-ground parts of plants in each pot were weighted separately, weight of the roots was calculated from the combined mass of roots in that particular pot divided by the number of plants used in the experiment. After washing the roots, excess water was removed with paper towels. Separated parts were weighed on the Sartorium scale to obtain the fresh weight. Separated roots and shoots were put into paper bags and dried for 6 days at +70°C in a forced air Clayson drier (OM1500 ME, Clayson Laboratory Apparatus Pty. Ltd, Brisbane, Australia). Dry plant material was weighed on a top pan balance (PB303, Metler Toledo, Switzerland).
3.6.2 Laboratory analysis of samples

Analysis of nutrient content in shoot tissues and vermicasts was conducted at the accredited laboratory CSBP Soil and Plant Analysis Laboratory in Western Australia. For that, dry shoots of all harvested plants from each NFT-channel were ground with a rotary grinder (ZM1000, Retsch, Haan, Germany) fitted with a 0.1 mm mesh and packed in 50 ml falcon tubes. Ground material from each NFT-channel, replicating one treatment, was combined in equal parts to make a sample material for each treatment. Such composite samples were considered to be optimally representative for each treatment in terms of nutrient composition.

Methods of extraction from the vermicasts and ground shoot tissues and analyses followed the standard procedures in the Australian accredited commercial laboratory of CSBP, Western Australia: samples were dried at 70°C to constant weight. The samples were analysed for total nitrogen (0.4 g sample digested by concentrated H₂SO₄ plus selenium catalyst for 3 hours, N measured in segmented flow analyser), nitrate nitrogen and chloride (0.4 g sample boiled in deionised water for 1 hour, nitrate and chloride measured colorimetrically in segmented flow analyser), total phosphorus, sulphur, potassium, calcium, magnesium, sodium copper, zinc, manganese, iron and boron (1.6 g sample digested in concentrated HNO₃ measured using ICP AES (inductively coupled plasma, argon emission spectrometer)).

Root samples were not sent for analysis, because it was practically impossible to absolutely remove surface organic compounds capping the roots in vermiliquer treatments and, thus, separate root tissues from the contaminants.

Composite samples of vermiliquer were analysed for nutrient composition at the Australian Centre for Tropical Freshwater Research, James Cook University Townsville, Australia.

Nitrogen was determined colorimetrically by the salicylate-hypochlorite method of Baethgen and Alley (1989), and phosphorus by an adaptation of Murphy and Riley’s (1967) single solution method (Anderson and Ingram, 1989). Na, K, Ca, Mg were determined using atomic absorption spectrophotometry.
3.6.3 Statistical analysis

All data were statistically analysed using Genstat (2007). Data were analysed with the appropriate model analysis of variance (ANOVA) for each experimental design and regression analysis where appropriate. Pair-wise comparisons of treatment means were made using LSD (significance level of $p < 0.05$) and for interaction means. Due to a limited number of replicates, statistical analysis of parameters that changed with time (for more than two sampling dates) was not appropriate, so that the relevant trends could be gained by visual inspection of the graphs. Vertical bars in figures represent the means and standard deviation of the parameter.

Data gathering was done with all possible care, however, for some experiments some data were declared missing. For example, a few hours of pump stoppage in experiment 1 severely affected the yield in one NFT-channel with the Boxsell treatment. Such an effect was not treatment-related and for this reason the data were excluded from further statistical analysis.

In another example, dripper blockages at an early stage of experiment 3 temporarily suspended inflow of nutrient solution to a few pots which resulted in severely retarded growth of plants in those pots. In other words, these pots did not receive the intended treatment, which could be regarded as improper treatment. Consequently, retarded growth of the plants in the pots was not the result of the treatment effect. Therefore, all observations made on those pots were considered invalid, and so omitted for the statistical analyses.

Outlier data, that is data visually recognized as being outliers after the data were recorded and transcribed, were also excluded from further analysis. For example, in some experiments temperature or dissolved oxygen curves showed outliers which may result from a transcribing error or an occasional instrumental error.

Data for ammonium concentration in nutrient solutions were considered as being incorrect. Apparently errors originated from incorrect calibration of the measuring instruments, or were due to the unsuitability of the measuring device for the purpose.

It should be noted that crop-deteriorating factors that affected plant yield were not always obvious. Some plants did lose weight due to pests (see section 5.5 Pests and diseases).
Nevertheless, the data from all harvested plants, even those affected by pests, were taken as representative and were not declared missing for statistical analysis. This was because the objective of the experiments was to evaluate the relative performance of plants in different treatments. Thus, one of the criteria for the superiority was tolerance to pests and diseases, and the loss of plants and reduced yield may have been treatment-related.
4. Overview of major practical results and findings for each experiment

In this section major findings are outlined experiment by experiment, and in the subsequent section data are presented on each of the parameters measured between treatments and across experiments.

During these studies, a few factors that could affect plant growth with vermiliquer in a hydroponic setup were manipulated separately and in combination with each other. Objectives of each experiment are presented in Table 3.3.

**Experiment 1**

To test the hydroponic system for functionality in the CQ environment and to choose the control for further experiments, the NFT batch system (Figure 3.19) was tested during mid-winter with two commercial hydroponic nutrient sources: Manutec and Boxsell (Figure 4.1).

Figure 4.1. Initial trial of hydroponics system with two inorganic fertilisers Manutec and Boxsell in experiment 1.

There was no significant difference in total dry weight between the two nutrient sources (9.22 g/plant Boxsell, 11.74 g/plant Manutec, LSD = 3.02 g/plant). In all further experiments Boxsell nutrient was used as the control.
Experiment 2

Experiment 2 was the first trial to compare the inorganic control with the vermiliquer treatment with both the NFT and pot setup.

a) The vermiliquer buffered to pH 7.0 with orthophosphoric acid produced significantly less plant growth than the control, and this difference was more pronounced in the NFT than in the pot system (see Table 5.17 in 5.3.3. Harvest parameters). Plants in the pot system with vermiliquer did not show signs of nutrient deficiency until 19 days after transplanting, compared to 2 days after transplanting in the NFT (Figure 4.2).

Figure 4.2. Initial ‘unsuccessful’ trial of vermiliquer buffered with orthophosphoric acid, compared to the control in the NFT (left) and pot system (right) in experiment 2.

b) To quantify the effects of other factors on plant development, three replicates of each NFT-treatment were modified as follows: one unit was operated with quartz as a filter, one was aerated at all times and one was operated non-filtered and non-aerated.

While quartz did not have any apparent effect on the plant growth, plants on aerated nutrient solution showed notably better yield (c. 190 g of fresh shoots per plant in the aerated hydroponic unit versus c. 160 g and c. 176 g of fresh shoots per plant in the replicates of the control treatment with the quartz and the non-filtered and non-aerated respectively). Due to suppressed growth in the vermiliquer treatment, the modifications with quartz and aeration did not have any apparent effect on growth (means for fresh shoot weight in the vermiliquer treatment were 21 g per plant in the unit with quartz and 26 g per plant in the aerated and non-filtered and non-aerated units). In all further experiments all nutrient solutions were kept aerated at all times.
Experiment 3

To investigate the effect of pH, the vermiliquer was buffered with nitric acid either to pH 7.0 or pH 5.5 (Figure 4.3). Experiment 3 was the first trial carried out in two blocks of the batch system (Figure 3.19).

Figure 4.3. First ‘successful’ trial with vermiliquer buffered with nitric acid in experiment 3.

a) The shoot fresh weight per plant was almost identical in vermiliquer buffered to pH 5.5 and the control also buffered to pH 5.5 (315 and 318 g respectively), with vermiliquer at pH 7.0 about 17% less (263 g). Fresh yield was significantly greater (p = 0.013, LSD = 34.16 g per plant) in the control and the vermiliquer treatment buffered to pH 5.5 compared to that buffered to pH 7.0. In all further experiments, where buffering was employed, all nutrient solutions were designed to be maintained at pH 5.5.

b) Despite the root fresh weight being 33% less in vermiliquer than the control and root dry weight was half that of the control (see Table 5.17 in section 5.3.3. Harvest parameters), the differences were not statistically significant (p = 0.068 and p = 0.067 respectively).

c) In contrast to the fresh shoot (and total) weight, the dry shoot (and total dry) weight per plant in both vermiliquer treatments was significantly less than in the control (9.70 and 9.20 g in the vermiliquer at pH 5.5 and 7.0 respectively versus 12.80 g in the control; p < 0.001, LSD = 1.13).
d) The initial concentration of nitrate was considerably higher in the vermiliquer solution than the control (c. 1200 mg/L compared to c. 400 mg/L) and had declined to c. 800 mg/L by the end of the experiment. In the control it declined steadily with growth to an almost immeasurable quantity (Figure 4.4).

![Figure 4.4. Nitrate concentration (mg/L) in nutrient solution in experiment 3.](image)

**Experiment 4**

Experiment 4 was run on different buffers to determine if poor plant performance in experiment 2 and better plant production in experiment 3 were related to the source of buffering. Vermiliquer treatments were buffered with nitric and orthophosphoric acid to pH 5.5 and the control was buffered with nitric acid only.

![Figure 4.5. Two pH buffers – nitric and orthophosphoric acids – were trialled in experiment 4.](image)
a) Plant performance using nitric acid as a buffer was far superior to that with orthophosphoric acid for most measured parameters – leaves remained green (as indicated by readings of chlorophyll concentration (Figure 4.6) and visual appearance (Figure 4.5).

![Graph showing SPAD readings (arbitrary units) in experiment 4 in the treatments: control, vermi-liquer buffered with orthophosphoric (Vermi-PO₄) and nitric (Vermi-NO₃) acids.]

b) Fresh and dry shoot weight in the vermi-liquer buffered with nitric acid matched that of the control (see Table 5.17 in 5.3.3. Harvest parameters). Both treatments significantly out-performed the vermi-liquer treatment buffered with orthophosphoric acid. For example, fresh shoot weight per plant was 314.6 g in the control, 280.8 g in the vermi-liquer buffered with nitric acid and only 24.4 g in the vermi-liquer buffered with orthophosphoric acid (p < 0.001, LSD = 41.48 g per plant).

**Experiment 5**

This experiment investigated the effect of dilution (manipulating EC) of vermi-liquer on plant yield, to see if it were possible to reduce the amount of vermi-liquer used for the hydroponic plant production and to reduce nitrate content in plants grown on vermi-liquer. Because of the nature of growing the plants in open pots (Figure 4.7), and due to the unseasonably wet month of January, an approximate 50% dilution took place (based upon data recorded for treatment ECs). This resulted in the 100%- vermi-liquer treatment effectively turning into the 50% and the 50% to the 25% vermi-liquer.
Figure 4.7. Plants in the pot system in experiment 5.

a) Of great interest, potassium concentration in solution dropped to close to immeasurable in all other treatments (Figure 4.8) and this was also reflected in the sap potassium concentration (Figure 4.9).

Figure 4.8. Potassium concentration (mg/L) in nutrient solution in the control, 100%-vermilique and 50%-vermilique treatments in experiment 5.

Figure 4.9. Potassium concentration (mg/L) in sap in experiment 5.
Fresh and dry shoot and total weights did not differ between the control and 100%-vermiliquer (Table 4.1), but both exceeded the 50%-vermiliquer, and, as in previous experiments, root dry weight was less, but not significantly so, in both the vermiliquer treatments than in the control.

Table 4.1. Yield (g per plant) in experiment 5.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Fresh weight (g) per plant</th>
<th>Dry weight (g) per plant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>shoots</td>
<td>roots</td>
</tr>
<tr>
<td>Control</td>
<td>401.2</td>
<td>40.8</td>
</tr>
<tr>
<td>50%-vermiliquer</td>
<td>283.3</td>
<td>29.3</td>
</tr>
<tr>
<td>100%-vermiliquer</td>
<td>414.6</td>
<td>37.3</td>
</tr>
<tr>
<td>LSD p&lt;0.05 for treatment effect</td>
<td>46.26</td>
<td>11.59</td>
</tr>
</tbody>
</table>

Experiment 6

The aim of experiment 6 was to test direct linkage of the hydroponics system to the vermisfarms and to compare the yield with the inorganic control. Hydroponic units were connected ‘in-line’ to the vermiliquer collecting tanks with ‘live’ vermiliquer recirculating through the vermisipits. In this and further experiments employing the in-line treatments, vermiculture and hydroponics were literally and physically integrated into one system. Experiment 6 was the first trial carried out in the in-line hydroponic system (Figure 3.19).

a) Starting in-line linkage with vermiliquer with a relatively low EC (0.45-0.92 μS/cm), and with the same dilution effects caused by rainfall as in experiment 5, the EC rose over a 10 day period and remained at c. 2 μS/cm until the end of the experiment when it declined somewhat.

b) Nitrate concentration in the in-line vermiliquer was initially considerably lower than in the control solution, but reversed by the end of the experiment (Table 4.2). The steady decline in nitrate concentration in the solution in the control reflected the nutrient uptake by plants. Nitrate concentration in the in-line treatments (in the vermiliquer collecting tanks) fluctuated greatly. The changes were caused by the saturation of vermiliquer with nitrate as vermiliquer matured (first and second sampling date) and the dilution of vermiliquer with rainwater (third date).
Table 4.2. Nitrate concentration (mg/L) in the nutrient solutions in experiment 6.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Date (days after transplanting)</th>
<th>06/02/09 (4 days)</th>
<th>19/02/09 (17 days)</th>
<th>02/03/09 (28 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In line Vermiliquer (tank 1)</td>
<td>40.00</td>
<td>220.00</td>
<td>170.00</td>
<td></td>
</tr>
<tr>
<td>In line Vermiliquer (tank 2)</td>
<td>40.00</td>
<td>390.00</td>
<td>160.00</td>
<td></td>
</tr>
<tr>
<td>In line Vermiliquer (tank 3)</td>
<td>40.00</td>
<td>200.00</td>
<td>53.00</td>
<td></td>
</tr>
<tr>
<td>Control (reservoir 1)</td>
<td>500.00</td>
<td>150.00</td>
<td>5.00</td>
<td></td>
</tr>
<tr>
<td>Control (reservoir 2)</td>
<td>400.00</td>
<td>170.00</td>
<td>6.00</td>
<td></td>
</tr>
<tr>
<td>Control (reservoir 3)</td>
<td>250.00</td>
<td>130.00</td>
<td>6.00</td>
<td></td>
</tr>
</tbody>
</table>

c) Fresh and dry yield in the in-line vermiliquer treatment was significantly less (only one quarter) that of the control (Figure 4.10) (see also Table 5.17 in section 5.3.3. Harvest parameters).

Figure 4.10. In-line vermiliquer and control treatments in experiment 6.

Experiment 7

Experiment 7 was a repetition of experiment 5 (to investigate the effect of dilution to manipulate EC) in a drier season in order to avoid the confounding effect of dilution through rain. Thus, 100% and 50% vermiliquer treatments were trialled to compare the yield with the control.

a) Nitrate concentration in solution was highest in the 100%- vermiliquer treatment at all times (Figure 4.11). The concentration in 50%- vermiliquer treatment and the control was the same for three weeks. After that nitrate in the control steadily decreased and there was almost no
measurable nitrate at the end of the experiment. In contrast, both vermiliquer treatments had high nitrate concentration: more than 700 mg/L in the 50%-vermiliquer and more than 800 mg/L in the 100%-vermiliquer (Figure 4.11).

![Figure 4.11. Nitrate concentration (mg/L) in nutrient solution in experiment 7.](image)

b) Despite the differences in concentration of N sources, sap nitrate did not differ significantly between treatments and decreased with time (Figure 4.12).

![Figure 4.12. Nitrate concentration (mg/L) in sap in experiment 7.](image)

c) Potassium in solution declined in all treatments over time, more so for the control (Figure 4.13) and this was reflected in the concentration of potassium in the sap (Figure 4.14).
Figure 4.13. Potassium concentration in nutrient solution in experiment 7.

Figure 4.14. Potassium concentration (mg/L) in sap in experiment 7.

d) In this experiment the control significantly out-performed both vermiliquer treatments – fresh and dry yield of the 100% vermiliquer treatment was 30% less than that of the control, and did not differ from the 50% vermiliquer (Table 4.3).

Table 4.3. Yield (g per plant) in experiment 7.

<table>
<thead>
<tr>
<th></th>
<th>Fresh weight (g) per plant</th>
<th>Dry weight (g) per plant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>shoots</td>
<td>roots</td>
</tr>
<tr>
<td>Control</td>
<td>445.0</td>
<td>30.5</td>
</tr>
<tr>
<td>50% vermiliquer</td>
<td>233.8</td>
<td>19.7</td>
</tr>
<tr>
<td>100% - vermiliquer</td>
<td>301.4</td>
<td>21.7</td>
</tr>
<tr>
<td>LSD P&lt;0.05 for treatment effect</td>
<td>136.5</td>
<td>14.3</td>
</tr>
</tbody>
</table>
The object of this experiment was to compare the yield and plant growth between the in-line (not buffered) and the off-line (buffered and unbuffered) vermiliquer treatments. For that, four units in the in-line hydroponic system (Figure 3.19) were disconnected from the vermiform collecting tanks and connected to 100 L reservoirs with batch vermiliquer. In this experiment, each vermiliquer treatment had only two replicates and there was no control treatment.

a) pH was very high in the in-line and the unbuffered off-line (batch) treatments (c. pH 8.5) compared to c. pH 5.6-7.3 for the buffered treatment.

![Figure 4.15. Off-line (buffered and unbuffered) and in-line vermiliquer treatments were trialled in experiment 8.](image)

b) Buffered batch vermiliquer treatments had the highest chlorophyll (see section 5.3.1. Chlorophyll estimation, Figure 5.40). SPAD readings in the in-line and unbuffered vermiliquer treatments were comparable and significantly lower than in the buffered batch vermiliquer.

c) The nitrate concentration of the buffered batch vermiliquer was greater (by c. 150-200 mg/L) than the unbuffered batch vermiliquer. However, by the end of the experiment nitrate concentration in sap in both the batch treatments was similar and nearly double that of the in-line treatment.

d) Fresh and dry total yield in the in-line and the buffered batch treatments did not differ markedly (Table 4.4), but they both significantly exceeded the un-buffered batch vermiliquer treatment (also see Table 5.17 in section 5.3.3. Harvest parameters).
Table 4.4. Yield (g per plant) in experiment 8.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Fresh weight (g) per plant</th>
<th>Dry weight (g) per plant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>shoots</td>
<td>roots</td>
</tr>
<tr>
<td>In-line vermiliquer</td>
<td>143.40</td>
<td>26.04</td>
</tr>
<tr>
<td>Unbuffered vermiliquer</td>
<td>34.83</td>
<td>6.13</td>
</tr>
<tr>
<td>Buffered vermiliquer</td>
<td>187.92</td>
<td>16.04</td>
</tr>
<tr>
<td>LSD p&lt;0.05 for treatment</td>
<td>84.7</td>
<td>18.7</td>
</tr>
</tbody>
</table>

Experiment 9

With the cooler autumn temperature, this experiment aimed to repeat the trials with the dilution of vermiliquer as in experiments 5 and 7, but this time the system was converted back from the pot system to the NFT. Therefore, the same 100%- vermiliquer, 50%- vermiliquer and the control treatments were repeated in the NFT-setup. Additionally, one block was placed under a polyethylene cover resulting in approximately 35% light reduction. The goal was to quantify differences in plant development in the shade under conditions of a polyhouse and in the open sun.

Figure 4.16. In experiment 9, first chlorosis symptoms were noticed in the 100%- vermiliquer treatment in the shade (10 days after transplanting).

Figure 4.17. In experiment 9, symptoms of chlorosis become apparent in the open a few days later (14 days after transplanting).
a) In the shade chlorosis became more evident with the 100% vermiliquer than the 50% vermiliquer, and showed the symptoms more quickly than in the open sun (Figure 4.16). However, later in the open the same symptoms were evident (Figure 4.17).

b) Photosynthetic rates varied significantly among nutrient treatments – the highest rate was in the control and the lowest in the 50% vermiliquer treatment, with the 100% vermiliquer treatment not differing from either, but there was no significant difference between the open and the shade – presumably irradiance under the shade was still sufficient to sustain maximum photosynthesis.

c) Of interest, the rate of transpiration differed between the open and the shade with the rate in the shade being greater than in the open. Quite possibly plants were more water-stressed in the open (leaf temperature was greater by 2.3°C) and transpiration constrained (see section 5.3.3.7 Shade effect and greenhouse microclimatic conditions).

Experiment 10

Experiment 10 was a repetition of experiment 5, 7 and 9 (to investigate the effect of dilution via manipulating EC) in the tropical winter conditions. The previous experiments were carried out either with the pot or the NFT setup. The current experiment was conducted with the combined pot/NFT setup (Figure 3.12) in two blocks - in the shaded polyhouse and in the open sun – in order to estimate plant production in the NFT/pot setup, compare the treatments and to quantify the differences between the shade and the open. To measure the dynamics of biomass changes, sequential harvest was employed at weekly intervals. Besides other parameters, total leaf area was measured.

a) Total leaf area increased in all treatments over time, but for the NFT plants the increase in leaf area was significantly higher than in the pot system (Figure 5.55).

b) At the beginning of the experiment SPAD readings were significantly lower in the 50% vermiliquer treatment and did not differ significantly between the control and the 100% vermiliquer treatments (Figure 4.18). SPAD values in the 100% vermiliquer treatment
remained high during the experiment, slightly increased in the 50%-vermiliquer treatment and decreased in the control.

Figure 4.18. SPAD readings (arbitrary units) in experiment 10.

c) Concentration of nitrate and potassium in sap decreased with time in all treatments (Table 4.5) (also see Figure 5.27 and Figure 5.30).

d) Plants in the pot and the NFT system showed different dynamics of nitrate and potassium accumulation in sap. At the beginning of the experiments both were higher in plants in the NFT system, while at the end of the experiment they were higher in plants in the pot system (Table 4.5, and also illustrated by Figure 5.28 and Figure 5.35).

Table 4.5. Nitrate and potassium concentration (mg/L) in the NFT and pot systems in experiment 10.

<table>
<thead>
<tr>
<th></th>
<th>system /date 18.07.09</th>
<th>31.07.09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Means for nitrate in sap</td>
<td>pot</td>
<td>6281</td>
</tr>
<tr>
<td></td>
<td>NFT</td>
<td>6450</td>
</tr>
<tr>
<td>Means for potassium in sap</td>
<td>pot</td>
<td>2581</td>
</tr>
<tr>
<td></td>
<td>NFT</td>
<td>2808</td>
</tr>
</tbody>
</table>

Means for nitrate in sap LSD P<0.05
<table>
<thead>
<tr>
<th></th>
<th>system /date 18.07.09</th>
<th>31.07.09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Means for potassium in sap LSD P&lt;0.05</td>
<td>pot</td>
<td>2581</td>
</tr>
<tr>
<td></td>
<td>NFT</td>
<td>2808</td>
</tr>
<tr>
<td></td>
<td></td>
<td>172</td>
</tr>
</tbody>
</table>

e) Fresh yield in the 100%-vermiliquer treatment was c. 80% and in the 50%-vermiliquer treatment one half of that in the control (see Table 5.17).

f) Plants in the NFT-system had significantly higher yield than in the pot system but much of the difference, as discussed later in section 5.3.3.4, was due to the greater space available per plant in the NFT (Table 5.17).
Experiment 11

To test different sources of organic wastes, two off-line (batch) vermiliquer treatments – the 'liquor' (with the paunch material) and the 'vege-liquor' (with kitchen waste) – were compared with the control (Figure 5.50, Figure 5.51).

a) In absolute values yield in 'vege-liquor' with the kitchen waste was lower than in the 'paunch' vermiliquer treatment, but statistically there were no significant differences among any treatments (see Table 5.17).

b) The 'vege-liquor' treatment required approximately 23% more total pH buffer during the experiment than the 'paunch' vermiliquer treatment (Table 5.4, and will be discussed later in section 5.1.1.1 Buffer application).

c) Initial potassium concentration in the 'vege-liquor' (with kitchen waste) was the same (c. 110 mg/L) as in the control. Potassium in the vermiliquer obtained from 'paunch' was significantly lower (c. < 40 mg/L) than in the other two treatments (Figure 5.31). During the experiment potassium concentration decreased in the control and dropped close to immeasurable in the 'paunch' vermiliquer, while in the 'vege-liquor' it increased (see section 5.2.2.1 Potassium in nutrient solution).

d) Accordingly, throughout the experiment potassium in the sap was higher in the control and the vege-liquor treatments compared with the paunch vermiliquer treatment (Figure 5.32).

e) At the beginning of the experiment SPAD readings did not differ significantly among the treatments (Figure 5.49). During the last week of the experiment the vege-liquor treatment showed marked increase in SPAD values. SPAD readings for the 'paunch' vermiliquer treatments remained high through the experiment, but in the control decreased during the third week of the experiment and from that time remained the lowest across all treatments. Therefore, by the end of the experiment SPAD values in both vermiliquer treatments were significantly higher than in the control (will also be discussed later in section 5.3.1. Chlorophyll estimation).
Experiment 12

This experiment compared two in-line vermiliquer treatments: the ‘liquor’ (with the paunch material) and the ‘vege-liquor’ (with kitchen waste) (Figure 4.19).

Figure 4.19. Liquer (with paunch) and vege-liquor (with kitchen waste) treatments in experiment 12.

a) pH in both the in-line treatments was high (c. 8.5 - 9.0) over the life span of the experiment.

b) Despite nitrate concentration in the ‘paunch’ vermiliquer being significantly higher than in the ‘vege-liquor’ with kitchen waste (Figure 4.20), sap nitrate was significantly higher in the ‘vege-liquor’ (Figure 4.21).

Figure 4.20. Nitrate concentration (mg/L) in nutrient solution in experiment 12.
Figure 4.21. Nitrate concentration (mg/L) in sap in experiment 12.

c) Both treatments showed very low harvest parameters compared with the other treatments across all experiments. In absolute values, the ‘vege-liquor’ treatment (with kitchen waste) showed half of the yield in the ‘paunch’ vermiliquer treatment, but statistically they were not found to be significantly different for any of fresh/dry weights (see section 5.3.3. Harvest parameters, and Table 5.17) - and chlorophyll concentration was close to ‘zero’ at harvest time (Figure 5.41).
5. Results integrated across experiments and discussion

'If it is not true it is well found (ben trovato)'

Italian saying*

(*cited by Edward de Bono)

This section interprets the results in relation to variables and treatments applied across the experiments described in the previous chapter, on various parameters of the hydroponic systems, and their effect on growth and yield of pak choi. The data collected spanned more than one calendar year, and are relevant to tropical and subtropical locations (especially the tropical 'summer' data) and temperate summer locations (the tropical 'winter' data).

Both vermicultural and hydroponic components are complex systems in their own right. Integration of the two systems leads to increased complexity and reduces the ability to manage each component. There are complex biological, chemical and physical interactions between worms, plants and micro-biota in vermiliqueur that are not well understood. As with most complex systems, any integration, while theoretically promising, in reality is more demanding and may display unexpected interactive effects.

5.1 Nutrient solution

5.1.1 pH

*Natural pH of vermiliqueur.* The vermiliqueur was highly alkaline with a pH \( \geq 8.0 \).

Measurements of pH in the vermifarm collecting tanks during experiments employing direct linkage, showed that pH remained high at all times. To illustrate this, Figure 5.1 shows pH in the nutrient solution in experiment 6 in which three in-line vermiliqueur treatments were compared with the control. The unbuffered in-line vermiliqueur treatment showed a steady level of pH c. 8.0 during the whole experiment. The control was buffered only once during this experiment - on 07.02.09 to pH 5.7.
The initial pH of vermiliquer (that is, pH before pH-adjustment) ranged between 7.69 and 9.20 across experiments (Table 5.1). As an example, in experiment 12 where vermiliquer was obtained from different waste sources pH in both treatments was c. 8.7.

![Figure 5.1. Dynamics of pH in experiment 6.](image)

**Table 5.1. Initial pH of vermiliquer and the control solutions (before pH-buffering) across experiments.**

<table>
<thead>
<tr>
<th>Exp No.</th>
<th>Treatment</th>
<th>Initial pH (before buffering)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp 1</td>
<td>Control</td>
<td>6.80</td>
</tr>
<tr>
<td></td>
<td>Manutec</td>
<td>6.80</td>
</tr>
<tr>
<td>Exp 2</td>
<td>Control</td>
<td>6.80</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer</td>
<td>8.72</td>
</tr>
<tr>
<td>Exp 3</td>
<td>Control</td>
<td>6.50</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer</td>
<td>8.50</td>
</tr>
<tr>
<td>Exp 4</td>
<td>Vermiliquer</td>
<td>6.60</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer</td>
<td>8.46</td>
</tr>
<tr>
<td>Exp 5</td>
<td>Control</td>
<td>5.70</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer</td>
<td>7.82</td>
</tr>
<tr>
<td>Exp 6</td>
<td>Control</td>
<td>5.94</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer</td>
<td>7.69</td>
</tr>
<tr>
<td>Exp 7</td>
<td>Control</td>
<td>6.50</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer</td>
<td>9.20</td>
</tr>
<tr>
<td>Exp 8</td>
<td>Vermiliquer</td>
<td>9.20</td>
</tr>
<tr>
<td>Exp 9</td>
<td>Control</td>
<td>6.00</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer</td>
<td>8.35</td>
</tr>
<tr>
<td>Exp 10</td>
<td>Control</td>
<td>6.70</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer</td>
<td>8.40</td>
</tr>
<tr>
<td>Exp 11</td>
<td>Control</td>
<td>6.90</td>
</tr>
<tr>
<td></td>
<td>Vege-liquer (kitchen wastes)</td>
<td>8.75</td>
</tr>
<tr>
<td></td>
<td>Liquer (paunch)</td>
<td>8.62</td>
</tr>
<tr>
<td>Exp 12</td>
<td>Vege-liquer (kitchen wastes)</td>
<td>8.78</td>
</tr>
<tr>
<td></td>
<td>Liquer (paunch)</td>
<td>8.69</td>
</tr>
</tbody>
</table>

Thus, high pH was originally identified as one of the major issues with vermiliquer as a hydroponic fertiliser and some adjustment was necessary to improve ion solubility and availability for plants.
Necessity to buffer. To make the vermiliquer suitable to meet plant growth requirements, pH of the solution was reduced towards neutrality with different buffers (discussed later in section 5.1.1.1. Buffer Application).

Once buffered, vermiliquer demonstrated exceptional stability in pH, so that further corrective buffering of the system required only small amounts of buffer during each experiment. Such stability is considered one of the major advantages for future use of the product as a liquid fertiliser in hydroponics.

In this study, throughout all experiments vermiliquer treatments showed a tendency to a very slow but steady increase in pH, that was easily overcome with negligible amounts of a buffer. Figure 5.2 shows dynamics of pH in experiment 9. Occasional sharp decreases in pH reflect buffer application (14-15.05.09, 27.05.09 and 03.06.09).

Therefore, at all times pH buffer was required to decrease pH of the vermiliquer, never to increase pH.

![pH in experiment 9](image)

Figure 5.2. pH in experiment 9.

Daily pH fluctuations. Results from a few experiments show that the pH of the nutrient solution changed somewhat during the course of the day. Table 5.2 shows daily pH fluctuations measured in experiment 9 between 9:00 and 17:00 on 18.05.09 in each NFT-channel which represented a replicate of different treatments.
Table 5.2. Daily changes in the pH in each replicate in experiment 9 (18.05.09).

<table>
<thead>
<tr>
<th>NFT-channel</th>
<th>9:00-9:15</th>
<th>10:00-10:15</th>
<th>11:00-11:15</th>
<th>14:00-14:15</th>
<th>15:30-15:45</th>
<th>17:15-17:30</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 50% vermi</td>
<td>5.36</td>
<td>5.36</td>
<td>5.34</td>
<td>5.34</td>
<td>5.3</td>
<td>5.32</td>
</tr>
<tr>
<td>2 - 100% vermi</td>
<td>5.95</td>
<td>5.98</td>
<td>5.94</td>
<td>5.93</td>
<td>5.91</td>
<td>5.92</td>
</tr>
<tr>
<td>4 - 100% vermi</td>
<td>6.15</td>
<td>6.13</td>
<td>6.11</td>
<td>6.1</td>
<td>6.08</td>
<td>6.1</td>
</tr>
<tr>
<td>5 - 50% vermi</td>
<td>5.59</td>
<td>5.58</td>
<td>5.58</td>
<td>5.57</td>
<td>5.56</td>
<td>5.56</td>
</tr>
<tr>
<td>6 - Control</td>
<td>6.21</td>
<td>6.2</td>
<td>6.19</td>
<td>6.18</td>
<td>6.16</td>
<td>6.16</td>
</tr>
<tr>
<td>7 - Control</td>
<td>6.28</td>
<td>6.22</td>
<td>6.21</td>
<td>6.19</td>
<td>6.2</td>
<td>6.18</td>
</tr>
<tr>
<td>8 - 100% vermi</td>
<td>5.52</td>
<td>5.47</td>
<td>5.49</td>
<td>5.47</td>
<td>5.47</td>
<td>5.45</td>
</tr>
<tr>
<td>9 - 50% vermi</td>
<td>5.43</td>
<td>5.43</td>
<td>5.45</td>
<td>5.41</td>
<td>5.43</td>
<td>5.39</td>
</tr>
<tr>
<td>10 - Control</td>
<td>6.27</td>
<td>6.21</td>
<td>6.15</td>
<td>6.14</td>
<td>6.18</td>
<td>6.15</td>
</tr>
<tr>
<td>11 - 50% vermi</td>
<td>4.47</td>
<td>4.42</td>
<td>4.38</td>
<td>4.38</td>
<td>4.38</td>
<td>4.38</td>
</tr>
<tr>
<td>12 - 100% vermi</td>
<td>5.68</td>
<td>5.7</td>
<td>5.68</td>
<td>5.66</td>
<td>5.68</td>
<td>5.68</td>
</tr>
</tbody>
</table>

*Daily pH fluctuations.* Results from a few experiments show that the pH of the nutrient solution changed somewhat during the course of the day. Table 5.2 shows daily pH fluctuations measured in experiment 9 between 9:00 and 17:00 on 18.05.09 in each NFT-channel which represented a replicate of different treatments.

Table 5.2 shows that in the morning pH was slightly higher than later in the day. As the day progressed pH steadily decreased in all NFT-channels and stabilized in the afternoon hours.

Fluctuations in pH during the day ranged from 0.03 to 0.10. Highest fluctuations were noticed in the control treatment (NFT-channels 3, 6, 7, 10 in Table 5.2). Nevertheless, the difference in pH between times of day was not so great as to affect comparisons between days when pH was measured at slightly different times.

The pH fluctuations are likely to be related to the changing temperature of the nutrient solution and also due to the internal physiological cycles of plants, and the uptake and release of ions that influence solution pH. These fluctuations are likely to be too small to affect plant growth.
5.1.1.1 **Buffer application**

Several products were trialled to quantify their efficiency in reducing solution pH to a suitable level. These were only trialled in the batch systems – no buffering was done in the in-line systems. The choice of buffer and the procedure had exceptional importance in management practices of hydroponic pak choi produced with vermiliquer.

Initially, buffering was done with orthophosphoric acid, but this was accompanied by poor development of plants in the vermiliquer treatment in experiment 2. This is consistent with published data (Bugbee, 2003) that show that concentrations of phosphorus in phosphoric acid required to stabilise pH might be toxic to plants. Comparison of orthophosphoric and nitric acids as pH-buffers in experiment 4 revealed higher yield in the vermiliquer treatment buffered with nitric acid. Consequently, only nitric acid (10% HNO₃) was used as a pH-buffer for all further experiments.

Throughout all experiments, to maintain a designated pH in the solution, buffering of vermiliquer (c. 90% of the total buffer applied) was needed mainly in the first days (Table 5.3). After that, pH of the solution remained relatively stable to the end of experiment, sometimes only requiring small amounts of buffer to compensate for the slow upward trend in pH.

<table>
<thead>
<tr>
<th>Table 5.3. Average quantity of buffer (ml 10% HNO₃) applied to treatments during experiment 3.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
</tr>
<tr>
<td>Control</td>
</tr>
<tr>
<td>Vermiliquer pH 7.0</td>
</tr>
<tr>
<td>Vermiliquer pH 5.5</td>
</tr>
</tbody>
</table>

Quantities of buffer applied. It is difficult to compare the total amount of buffer used in different experiments, because they were conducted on different vermiliquers at different times of year and were subject to different ambient temperatures and numerous other factors. As a general
guide only, buffering a 100 L vermiliquer reservoir in this experimental setup required from 500 to 1000 ml of 10%- HNO$_3$.

In the experiments where treatment pairs of 50% and 100%- vermiliquer were compared, the amount of the buffer used in 50%- vermiliquer treatments was as expected much lower than in the 100%-vermi treatment (Table 5.4). Generally, the amount of buffer required was roughly proportional to the dilution rate. The 50%- vermili quer treatment required one half (experiments 5 and 9) or two thirds (experiment 7) of buffer required for 100%-vermili quer treatment.

Addition of nitric acid to the solution caused an intensive reaction that resulted in the formation of a thick cap of foam as the buffer reacted with the compounds dissolved or suspended in vermili quer. Nitric acid added to the vermili quer may trigger a release of some inorganic elements from organic compounds into the solution, or, conversely, bind nutrients otherwise available for the plants into the precipitated foam/biofilm. The effect of the buffer on the nutrient balance and nutrient availability of the vermili quer is not understood, but nitric acid buffer added nitrate to the system, which was reflected in measurements of nitrate (Figure 4.4).

For treatments that lost some volume through leakages, the original vermili quer was topped up and repeatedly buffered, with the volume of buffer re-calculated to obtain the appropriate pH.

Due to the recognised buffer capacity of the vermili quer itself, in these and other experiments buffering of vermili quer never happened in one step (Table 5.4). It usually took a few days for the system to achieve pH-equilibrium during initial buffering.

During the first days in experiments 3 and 4, pH in the vermili quer treatments returned to its original high pH within a few hours after buffering. After subsequent application of buffer over a few days (5 to 7 in experiments 3 and 4), pH of the solution was stabilised at the designated level and from that time changed only slightly, thus not requiring further buffering.

To investigate buffer capacities of the vermili quer and to reduce the amount of pH buffer required, a number of buffer application schemes were tested.

a) Initial and corrective buffering. From here onwards, ‘initial buffering’ means buffering employed from the beginning of experiment to the point when pH was relatively stable and did
not require further buffering to maintain a designated pH 5.5-6.5 range. ‘Corrective buffering’ refers to subsequent or further buffering to keep the pH between pH 5.5-6.5.

Table 5.4 shows that in all experiments where buffering took place, corrective buffering did not exceed 30% of the total amount of buffer and for most experiments it was less than 10%. After initial buffering, the proportion of the buffer required to correct pH was somewhat higher in the 50%-vermiliquer treatments. In contrast, for 100%-vermiliquer, once the initial buffering was completed it required little or no further buffering.
Table 5.4. The amounts (ml) and timings of 10%- HNO₃ used in different experiments to buffer to pH 5.5. The volume of nutrient solution to buffer initially – 100 L.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Origin of vermiliquer</th>
<th>Treatment</th>
<th>Time for initial buffering</th>
<th>Initial buffering* (ml) – I</th>
<th>Total buffering (ml) – T</th>
<th>Proportion I/T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp 3</td>
<td>paunch</td>
<td>100%-vermi</td>
<td>7 days (31/10/08-06/11/08)</td>
<td>702</td>
<td>777</td>
<td>90%/100%</td>
</tr>
<tr>
<td>Exp 4</td>
<td>paunch</td>
<td>100%-vermi</td>
<td>5 days (05/12/08-09/12/08)</td>
<td>720</td>
<td>750</td>
<td>96%/100%</td>
</tr>
<tr>
<td>Exp 5</td>
<td>paunch</td>
<td>100%-vermi</td>
<td>10 days (22/01/09-03/02/09)</td>
<td>1060</td>
<td>1330</td>
<td>80%/100%</td>
</tr>
<tr>
<td>Exp 5</td>
<td>paunch</td>
<td>50%-vermi</td>
<td>10 days (22/01/09-03/02/09)</td>
<td>550</td>
<td>770</td>
<td>71%/100%</td>
</tr>
<tr>
<td>Exp 7</td>
<td>paunch</td>
<td>100%-vermi</td>
<td>3 days (26/03/09-28/03/09)</td>
<td>855</td>
<td>943</td>
<td>91%/100%</td>
</tr>
<tr>
<td>Exp 7</td>
<td>paunch</td>
<td>50%-vermi</td>
<td>3 days (26/03/09-28/03/09)</td>
<td>420</td>
<td>614</td>
<td>68%/100%</td>
</tr>
<tr>
<td>Exp 8</td>
<td>paunch</td>
<td>100%-vermi</td>
<td>3 days (26/03/09-28/03/09)</td>
<td>835</td>
<td>905</td>
<td>92%/100%</td>
</tr>
<tr>
<td>Exp 9</td>
<td>paunch</td>
<td>100%-vermi</td>
<td>2 days (14/05/09-15/05/09)</td>
<td>550</td>
<td>633</td>
<td>87%/100%</td>
</tr>
<tr>
<td>Exp 9</td>
<td>paunch</td>
<td>50%-vermi</td>
<td>2 days (14/05/09-15/05/09)</td>
<td>313</td>
<td>385</td>
<td>81%/100%</td>
</tr>
<tr>
<td>Exp 10</td>
<td>paunch</td>
<td>100%-vermi</td>
<td>1 day (29.06.09)</td>
<td>400</td>
<td>403</td>
<td>99%/100%</td>
</tr>
<tr>
<td>Exp 10</td>
<td>paunch</td>
<td>50%-vermi</td>
<td>1 day (29.06.09)</td>
<td>200</td>
<td>238</td>
<td>84%/10%</td>
</tr>
<tr>
<td>Exp 11</td>
<td>vegetable (kitchen waste)</td>
<td>100%-vermi</td>
<td>1 day (22-23.08.09)</td>
<td>599</td>
<td>708</td>
<td>90%/100%</td>
</tr>
<tr>
<td>Exp 11</td>
<td>paunch</td>
<td>100%-vermi</td>
<td>1 day (22-23.08.09)</td>
<td>489</td>
<td>541</td>
<td>85%/100%</td>
</tr>
</tbody>
</table>
b) Gradual buffering scheme. Table 5.4 shows that in experiment 5 initial buffering lasted 10 days. The ten-day fallow method was employed with the intention of reducing the overall amount of buffer to be applied. Initial buffering procedures were carried out in an operating hydroponic system without plants and the pH of the nutrient solution was initially adjusted to 6.5. To avoid any pH fluctuations that might resulted from plant-vermiliquer interactions, in the beginning of the fallow period the system was kept recirculating without plants for one week. During this week pH of the vermiliquer returned to pH 8.0, which was the same as the initial pH of the unbuffered vermiliquer. The system was then buffered to pH 5.5. Seedlings were transplanted into the system the day after the second application of the pH-buffer.

This gradual buffering scheme did not reduce the overall amount of buffer used during the experiment and did not shorten the period of pH stabilisation after the second application of the buffer, when compared with other experiments. Consequently, the gradual buffering scheme was not investigated further in this study.

In experiment 7 and onwards initial buffering was completed during the first three days with a daily application of the buffer after transplanting.

c) One-step buffering and 'acidic shock'. In experiments 10 and 11, instead of gradually adding the buffer, total estimated amount of buffer was added to the solutions in one step at the beginning of each experiment. In two out of four units of 100%- vermiliquer treatment in experiment 10 and in two out of four units of the vege-liquer (with kitchen wastes) in experiment 11 this one-step buffer application caused so-called 'acidic shock', when the day after the initial stabilization at pH 5.0-5.5 – and without any more buffer or any interference with the system – the pH in the nutrient solution fell to c. pH 3.0 and remained relatively low for the rest of the experiment, only showing a very slow increase with time (Figure 5.3). The reason for this is unclear and needs further investigation.

It is interesting to note that with the ‘acidic shock’, pH in the 100%- vermiliquer units dropped more in the shade than in the open, although due to the limited number of replicates the difference was not statistically confirmed. Figure 5.3 shows that pH in nutrient solution remained the lowest throughout the experiment in the shaded 100%- vermiliquer treatment.
As discussed in a later section on growth and yield, the plants grown under strong acidic condition (< pH 4 for two or more weeks and < pH 5.0 during the rest of the experiment) did not show any signs of deficiencies or retarded growth. Bugbee (2003) similarly reported no differences in growth between pH 4 and pH 5.8 with hydroponic wheat and their practice was to grow wheat crops at pH 4.0 during the entire life cycle.

Figure 5.3. Trends for pH in experiment 10.

In the 50%-vermiliquer treatment in experiment 10 the initial buffering from 8.5 to 5.5 was done with 200 ml of buffer (exactly half the dose for the 100%-vermiliquer treatment). Although the replicates in the shade showed a slight decrease in pH during the next two days, it did not cause ‘acidic shock’ and pH in these treatments remained stable for about 10 days after the initial buffering. After that pH steadily increased, and on the 18th of July, after three weeks, a corrective buffering was applied. pH in the 50%-vermiliquer treatment was at all times higher than in the 100%-vermiliquer treatment and within the ‘ideal’ range pH 5.5-6.5.

Taking into the account the complexity of the system (reservoirs with the nutrient solution, pipes, media), vermiliquer components (inorganic and organic compounds, and microbiota), and plant-vermiliquer interactions, the choice of buffer and procedure of buffer application will often be site-specific and requires further investigation.
**Relationship between the applied amount of buffer and the produced change in pH in vermiliquer.** As expected, statistical analysis confirmed a strong relationship between the amount of buffer added to the nutrient solution and change in pH (p < 0.01) across all experiments where buffering was employed (e.g. Figure 5.4 showing data for experiment 3). However, the potential for pH stabilisation and buffering of vermiliquer was non-linearly related to buffer quantity, that is initial buffering required large amounts of the buffer, producing little long-term result in terms of pH-reduction, while after stabilizing pH at a designated level pH of vermiliquer remained relatively stable, sometimes only requiring corrective buffering with a small amount of buffer.

Buffering of vermiliquer, a ‘living’ organic media of high complexity, was superimposed onto the tendency of vermiliquer to increase in pH and comprised all physical and chemical reactions and possible changes in microbiota populations in vermiliquer that were triggered by the application of buffer. The non-linear relationship between the amount of buffer added to the vermiliquer and the change in pH best fitted a polynomial model (Figure 5.4).

![Figure 5.4. Relationship between the amount of buffer (10% HNO₃) and the produced change in pH (within a day after buffering) in experiment 3.](image-url)
Figure 5.4 shows clusters of values that correspond to the initial and corrective buffering. For example, during initial buffering at the beginning of the experiment c. 750 ml of 10%-HNO₃ were required to change pH of vermiliquer from pH 8.0 to pH 4.5 (change in pH is ‘-3.5’) and c. 450 ml of the buffer to change pH from pH 8.0 to pH 6.0-6.5 (change in pH is ‘-2’). At the end of the experiment only small amounts of buffer were used to compensate the upward shift in pH in vermiliquer. Where the amount of buffer was not enough to compensate the slowly increasing pH of the nutrient solution, values for pH-changes were positive (i.e. ‘+0.5’).

Figure 5.5 shows the same data conditionally grouped into the stages of initial (at the beginning of the experiment), repeated (in the middle of the experiment) and corrective (in the end of the experiment) buffering with a linear equation best expressing the relationship at each stage.

![Graph showing the relationship between the amount of applied buffer (10%-HNO₃) and the produced change in pH (within a day after buffering) at different stages in experiment 3: during initial buffering, repeated buffering in the middle of the experiment and corrective buffering at the end of the experiment.]

Regression analysis with the stage of experiment as a grouping factor did not confirm a significant difference between the initial, repeated and corrective buffering due to the high variance of responses in large values (characteristic of the initial buffering) and little variance in responses in small values (characteristic of the corrective buffering).
Other experiments further illustrate the differences between the initial application of buffer and the ensuing buffering. For example, in experiment 5 (Figure 5.6), initial buffering with c. 400 ml 10%-HNO₃ to the 100%-vermiliquer treatment and c. 200 ml to the 50%-vermiliquer was compensated by increase in pH within a day. In Figure 5.6 the initial buffering of both 100%- and 50%-vermiliquer treatments appears to have produced no effect at all. Repeated buffering with c. 700 ml of the buffer to the 100%-vermiliquer and c. 400 ml to the 50%-vermiliquer two days later reduced the pH level. After that, corrective buffering of both treatments to effectively reduce pH of the solution required only a small amount of buffer.

![Figure 5.6](image)

Figure 5.6. Relationship between the amount of applied buffer (10%-HNO₃) and the produced change in pH (within a day after buffering) in the 100%- and 50%-vermiliquer treatments at different stages of experiment 5: during initial buffering, repeated buffering two days later and corrective buffering for the rest of the experiment.

Application of buffer during experiments 9 (Figure 5.7) and 7 (Figure 5.8) confirms the pattern found in experiment 3 (pattern is a bit different in experiment 5) and clearly shows the remarkable pH-stability of vermiliquer. Relatively large amounts of buffer were needed to initially decrease pH of the nutrient solution, but once buffered the vermiliquer treatments demonstrated exceptional pH stability.
Comparing the 50%- and 100%- vermiliquer treatments, the initial amount of buffer required in the former was a half or more of that in the latter. The amount of the buffer required for the corrective buffering was relatively small, as compared with the initial buffering, and was nearly the same for both vermiliquer treatments.

In experiment 10 (Figure 5.9), in which one-step buffering was used, the total calculated amount of buffer was added to the vermiliquer treatments at the beginning of the experiment. In 100%-vermiliquer treatment this practice caused a marked drop in pH of the solution (to c. pH 3.0) and until the end of the experiment pH remained low, so that no corrective buffering was required.
In the 50%-vermiliquer treatment half the amount of buffer applied to the 100%-vermiliquer treatment did not reduce the pH so markedly, so during the experiment some corrective buffering was required.

![Graph](image1)

**Figure 5.9.** Relationship between the amount of applied buffer (10%-HNO₃) and the produced change in pH (within a day after buffering) in the 100%- and 50%-vermiliquer treatments in experiment 10.

While discussing buffering requirements of vermiliquer, it should be noted that vermiliquer ‘response’ to buffering with different acids (HNO₃ and HPO₄ used as different buffers in experiment 4) was similar: initial buffering required considerable amounts of buffer and produced little effect on change in pH, repeated buffering also required substantial amounts of buffer and lowered pH to a designated level, and the corrective buffering was either not required or done with relatively small amounts of buffer (Figure 5.10).

![Graph](image2)

**Figure 5.10.** Relationship between the amount of applied buffer (10%-HNO₃ or 10%-HPO₄) and the produced change in pH in the 100%-vermiliquer treatments in experiment 4.
Figure 5.10 shows that after initial buffering with comparable amounts of HNO₃ and HPO₄, vermiliquer treatment buffered with HPO₄ required about thirty percent more buffer than when nitric acid was used. This could result from chemical properties of the acids: HNO₃ is stronger than HPO₄. However, at later stages of the experiment the vermiliquer treatment buffered with HNO₃ required corrective buffering, while pH in the vermiliquer treatment buffered with HPO₄ was stable. This could result from nitrate uptake from the buffer as a nutrient for plants and faster plant growth in the vermiliquer treatment buffered with HNO₃.

Buffer requirements of vermiliquer naturally depend on the source of waste (Figure 5.11). Experiment 11 comprised treatments with vermiliquer obtained from two sources: liquer (‘paunch’ material) and ‘vege-liquer’ (kitchen waste). The results showed that in terms of buffering, to maintain stable pH of the nutrient solution the paunch ‘liquer’ required less buffer than the ‘vege-liquer’. In addition, the amounts of buffer applied and the effect it had on pH of the solution during initial and corrective buffering were more consistent for the ‘liquer’ than for the ‘vege-liquer’ treatments.

Figure 5.11. Relationship between the amount of applied buffer (10% HNO₃) and the produced change in pH (within a day after buffering) of vermiliquer obtained from different wastes in experiment 11: ‘liquer’ (paunch material) and ‘vege-liquer’ (kitchen waste).
**Control treatment.** Buffering of the control treatments was done across experiments with small quantities of acid (orthophosphoric in experiments 1, 2 and 4 and nitric acid in experiment 3 and 4 and all further experiments) to maintain the nutrient solution within a designated pH range. In the experiments where 10%- HNO₃ was applied, the amount of buffer required to maintain pH in the control treatments within the acceptable range of pH 6.5-7.0 during the first two-three weeks of experiment varied from 3 to 15 ml. After that, due to the restricted initial volume of the solution and uneven uptake of elements by plants, pH in the control treatments increased, but application of the buffer had only a temporary effect. Nitric acid was apparently used by plants as a source of available nitrogen and did not provide pH-stability of the nutrient solution. Electrical conductivity in the control treatment at the end of the experiments fell below 0.4 μS/cm and in some experiments was close to zero, indicating depletion of nutrients. For this reason, further application of the buffer to the control treatment at the end of the experiment was not considered worthwhile. In a few cases small quantities of nitric acid were applied to feed the plants rather than to buffer the solution. On the whole, total amount of 10%- HNO₃ applied to the control treatment throughout the experiments ranged from 3 to 58 ml, the latter illustrated in Table 5.3.
5.1.2 Electrical conductivity of the nutrient solutions

For organic fertilisers, interpretation of the nutrient balances from EC measurements is problematic. However, electrical conductivity remains an indicator of the total amount of ions in their soluble form.

EC of vermiliquer in the vermifarm collecting tanks depended on the nature of organic wastes and maturity of vermiliquer (time of the worm feeding cycle, or the time from re-setting the worm pit) (Figure 5.12).

The increase of EC and change of pH of vermiliquer in the collecting tanks over time since pit setting was consistent with the findings of Kale (1993) that soluble salts and electrical conductivity (EC) generally increased over the course of the vermicomposting. However, after approximately 25 days in the winter and 15 days in the summer the EC showed only minimal relative increase, reflecting a probable saturation of vermiliquer. Elvira et al. (1998) reported an eventual decrease in electrical conductivity that may indicate the stage of complete decomposition of organic matter had been reached. In this study – under conditions of regular feeding and irrigation schedule – having reached the level of EC between 2.2-2.6 μS/cm, vermiliquer remained at the same EC level over the life span of the study (a few months), until the next complete worm pit re-setting.

![Figure 5.12. Increase in EC with time after the worm pit re-setting.](image)
The initial EC of the ‘mature’ vermiliquer applied to the hydroponic system in our experiments was between 1.8 to 2.4 μS/cm. In some experiments diluted 50%-vermiliquer was used and EC was lower. Electrical conductivity during the experiments was not manipulated, except on a few occasions at the end of experiments 7, 10 and 11 when, in order to lower EC of the nutrient solution when it exceeded 3.0 μS/cm and to prevent the solution from running dry (during intense evapo-transpiration), some reverse osmosis water was added.

Figure 5.13 shows the dynamics of electrical conductivity in the solutions in experiment 10. The EC in the unbuffered 100%-vermiliquer was identical to that in the control treatment (c. 1.5 μS/cm) and more than 50% higher that the EC in the 50%-vermiliquer treatments (< 1.0 μS/cm). After initial buffering EC in both vermiliquer treatments increased and from that time remained stable in all treatments as follows: EC in the control was c. 1.5 μS/cm, EC in the 50%-vermiliquer treatment was c. 1.4 μS/cm, EC in the 100%-vermiliquer treatment ranged from 2.2-2.4 μS/cm.

![Graph showing EC in experiment 10](image)

**Figure 5.13. Trend of EC over time in experiment 10.**

From the third week of experiment 10, EC in the control treatment began to gradually decrease, which indicated nutrient depletion. EC in the 100%-vermiliquer treatment increased, which was a result of continuous release of soluble inorganic material from organic compounds and an increase in evapo-transpiration. EC in some 50%-vermiliquer treatment replicates increased but decreased in others, which may indicate an interaction between the rates of nutrient uptake by plants, the rate of evapo-transpiration and the rate of release of inorganic particles from organic
compounds into the nutrient solution. As discussed later (see 5.4. Water use efficiency of the integrated system), it was apparent that in all experiments losses of water through evapotranspiration were considerably (c. 50%) higher in the control treatment.

Figure 5.14 shows the dynamics of electrical conductivity in the solutions in experiment 11, where the vermiliquer sourced from different waste ('paunch' and kitchen scraps) was compared with the control. At the beginning of the experiment the EC in all treatments was the same (approximately 1.6-1.8 \( \mu \text{S/cm} \)). As in other experiments, during the life span of this experiment, the EC in both vermiliquer treatments steadily increased. After four weeks the EC exceeded 3.5 \( \mu \text{S/cm} \) and the solutions were diluted with some RO water to reduce the EC. The EC in the control remained stable for three weeks and after that decreased.

![EC in experiment 11](image)

**Figure 5.14.** EC in experiment 11.

Low EC in the control treatment at the end of experiments (in some experiments below 0.1 \( \mu \text{S/cm} \)) show that the amount of nutrients contained in 100 L of initial nutrient solution was just enough to grow a crop of pak choi in this experimental setup (20-25 plants in one NFT-channel). High EC in the vermiliquer treatments throughout the experiments shows that the vermiliquer provides a steady release of nutrients in the nutrient solution that was enough to produce a crop of pak choi to the capacity of the NFT-channel and beyond.
Daily fluctuations in EC. Results from a few experiments in which variation in EC throughout the day was recorded show that it changed slightly during the day. As an example, Table 5.5 shows daily EC fluctuations in nutrient solution in each replicate, measured between 9:00 and 17:00 on 18.05.09 (experiment 9). In the morning EC was slightly lower than later during the day in the control and the 50% vermiliquer treatment.

Table 5.5. Daily changes in the EC in each replicate in experiment 9 (18.05.09).

<table>
<thead>
<tr>
<th>NFT-channel</th>
<th>9:00-9:15</th>
<th>10:00-10:15</th>
<th>11:00-11:15</th>
<th>14:00-14:15</th>
<th>15:30-15:45</th>
<th>17:15-17:30</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 50% vermi</td>
<td>0.96</td>
<td>0.96</td>
<td>0.97</td>
<td>0.97</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>2 - 100% vermi</td>
<td>1.80</td>
<td>1.82</td>
<td>1.80</td>
<td>1.81</td>
<td>1.82</td>
<td>1.81</td>
</tr>
<tr>
<td>3 - control</td>
<td>1.27</td>
<td>1.28</td>
<td>1.27</td>
<td>1.29</td>
<td>1.28</td>
<td>1.27</td>
</tr>
<tr>
<td>4 - 100% vermi</td>
<td>1.86</td>
<td>1.76</td>
<td>1.85</td>
<td>1.86</td>
<td>1.85</td>
<td>1.87</td>
</tr>
<tr>
<td>5 - 50% vermi</td>
<td>1.03</td>
<td>1.02</td>
<td>1.02</td>
<td>1.03</td>
<td>1.02</td>
<td>1.03</td>
</tr>
<tr>
<td>6 - control</td>
<td>1.26</td>
<td>1.25</td>
<td>1.25</td>
<td>1.26</td>
<td>1.26</td>
<td>1.26</td>
</tr>
<tr>
<td>7 - control</td>
<td>1.35</td>
<td>1.33</td>
<td>1.34</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
</tr>
<tr>
<td>8 - 100% vermi</td>
<td>1.85</td>
<td>1.83</td>
<td>1.84</td>
<td>1.83</td>
<td>1.83</td>
<td>1.83</td>
</tr>
<tr>
<td>9 - 50% vermi</td>
<td>0.96</td>
<td>0.96</td>
<td>0.97</td>
<td>0.98</td>
<td>0.99</td>
<td>0.98</td>
</tr>
<tr>
<td>10 - control</td>
<td>1.28</td>
<td>1.29</td>
<td>1.29</td>
<td>1.29</td>
<td>1.30</td>
<td>1.30</td>
</tr>
<tr>
<td>11 - 50% vermi</td>
<td>0.98</td>
<td>0.98</td>
<td>0.93</td>
<td>0.98</td>
<td>0.99</td>
<td>1.00</td>
</tr>
<tr>
<td>12 - 100% vermi</td>
<td>1.81</td>
<td>1.80</td>
<td>1.81</td>
<td>1.82</td>
<td>1.83</td>
<td>1.82</td>
</tr>
</tbody>
</table>

Fluctuations in EC during the day ranged from 0.01 to 0.02 μS/cm (Table 5.5). The difference in EC between times during a day was not so great as to affect comparisons between days when EC was measured at slightly different times. The EC fluctuations are likely to be related to the changing temperature of the nutrient solution (Carruthers, 1998).
5.1.3 Temperature

Fluctuations in nutrient solution temperature on different days naturally followed fluctuations in ambient temperature.

Figure 5.15 and Figure 5.16 show ambient temperature and the nutrient solution temperature at the time of daily measurement throughout simultaneous experiments 11 (batch treatments) and 12 (in-line treatments). Nutrient solutions in the in-line treatments were less prone to temperature fluctuations than in the batch treatments (compare in-line treatments in experiment 12 versus batch treatments in experiment 11) due to the former's larger tank capacity and less exposure to the sun (sunken collecting 500 L vermiliquer tanks in the shed versus 100 L reservoirs in the open for the batch treatments).

![Figure 5.15. Ambient temperature and temperature of the nutrient solutions (°C) in experiment 11 (off-line (batch) treatments).](image)

![Figure 5.16. Ambient temperature and temperature of the nutrient solutions (°C) in experiment 12 (in-line treatments).](image)
Figure 5.17 illustrates the temperature in solution in experiment 6 where the in-line vermiliquer treatments were compared with the control. Changes in temperature in the in-line vermiliquer may have been offset by the greater heat sink capacity (500 L versus c. 100 L in the control).

In the other experiments employing direct linkage – experiments 8 and 12 – temperature of the nutrient solution differed slightly between treatments. This can be explained by the different exposures of the collecting reservoirs to the sun. For example, in experiment 12 the position of the tanks containing vermiliquer obtained from vermicomposted paunch was on the side of the shed more exposed to the sun than the tanks containing ‘vege-liquor’ from kitchen waste, which were located in the middle of the shed, and as such, were less exposed to the sun.

![Graph of temperature changes](image)

**Figure 5.17. Temperature (°C) in the nutrient solutions in experiment 6: the control and the in-line vermiliquer treatments.**

In the tropical climate, the temperature of the nutrient solution was one of the major concerns and various practices were employed to minimise overheating. During the summer, pots were used rather than NFT. The pot medium (perlite in this case) contained enough water to allow pumps to work in alternating modes of 30 minutes pumping and 30 minutes rest. This prevented excess energy-consumption and overheating of pumps. Other practices to reduce nutrient solution temperature included painting all exterior parts of the hydroponic system white (experiments 1 and 2) and insulation of the nutrient solution reservoirs with reflective material from experiment 3 onwards (Figure 5.18).
Effectiveness of thermo-insulation reflective cover is illustrated by Figure 5.19. On a few subsequent hot summer days from 17.01.10 to 29.01.10, the temperature of the nutrient solution was measured in two reservoirs - one insulated with the thermo-insulation reflective material, used in our experiments, and one non-insulated reservoir exteriorly painted white. The reservoirs contained 50 L (average working volume of nutrient solution in most experiments). During the trial, pumps for recirculating were kept working to make the conditions as close to the actual conditions employed in the experiments as possible.

Figure 5.19 shows that the amplitude of temperature fluctuations in the non-insulated reservoirs was higher than in the insulated reservoirs. Thus, thermo-insulation covers protected the reservoirs from day-time heating. The lowest night temperatures (between 4:30 and 5:30 am) in the non-insulated reservoirs were 2-3°C lower than in insulated reservoirs, while the difference during the highest midday temperatures (between 12:30 and 4:30) was 5-6 °C. On hot days the
temperature in the non-insulated reservoir easily exceeded 30°C, while the insulated reservoir kept the solution temperature below 30°C even in the hottest weather. High solution temperature (> 30 °C) is considered detrimental for hydroponically grown lettuce (Frantz et al., 2004). High temperature can result in increased respiration rate of the roots and increased requirement for oxygen while the oxygen carrying capacity decreases. For example, when the solution is 20 °C it holds 9 mg/L dissolved oxygen when fully saturated but only 7.5 mg/L dissolved oxygen at 30 °C (Thompson et al., 1998). Therefore, reducing excessive solution temperatures ensures more oxygen can be held by the solution and the rate of root respiration is at adequate levels.

Daily fluctuations of the solution temperatures and the difference in ambient temperature in the shade and the open. The temperature in the nutrient solutions steadily increased during the day reflecting the trend of ambient temperature in the open (Figure 5.20). The lower temperature in the nutrient solution compared to the ambient temperature during the daytime demonstrated the greater heat-buffer capacities of the nutrient solutions compared to the air.

![Temperature graph](image)

**Figure 5.20.** Daily changes in the ambient air temperature and temperature of the nutrient solutions (°C) in the shade and in the open (experiment 9, 19.05.09).

Figure 5.20 shows significantly higher ambient temperature in the shade; that increased after sunrise and reached its peak at 10 am. The ambient shade temperature decreased in the mid afternoon, and in the late afternoon hours (after 5 pm) fell below that in the open.
5.1.4 Dissolved oxygen

Both the vermifarm collecting tanks and the reservoirs with batch vermiliquer for the hydroponics were continuously aerated. The increased inherent biological oxygen demand, as vermiliquer production proceeded, did not result in reduction in dissolved oxygen in the vermiliquer reservoirs, for they were adequately supplied with air (Figure 5.21). However, the dissolved oxygen in the reservoir with the nutrient solutions likely differed to that in the NFT-channels.

![Graph showing dissolved oxygen concentration over days](image)

**Figure 5.21.** Dissolved oxygen (mg/L) in the vermifarm collecting tank during 20 days after the worm bed re-setting (October 2008).

In all experiments a close relationship was evident between the dissolved oxygen concentration across all nutrient treatments and the temperature of the solution within the reservoir (as illustrated by Figure 5.22 for experiment 10) emphasizing the importance of temperature insulation for an adequate supply of oxygen.

![Graph showing dissolved oxygen vs temperature](image)

**Figure 5.22.** Relationship between dissolved oxygen (mg/L) and nutrient solution temperature (°C) in experiment 10.
In the experiments comparing in-line and batch treatments, values for dissolved oxygen at a given temperature in the in-line vermiliquer were lower than in the batch treatments (Figure 5.23). Aeration of the nutrient solution seemingly met the microbial demand for the oxygen associated with the in-line vermiliquer treatment at any temperature.

![Graph showing relationship between dissolved oxygen and nutrient solution temperature](image)

**Figure 5.23.** Relationship between dissolved oxygen (mg/L) and nutrient solution temperature (°C) in experiment 6.

Linear models of regression confirmed ($p < 0.001$) the strong relationship between dissolved oxygen in the nutrient solution and the temperature across all treatments.

Table 5.6 summarises regression equations for dependency of dissolved oxygen concentration on solution temperature across experiments.
Table 5.6. Relationship between dissolved oxygen concentration ($y$) and temperature of nutrient solution ($x$) in the equation $y = a - bx$, where $a$ and $b$ are constants; $r^2$ is the coefficient of determination.

<table>
<thead>
<tr>
<th>Exp</th>
<th>Treatment</th>
<th>$a$</th>
<th>$b$</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Control</td>
<td>35.88</td>
<td>-2.1713</td>
<td>0.658</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer buffered with HPO$_4$</td>
<td>38.74</td>
<td>-2.4960</td>
<td>0.796</td>
</tr>
<tr>
<td>3</td>
<td>Control</td>
<td>50.28</td>
<td>-3.6059</td>
<td>0.902</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer at pH 7.0</td>
<td>47.00</td>
<td>-3.2409</td>
<td>0.801</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer at pH 5.5</td>
<td>45.79</td>
<td>-3.1356</td>
<td>0.769</td>
</tr>
<tr>
<td>4</td>
<td>Control</td>
<td>15.99</td>
<td>-0.2865</td>
<td>0.918</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer buffered with HNO$_3$</td>
<td>25.21</td>
<td>-0.2702</td>
<td>0.901</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer buffered with HPO$_4$</td>
<td>15.28</td>
<td>-0.2704</td>
<td>0.815</td>
</tr>
<tr>
<td>5</td>
<td>Control</td>
<td>50.86</td>
<td>-2.8993</td>
<td>0.866</td>
</tr>
<tr>
<td></td>
<td>100%- vermiliquer</td>
<td>51.77</td>
<td>-3.1116</td>
<td>0.882</td>
</tr>
<tr>
<td></td>
<td>50%- vermiliquer</td>
<td>50.97</td>
<td>-3.0289</td>
<td>0.853</td>
</tr>
<tr>
<td>6</td>
<td>Control</td>
<td>49.84</td>
<td>-2.8110</td>
<td>0.799</td>
</tr>
<tr>
<td></td>
<td>In-line vermiliquer</td>
<td>41.53</td>
<td>-1.8580</td>
<td>0.585</td>
</tr>
<tr>
<td>7</td>
<td>Control</td>
<td>42.89</td>
<td>-2.5238</td>
<td>0.652</td>
</tr>
<tr>
<td></td>
<td>100%- vermiliquer</td>
<td>48.11</td>
<td>-3.1958</td>
<td>0.825</td>
</tr>
<tr>
<td></td>
<td>50%- vermiliquer</td>
<td>47.44</td>
<td>-3.0880</td>
<td>0.803</td>
</tr>
<tr>
<td>8</td>
<td>In-line vermiliquer</td>
<td>46.90</td>
<td>-3.0428</td>
<td>0.659</td>
</tr>
<tr>
<td></td>
<td>Buffered off-line vermiliquer</td>
<td>45.08</td>
<td>-2.7970</td>
<td>0.768</td>
</tr>
<tr>
<td></td>
<td>Unbuffered off-line vermiliquer</td>
<td>46.97</td>
<td>-3.0279</td>
<td>0.810</td>
</tr>
<tr>
<td>9</td>
<td>Control</td>
<td>40.31</td>
<td>-2.3060</td>
<td>0.931</td>
</tr>
<tr>
<td></td>
<td>100%- vermiliquer</td>
<td>41.37</td>
<td>-2.4345</td>
<td>0.957</td>
</tr>
<tr>
<td></td>
<td>50%- vermiliquer</td>
<td>38.57</td>
<td>-2.1221</td>
<td>0.859</td>
</tr>
<tr>
<td>10</td>
<td>Control</td>
<td>17.62</td>
<td>-0.4366</td>
<td>0.959</td>
</tr>
<tr>
<td></td>
<td>100%- vermiliquer</td>
<td>17.67</td>
<td>-0.4404</td>
<td>0.968</td>
</tr>
<tr>
<td></td>
<td>50%- vermiliquer</td>
<td>17.54</td>
<td>-0.4331</td>
<td>0.970</td>
</tr>
<tr>
<td>11</td>
<td>Control</td>
<td>14.93</td>
<td>-0.2980</td>
<td>0.957</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer (paunch)</td>
<td>14.76</td>
<td>-0.2925</td>
<td>0.972</td>
</tr>
<tr>
<td></td>
<td>Vermiliquer (kitchen waste)</td>
<td>14.70</td>
<td>-0.2887</td>
<td>0.961</td>
</tr>
<tr>
<td>12</td>
<td>In-line vermiliquer (paunch)</td>
<td>13.93</td>
<td>-0.2651</td>
<td>0.683</td>
</tr>
<tr>
<td></td>
<td>In-line vermiliquer (kitchen waste)</td>
<td>14.54</td>
<td>-0.2920</td>
<td>0.794</td>
</tr>
</tbody>
</table>
Daily fluctuations in the dissolved oxygen.

In the morning, concentration of the dissolved oxygen in nutrient solution was higher than later in the day (Figure 5.24).

![Daily changes in dissolved oxygen](image)

Figure 5.24. Average dissolved oxygen at each time of day in treatments in experiment 9 (18.05.09).

With the increased temperature during the midday hours the amount of dissolved oxygen naturally decreased, and so concentration of dissolved oxygen was the lowest between 3 pm and 4 pm.

It should be noted, that the exact amount of dissolved oxygen available for plants is unknown. Dissolved oxygen concentration was measured in the nutrient solution reservoir, not in the root zone. We assume that using vermiliquer in the NFT-setup may create anaerobic conditions around roots and consequently suppress growth (Figure 5.25).

![Figure 5.25. Sludge from the verminfarm collecting tanks creates thick mud around roots (experiment 8 with the in-line vermiliquer, 20.09.09).](image)
5.2 Nutrients

5.2.1 Nitrogen

5.2.1.1 Nitrogen mass balance estimation

It is difficult to accurately estimate and interpret mass balances for forms of nitrogen in organic
vermiliquer.

To quantify the total nitrogen in the organic nutrient solution I estimated the input/output
elemental balance and volumes. Using the data of laboratory analysis for the total nitrogen in
vermiliquer at the beginning and at the end of experiment 10, together with losses in volume of
the solution during an experiment and the amount of added buffer (nitric acid), it was estimated
that on average 100 L of the buffered vermiliquer contained 53.02 g of nitrogen: 46.4 g N
originated from the initial unbuffered vermiliquer (see Table 3.2) and 8.9 g N was added with
nitric acid equivalent to 84% of the total nitrogen coming from the initial vermiliquer and 16%
from the buffer.

Knowing the percentage of total nitrogen contained in the dry shoots and total dry weight of
shoots produced in the system, it was estimated that the average amount of total nitrogen
accumulated in shoot tissues in one replicate of a 100%-vermiliquer treatment was 5.8 g N.

Therefore, according to our estimations, only 12% of total nitrogen containing in the buffered
vermiliquer was accumulated in shoot tissues of pak choi.

It is unlikely that all the nitrogen in the original vermiliquer was mineralised over a four week
period to be become available for root uptake. It is assumed that the balance of the nitrogen lost
from the system during the experiment and not accumulated in the shoot tissues was contained
in the roots, tied to the media, precipitated or volatilised (converted to gaseous form).

For comparison, each replicate of the inorganic control solution contained 23.65 g of nitrogen in
the initial solution (calculated from the composition of the Boxsell starting nutrient mix in
Error! Reference source not found. and concentration of the solution 3.4 L Part A + 3.4 L
Part B per 1000 L water) which is only half of that in the initial unbuffered vermiliquer. Then, 1.25 g of nitrogen was added with nitric acid which is seven times less than the amount of buffer added to the vermiliquer. Summing up, total nitrogen in 100 L of the control was 24.9 g — 95% of the total nitrogen coming from the initial solution and 5% from the buffer.

The average amount of total nitrogen accumulated in shoot tissues in one replicate of the control treatment was 5.8 g N, exactly the same as in the 100%-vermiliquer. Therefore, 23% of total nitrogen in the buffered control was accumulated in shoot tissues. As for the vermiliquer treatment, it is assumed that the balance of the nitrogen lost from the system was contained in the roots (which comprised <10 to 30% of total dry weight), tied to the perlite media, precipitated or volatilised.

In conclusion, in the present study the vermiliquer contained double the amount of total nitrogen compared to the control treatment, however, the ability of plants to utilise the element in shoot tissues in the vermiliquer treatment was only one half of that in the control. The total amount of nitrogen accumulated in shoot tissues per replicate was the same for both treatments.

5.2.1.2 Nitrate in nutrient solution

The nitrate concentration in vermiliquer was quite high throughout all experiments and is likely to be caused by the use of nitric acid to adjust pH in vermiliquer. Table 5.7 shows that nitrate concentration in both vermiliquer treatments increased after application of nitric acid. The control treatment was not buffered and the slight reduction in nitrate concentration in the solution overnight might be explained by initial ‘loading’ of the perlite media with nutrients, plant uptake and measurement error.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>14/05/09, 4:30 pm, before buffering</th>
<th>15/05/09, 9:00 am, after buffering</th>
<th>used buffer (ml 10% HNO3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% vermiliquer</td>
<td>460</td>
<td>665</td>
<td>550</td>
</tr>
<tr>
<td>50% vermiliquer</td>
<td>365</td>
<td>405</td>
<td>313</td>
</tr>
<tr>
<td>Boxsell</td>
<td>493</td>
<td>465</td>
<td>0</td>
</tr>
</tbody>
</table>
For the buffered and unbuffered batch and unbuffered in-line vermiliquer treatments in experiment 8, during the first three days nitrate in the unbuffered batch vermiliquer decreased, but increased in the buffered batch vermiliquer after addition of nitric acid, and remained unchanged in the in-line (unbuffered) vermiliquer (Table 5.8). The decrease in the nitrate in the unbuffered treatment most probably is attributed to the initial perlite media ‘loading’ and nutrient uptake by plants and microbiota. The unbuffered in-line treatment had five times more solution and therefore would not lose proportionately so much nitrate due to media ‘loading’.

Table 5.8. Nitrate concentration (mg/L) in the nutrient solutions at the beginning of experiment 8.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>26/03/09, before buffering (if applicable)</th>
<th>28/03/09, after buffering (if applicable)</th>
<th>Used buffer (ml 10% HNO3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbuffered in-line vermiliquer</td>
<td>305</td>
<td>305</td>
<td>n/a</td>
</tr>
<tr>
<td>Unbuffered batch vermiliquer</td>
<td>305</td>
<td>195</td>
<td>n/a</td>
</tr>
<tr>
<td>Buffered batch vermiliquer</td>
<td>305</td>
<td>510</td>
<td>835</td>
</tr>
</tbody>
</table>

As a rule, corrective pH buffering with nitric acid was done after taking measurements for nitrate in nutrient solution. Corrective buffering rarely was employed more often than once in 4-5 days, and so it is assumed that the time was enough for the system to stabilise and to utilize nitrate from the buffer.

Although there were some fluctuations (caused by natural release of nitrate mineralisation of organic compounds in the aerated vermiliquer and by the adding of buffer to the system) nitrate concentration remained remarkably stable in the vermiliquer treatments throughout all experiments. Nitrate concentration in the control treatment at the beginning of the experiment was significantly higher than at the end (Figure 5.26).
Figure 5.26. Nitrate concentration in the nutrient solutions in experiment 10.

Figure 5.26 illustrates the dynamics of nitrate in the solutions in experiment 10. In the beginning of the experiment it was highest in the 100%-vermiliquer and the control treatments. In the 50%-vermiliquer treatment it was half that of the 100%-vermiliquer, proportional to the dilution. Initial buffering significantly increased nitrate concentration in all treatments. Of note, the control treatment required only a small amount of buffer and the amount required to buffer vermiliquer was much larger (see 5.1.1.1. Buffer application).

During the experiment the nitrate concentration in the control treatment steadily decreased as expected for a finite amount of nutrient in an inorganic solution. By the end of the experiment there was practically no nitrate left in the control treatment, indicating complete nutrient depletion.

Nitrate concentration in both the vermiliquer treatments also declined with time, but remained significantly higher than that in the control. An increase in nitrate in the 50%-vermiliquer treatment on the 24.07.09 was a result of corrective buffering. By the end of the experiment the nitrate concentration in both vermiliquer treatments was still high. For the 50%-vermiliquer treatment it was the same at the end of the experiment as in the beginning.

The results from this and other experiments suggest that vermiliquer provides a continuous and steady supply of nitrate for hydroponic plants. This also implies that the concentration of nitrate in the buffered vermiliquer fully meets the requirements for successful plant growth.
5.2.1.3 Nitrate in sap

Nitrate concentration in sap in most of the experiments (Table 5.10, Figure 5.27, Figure 5.28) was significantly higher than the published guidelines for lettuce (Table 5.9) even for the control treatment. Parks (2009a) commented that guidelines for nitrate in lettuce were not appropriate for all leafy vegetables and that, in particular, Asian leafy vegetables in the Brassica family appeared to have a higher nitrate requirement.

Table 5.9. Guidelines for nitrate-N concentration in lettuce petiole sap (mg/L) from S. Parks (2009a) with a reference to Huett and White (1992).

<table>
<thead>
<tr>
<th>Plant part</th>
<th>Weeks after transplanting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Youngest fully expanded leaf</td>
<td>500</td>
</tr>
<tr>
<td>Oldest green leaf</td>
<td>400</td>
</tr>
</tbody>
</table>

My findings with pak choi suggest that the trend of nitrate concentration in sap in the life span of the crop differs from the guidelines. Table 5.9 gives data for lettuce and shows that nitrate concentration in both youngest fully expanded leaf and oldest green leaf increases with time (with some fluctuations), reaching its peak in the end of the experiment in the youngest fully expanded leaf and between 3-5 weeks in the oldest green leaf. In contrast, the data for nitrate in the sap of youngest fully expanded leaves of pak choi showed that the highest nitrate concentration in sap was always at the beginning of experiment with a subsequent decrease as plants matured (Figure 5.27).

Figure 5.27. Nitrate concentration in sap of pak choi in the control, 100%- and 50%-vermiliquer treatments in experiment 10.
Links between nitrate concentration in sap and in nutrient solution. Changes in nitrate concentration in sap generally reflected changes in nitrate in nutrient solution. For example, in experiment 10, the addition of nitrate as buffer in the 50%-vermiliquer treatment on 24.07.09 (Figure 5.27) did not lead to an immediately higher nitrate in sap one day later, but it did six days later compared to the inorganic control (Figure 5.26).

Absolute values at the end of the experiments were the lowest in the control treatment and corresponded to the lowest nitrate concentration in the nutrient solution at the end of the experiments for this treatment. However, the overall decrease of nitrate in sap in all treatments, including both vermiliquer treatments in experiment 10, despite a relatively stable or even increasing nitrate concentration in the nutrient solution for vermiliquer treatments, suggests that besides availability of nitrate in the solution the capacity of the plant to utilise nitrate greatly depends on maturity. This observation suggests a simple and practical approach to solve the ‘nitrate problem’ in pak choi – through delayed harvest.

However, findings from the in-line experiment 12, where two treatments with different waste sources were compared, showed that although nitrate concentration was significantly higher in the ‘paunch’ vermiliquer (Figure 4.20), the sap nitrate was significantly higher in the ‘vege-liquor’ treatment with kitchen waste (Figure 4.21). This may indicate different ability of plants to accumulate and concentrate nitrate in sap under conditions of reduced growth.

Links between nitrate in shoot tissues of harvested plants and nitrate concentration in sap. The nitrate concentration in the shoot tissues of harvested plants was high in all treatments (see 5.2.4. Nutrients in shoot tissues), which may indicate the natural tendency of the Brassicaceae to absorb and store more nitrate than required for plant development (Parks, 2009a). As with the nitrate concentration in sap, the nitrate in shoot tissues in the 100%-vermiliquer treatment was the highest in treatments at the end of the experiments in which nitric acid was used as pH buffer, while the control was the lowest (Table 5.11, will be discussed later in Section 5.2.4. Nutrients in shoot tissues). Both observations are not in agreement with the data for lettuce published by Reinink and Eenink (1988), who wrote: ‘plant age had only a small effect on nitrate content. Nitrate content in the nutrient medium had no effect on shoot nitrate content,
which indicates that nitrate uptake and transport to the shoot is regulated in such a way that the need for nitrate is exactly met'.

**Nitrate in sap in the NFT and pot system.** Experiment 10 was run in a combined NFT/pot setup where plants in both systems received the same nutrient solution. Table 5.10 gives means for nitrate concentration in sap in the beginning (10 days after transplanting) and at the end of the experiment and Figure 5.28 shows the dynamics of changes in the nitrate concentration in sap across treatments during the experiment.

**Table 5.10. Nitrate concentration (mg/L) in sap for treatments in the beginning and at the end of experiment 10.**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Date</th>
<th>09.07.09</th>
<th>31.07.09</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Setup</td>
<td>pot</td>
<td>NFT</td>
</tr>
<tr>
<td>Control Boxsell</td>
<td>7183</td>
<td>7442</td>
<td>1730</td>
</tr>
<tr>
<td>100%-vermiliquer</td>
<td>6500</td>
<td>6892</td>
<td>3875</td>
</tr>
<tr>
<td>50%-vermiliquer</td>
<td>6558</td>
<td>7383</td>
<td>2958</td>
</tr>
<tr>
<td>LSD p &lt;0.05 NFT/pot effect</td>
<td>500</td>
<td>246</td>
<td></td>
</tr>
</tbody>
</table>

In the beginning (on 09.07.09) absolute values of the sap nitrate concentration in the NFT system were higher than those in the pot system in all treatments, although the difference between the NFT and pot plants was significant only for the 50%- treatment (p = 0.053). At the end of the experiment (31.07.09) differences between all treatments (p = 0.002) were as follows: the highest nitrate was registered in the 100%- vermiliquer treatment, the lowest – in the control, and the 50%-vermiliquer treatment being in the middle and nitrate was higher in the pot than in the NFT system, although only for the vermiliquer treatments (p = 0.034).
Figure 5.28. Nitrate concentration in sap in the NFT and pot plants in experiment 10.
5.2.2 Potassium

5.2.2.1 Potassium in nutrient solution

In most experiments the potassium concentration in vermiliquer was consistently lower than in the control; for example, in the vermiliquer obtained from paunch potassium was three to four times lower than that in the control. Figure 5.29 shows that at the beginning of experiment 10 potassium in the nutrient solution in the control was three times higher than in the 100%-vermiliquer treatment, and, according to dilution, five times higher than in the 50%-vermiliquer treatment.

![Potassium in nutrient solution in experiment 10](image)

Figure 5.29. Potassium concentration in the nutrient solutions in experiment 10.

In the first two weeks of any experiment the potassium concentration remained stable. After that, reflecting higher demand, potassium in all treatments declined and by the end of most experiments was undetectable.

5.2.2.2 Potassium in sap

The data showed a steady decrease in potassium concentration in sap over time for all treatments in all experiments.

As with the nitrate in sap, potassium concentration in sap decreased as plants matured, but the difference between the two nutrients was that the decrease in potassium in sap was accompanied by severe reduction of the nutrient in the solution. In contrast, a decrease in nitrate concentration in sap occurred while that nutrient was abundant in the vermiliquer treatments.
To illustrate the dynamics of potassium in the life span of a crop, Figure 5.30 shows the results from experiment 10. The only exception was a slight rise in potassium for the control treatment on the second sampling date, although the difference over time between the first and the second sampling dates for this treatment was not statistically significant.

![Potassium in sap, experiment 10](image)

**Figure 5.30. Potassium concentration in sap in experiment 10.**

Throughout all experiments potassium was higher in the control treatment than in either vermiliquer treatments. For experiment 10, statistical analysis confirmed a significant difference between the control and either of the vermiliquer treatments starting from the 2nd sampling date onwards (p < 0.001).

Figure 5.30 also shows that potassium concentration in sap of the 100% and 50%-vermiliquer treatments did not differ significantly. This is an interesting finding, because potassium concentration in the nutrient solution in the 50%-vermiliquer, according to the dilution proportion, at all times was half that in full-strength vermiliquer and by the third week of the experiment was practically absent in the nutrient solution. This would suggest that the amount of potassium accumulated in the sap, though primarily defined by the concentration of potassium ions in the nutrient solution, was not limiting in the half strength nutrient solution or was also influenced by other factors.

As mentioned earlier, despite significantly lower potassium concentration in both the nutrient solution and sap of vermiliquer treatments than in the control, plants in the vermiliquer treatments did not show any obvious signs of nutrient deficiencies. Whatever the reason, even
though the potassium concentration was significantly lower than in the inorganic fertiliser, it did
not appear to be a critical factor for plant growth. The data for potassium concentration in sap of
treatments run with vermiliquer obtained from the ‘paunch’ material agree with published
‘rough’ requirements for potassium concentration in sap for leafy crops: 700-1300 mg/L in
young expanding leaves and 1900-2600 mg/L in mature leaves (Parks, 2009a).

The link between concentration of potassium in sap and in the nutrient solution is supported by
the results of experiment 11, in which the control was compared with the vermiliquer treatments
run with different sources of waste. Concentration of potassium in ‘vege-liquer’ (obtained from
kitchen waste) was identical to the control at the beginning of the experiment, and even
increased with time, while potassium in the ‘liquer’ (obtained from paunch material) was two-
three times lower at the beginning of the experiment and remained at one half or less than that
of the control throughout the experiment (Figure 5.31). Accordingly, potassium in sap was the
highest in the vege-liquer treatment (with kitchen waste), and slightly lower in the control
(Figure 5.32). Potassium in ‘liquer’ treatment (with paunch material) was one half of that in the
two other treatments. This suggests that in this experiment potassium in sap depended on
potassium availability in the nutrient solution.

Figure 5.31. Potassium concentration in the nutrient solution in experiment 11 in the
‘vege-liquer’ (with kitchen waste), the ‘liquer’(with paunch material) and the control
treatments.
Figure 5.32. Potassium concentration in sap in experiment 11 in the ‘vege-liquer’ (with kitchen waste), the ‘liquer’ (with paunch material) and the control treatments.

Data from the experiments with direct linkage also support this finding. For example, Figure 5.33 and Figure 5.34 show potassium in the nutrient solutions and in sap in experiment 12, which used vermiliquer obtained from different waste. Potassium in the ‘vege-liquer’, obtained from the kitchen scraps, was throughout the experiment three to four times higher than potassium in ‘liquer’, obtained from the paunch material throughout the experiment (Figure 5.33). Accordingly, potassium in sap in the vege-liquer treatment was three-four times higher than that in the paunch liquor (Figure 5.34).

Figure 5.33. Potassium concentration in the nutrient solutions in the in-line experiment 12 with the ‘vege-liquer’ (with kitchen waste) and the ‘liquer’ (with paunch material) treatments.
Figure 5.34. Potassium concentration in sap in the in-line experiment 12 with the ‘vege-liquer’ (with kitchen waste) and the ‘liquer’ (with paunch material) treatments.

Comparison between potassium concentration in sap in the NFT and pot plants.

Figure 5.35 shows the dynamics of potassium accumulation in experiment 10, employing a combined NFT and pot setup using exactly the same nutrient solution.

As with the nitrate, it appears that at the beginning of an experiment plants in the NFT had higher potassium concentration in sap than in the pot system.

In absolute values the trends were similar in all treatments, and for most pair-wise comparisons the difference was not statistically significant. On the second sampling date (18.07.09) potassium in the NFT section was significantly higher than in the pot system in both vermiliquer treatments, and on third sampling date (25.07.09) potassium in the pot section was significantly higher than in the NFT section in the control treatment. I assume that with the concentration of potassium in the nutrient solution close to zero after two weeks of the experiment, potassium was merely re-distributed within the plant tissues. The NFT plants developed larger biomass than the plants in the pot system. Consequently, by the end of the experiment, the plants in the NFT system had lower potassium concentration per unit biomass.
Figure 5.35. Potassium concentration in sap in the NFT and pot plants in experiment 10.
5.2.3 Critical revision of conventional N:P:K ratios when applied to vermiliquer for hydroponic culture

The N:P:K ratio in the vermiliquer at the beginning of the experiments varied and was approximately $2(\pm 0.6):0.8(\pm 0.4):0.1$ (Table 3.2). The commonly recommended N:P:K ratios for leafy vegetables are 2:1:1 (Foerster, 2009) with nitrogen being a dominant component to promote vegetative growth (excessive phosphorus may lead to premature bolting). In the current study potassium was considerably below the level required by plants.

At the end of all experiments potassium in all the treatments was close to zero. This indicated that this nutrient was totally taken up by the plants (i.e. with the N:P:K ratio close to 200:40:1 at the end of experiment 10).

However, the plants never expressed any typical signs of potassium deficiency in the Brassicaceae such as burning of older leaves, severe marginal necrosis (scorching or tip burns) on older leaves and forward curling of leaf margins (Wallace, 1943). This may reflect the highly mobile nature of potassium allowing it to be re-distributed in the plant tissues.

Alternatively, the physiological role of potassium in managing water balance may be far less important in hydroponic culture, where water is always available. In these experiments, the N:P:K ratios in vermiliquer were not the same as those recommended for inorganic fertilisers. However, the plants seemingly coped well with a relatively low concentration of potassium in the nutrient solution, although in the 50%-vermiliquer treatment potassium was suspected to be one of the limiting factors responsible for a slower plant growth than in the other treatments (see section 5.3.3 Harvest parameters).
5.2.4 Nutrients in shoot tissues

A direct comparison of data among experiments is not appropriate because of confounding seasonal and climatic differences and sources of vermiliquer. In addition, shoot tissue mineral analysis was conducted on composite samples from replicates of each treatment as described in section 3.6.2. Laboratory analysis of samples, and therefore there was no possibility for statistical analysis for the treatments. As a result, many of the conclusions about the effects of treatments on shoot minerals and their relation to their concentration of the elements in sap and nutrient solution can not be backed up with solid statistical support. However, taking into account this limitation, some differences between the treatments do highlight issues for further investigation. Table 5.11 shows data on 14 essential elements in shoot tissues of harvested plants.

Total nitrogen:

1) Comparison of nitrogen concentration in the shoot tissues in this study (Table 5.11) and published data for other crops (Table 5.13) indicates that in most of my experiments the percentage of nitrogen was within average range of values for most crops, excluding the treatments that led to most 'unsuccessful' growth and yield, as follows.

2) The lowest nitrogen content in the shoots across all experiments were observed for the vermiliquer treatment buffered with orthophosphoric acid in experiment 4, for the in-line vermiliquer treatment in experiment 6 and for the off-line (batch) unbuffered treatment in experiment 8. These were the most 'unsuccessful' treatments across all experiments.

3) Generally, the highest nitrogen concentration was in the treatments showing the highest chlorophyll (arbitrary SPAD readings) at the end of the experiment. The highest nitrogen treatments were generally those with the highest yield: treatments such as the vermiliquer treatment buffered with NO₃ to pH 5.5 in experiment 3, the batch 100%-vermiliquer treatment in experiments 7, 8, 9 and 11, and the control in experiment 11.
Table 5.11. Summary of the concentration of some macro- and micronutrients in shoot tissues in different experiments, expressed as a dry weight basis.

| Exp | Treatment – type of pH buffer | Element | Pot/ nft | N | NO3 | P | K | Na | Ca | Mg | Cl | S | Cu | Zn | Mn | Fe | B |
|-----|-------------------------------|---------|---------|----|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|
|     |                               |         | mg/kg   | %  | %   | %  | %  | %  | %  | %  | %  | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg |
| EXP 3 | Vermi pH 5.5 - nitric acid | pot     | 4.99    | 18753 | 0.763 | 3.656 | 2.169 | 1.837 | 0.749 | 0.527 | 6.67 | 143.92 | 19.3 | 803.2 | 29.7 |
|       | Vermi pH 7.0 - nitric acid  | pot     | 3.92    | 6839  | 0.514 | 4.969 | 0.285 | 1.713 | 0.847 | 0.637 | 5.78 | 173.88 | 26.9 | 1007.1 | 40.3 |
|       | Control - buff. nitric acid | pot     | 4.64    | 12772 | 0.819 | 4.279 | 2.774 | 1.592 | 0.592 | 0.878 | 0.635 | 5.39 | 234.02 | 27.0 | 154.8 | 35.8 |
| EXP 4 | Vermi - nitric acid           | pot     | 5.08    | 22085 | 0.579 | 3.958 | 2.270 | 1.413 | 0.519 | 0.458 | 3.21 | 135.62 | 72.3 | 67.8 | 27.7 |
|       | Vermi - orthophosphoric acid  | pot     | 1.53    | 708   | 0.786 | 2.714 | 0.705 | 0.857 | 0.327 | 1.068 | 0.580 | 5.78 | 173.88 | 42.6 | 56.1 | 18.4 |
|       | Control - nitric acid         | pot     | 3.84    | 9273  | 0.464 | 4.999 | 0.180 | 2.078 | 0.649 | 0.462 | 0.635 | 5.39 | 234.02 | 27.0 | 154.8 | 35.8 |
| EXP 6 | In-line Vermi (unbuffered)    | pot     | 2.94    | 3080  | 0.647 | 4.690 | 1.426 | 1.524 | 0.491 | 0.714 | 0.635 | 5.39 | 234.02 | 27.0 | 154.8 | 35.8 |
|       |                                | nft     | 4.09    | 18310 | 0.636 | 3.333 | 2.766 | 1.654 | 0.608 | 1.502 | 0.594 | 4.33 | 132.77 | 24.5 | 108.7 | 30.3 |
|       |                                | nft     | 4.79    | 22065 | 0.614 | 3.184 | 2.362 | 1.780 | 0.663 | 2.427 | 0.496 | 4.31 | 128.00 | 36.9 | 80.6 | 31.3 |
|       |                                | nft     | 4.17    | 13801 | 0.445 | 5.398 | 0.138 | 2.185 | 0.692 | 0.304 | 0.704 | 3.70 | 36.62 | 16.1 | 175.1 | 43.8 |
| EXP 8 | Batch Vermi – nitric acid     | pot     | 5.23    | 18310 | 0.636 | 3.333 | 2.766 | 1.654 | 0.608 | 1.502 | 0.594 | 4.33 | 132.77 | 24.5 | 108.7 | 30.3 |
|       | Batch Vermi (unbuffered)      | pot     | 3.65    | 9120  | 0.700 | 4.860 | 2.183 | 1.297 | 0.663 | 2.384 | 0.635 | 5.35 | 90.67 | 41.6 | 61.9 | 29.8 |
|       | In-line Vermi - nitric acid   | pot     | 4.25    | 2641  | 0.600 | 4.213 | 1.661 | 1.288 | 0.337 | 1.329 | 1.604 | 3.78 | 71.18 | 10.2 | 47.1 | 23.5 |
| EXP 9 | Vermi - 100% - nitric acid    | nft     | 4.95    | 14189 | 0.590 | 2.701 | 2.389 | 1.498 | 0.723 | 1.088 | 0.357 | 4.06 | 135.33 | 62.3 | 381.6 | 35.5 |
|       | Vermi - 50% - nitric acid     | nft     | 3.86    | 3332  | 0.361 | 1.195 | 1.099 | 1.028 | 0.605 | 1.091 | 0.170 | 3.72 | 101.79 | 47.1 | 145.4 | 25.2 |
|       | Control - nitric acid         | nft     | 4.25    | 12220 | 0.438 | 4.826 | 0.909 | 1.783 | 0.729 | 0.262 | 0.667 | 3.08 | 30.25 | 29.8 | 258.8 | 46.1 |
| EXP 10 | Control - nitric acid         | nft     | 4.09    | 6260  | 0.370 | 2.290 | 0.840 | 0.700 | 3.81 | 33.34 | 15.6 | 176.8 | 44.0 |
|       |                                | nft     | 4.22    | 4580  | 0.270 | 2.620 | 0.830 | 0.770 | 3.68 | 42.51 | 19.1 | 183.9 | 52.4 |
|       |                                | nft     | 5.70    | 2500  | 2.850 | 2.080 | 0.650 | 0.280 | 4.69 | 90.42 | 88.0 | 210.3 | 37.5 |
|       |                                | nft     | 5.14    | 2260  | 3.600 | 2.460 | 0.780 | 0.290 | 4.81 | 133.13 | 97.3 | 186.8 | 49.1 |
|       |                                | nft     | 4.42    | 1890  | 2.190 | 1.980 | 0.810 | 0.170 | 4.16 | 97.21 | 15.1 | 174.1 | 48.3 |
|       |                                | nft     | 4.71    | 1699  | 2.120 | 2.180 | 0.930 | 0.240 | 4.79 | 133.70 | 22.5 | 208.9 | 62.1 |
| EXP 11 | Control - nitric acid         | nft     | 5.80    | 7940  | 1.560 | 2.380 | 0.870 | 1.020 | 6.18 | 109.27 | 70.1 | 194.4 | 78.9 |
|       | Vermiliquer (paunch) - nitric | nft     | 2.41    | 5020  | 2.900 | 2.320 | 0.770 | 0.710 | 5.29 | 137.81 | 53.1 | 159.3 | 55.6 |
|       | Vege-liquier (kitchen waste)  | nft     | 3.27    | 7450  | 1.030 | 3.070 | 1.050 | 1.080 | 4.50 | 72.28 | 40.8 | 219.7 | 68.4 |
|       |                                | nft     | 5.13    | 8300  | 1.250 | 1.940 | 0.890 | 1.310 | 5.91 | 85.96 | 37.0 | 183.6 | 58.5 |

1Total nitrogen, nitrate nitrogen and chloride were measured colorimetrically in segmented flow analyser; total phosphorus, sulphur, potassium, calcium, magnesium, sodium copper, zinc, manganese, iron and boron were measured using ICP AES (inductively coupled plasma, argon emission spectrometer).
Table 5.12. Summary of heavy metals concentration (by ICP AES) (µg/kg) in shoot tissues of plants in experiment 11.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Treatment</th>
<th>Pot/nft</th>
<th>As</th>
<th>Cd</th>
<th>Cr</th>
<th>Pb</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP 11</td>
<td>Control (Boxsell)</td>
<td>nft</td>
<td>2007.0</td>
<td>43.0</td>
<td>1380.0</td>
<td>92.0</td>
<td>1240.0</td>
</tr>
<tr>
<td>EXP 11</td>
<td>Vermiliqueur (paunch)</td>
<td>nft</td>
<td>1627.0</td>
<td>40.0</td>
<td>1592.0</td>
<td>72.0</td>
<td>1244.0</td>
</tr>
<tr>
<td>EXP 11</td>
<td>Vege-liquor (kitchen waste)</td>
<td>nft</td>
<td>556.2</td>
<td>44.0</td>
<td>1112.0</td>
<td>100.0</td>
<td>1480.0</td>
</tr>
</tbody>
</table>

Table 5.13. Interpretation of plant analyses for several crops on a dry weight basis (from Midmore, 2008b).

<table>
<thead>
<tr>
<th>Element</th>
<th>Tomato</th>
<th>Cucumber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>prior to fruiting</td>
<td>during fruiting</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>4.00 - 5.00</td>
<td>3.50 - 4.00</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>0.50 - 0.80</td>
<td>0.50 - 0.80</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>3.50 - 4.50</td>
<td>3.00 - 4.50</td>
</tr>
<tr>
<td>Calcium (Ca)</td>
<td>0.90 - 1.80</td>
<td>1.00 - 2.50</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>0.50 - 0.75</td>
<td>0.50 - 1.00</td>
</tr>
<tr>
<td>Boron (B)</td>
<td>35 - 60</td>
<td>35 - 60</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>8 - 20</td>
<td>8 - 20</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>50 - 300</td>
<td>50 - 300</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>50 - 200</td>
<td>50 - 200</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>25 - 100</td>
<td>25 - 100</td>
</tr>
</tbody>
</table>

1 - Prior to fruiting sampling: leaves adjacent to 2nd and 3rd clusters.

2 - During fruiting sampling: leaves from 4th to 6th clusters.

Table 5.14. Selected present Australian and superseded Queensland food standards for heavy metals (mg/kg), calculated and expressed as the metal (from Rayment, 1991).

<table>
<thead>
<tr>
<th>Metal (mg/kg)</th>
<th>As</th>
<th>Cd</th>
<th>Cu</th>
<th>Pb</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australian and superimposed Qld</td>
<td>1.0</td>
<td>0.05</td>
<td>10.0</td>
<td>1.5</td>
<td>150.0</td>
</tr>
<tr>
<td>MPC (maximum permitted concentrations)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.15. Maximum levels for heavy metals (mg/kg) in foods (FSANZ, Standard 1.4.1).

<table>
<thead>
<tr>
<th>Metal (mg/kg)</th>
<th>As</th>
<th>Cd</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPC (maximum permitted concentrations)</td>
<td>1 (Cereals)/1-2(Seafood)</td>
<td>0.1(Leafy vegetables)</td>
<td>0.3 (Brassicas)</td>
</tr>
</tbody>
</table>
4) However, it is hard to make a generalisation on the link between the total nitrogen and yield, because some treatments gave unexpected results. Experiment 12 was the most controversial and interesting example because the vege-liquer treatment (with kitchen waste) resulted in exceptionally stunted growth and ‘almost zero’ SPAD readings, despite a very high (5.13%) nitrogen content (one of the highest across all experiments). This suggests a luxury N uptake, without a functional use. The other treatment with vermiliquer obtained from paunch gave significantly greater yields despite one of the lowest levels (2.25%) of nitrogen across all experiments.

5) In general, total nitrogen content in the plant tissues was in accordance with the total amount of nitrogen contained in the nutrient solution, however it did not necessarily corresponded to the nitrate content in the plant tissues (or vice versa, nitrate concentration in the plant tissues did not necessarily reflected total nitrogen obtained by the plant). That suggests that the mechanism of nitrogen utilisation by plants, though promoted by the higher nitrogen/nitrate availability in the nutrient solution, was constrained by factors other than availability. This agrees with the earlier reports (Lyons et al., 1993) on poor correlations between total N and nitrate in vegetables.

6) Some of the data were not consistent with finding 5. For example, in experiment 11, the total nitrogen in the control was one of the highest across all experiments, but was extremely low in the vermiliquer treatments with kitchen waste and paunch. It is especially interesting that at the end of that experiment the nitrate concentration in the solutions of both vermiliquer treatments was many times higher than in the control, which did not contain any nitrate at all.

7) Because of the nitric acid input as buffer it is impossible to estimate how much total nitrogen in the plant tissues was derived from the nitrogen in the original vermiliquer (which, for example, in experiment 3 was half that in experiment 4). Nitric acid used as a buffer in most experiments might have affected the total nitrogen content in the plant tissues, however, the result of the in-line vermiliquer treatment in experiment 8 showed
that even without the external nitrogen input, the vermiliquer provided a sufficient source of nitrogen for hydroponically grown plants.

8) Calculation of a mass balance would be difficult to interpret, especially for the organic nutrient solution such as vermiliquer, in which the part of nutrients available for plants is unknown.

Nitrate:

1) Nitrate concentrations in the shoot tissues in the vermiliquer treatments buffered with nitric acid were the highest across experiments. It may be assumed that nitrate content in shoot tissues corresponds to the nitrate concentration in the nutrient solution and this agrees with earlier findings (Hopkins and Huner, 2004).

2) Nitric acid, used in most experiments as buffer, appears to be responsible for high nitrate in the nutrient solution, and, hence, in the plant sap and tissues. In support of this, the in-line vermiliquer treatments in experiments 6 and 8 showed significantly lower nitrate content in shoot tissues than vermiliquer treatments and the control treatments in other experiments, although I cannot discard the effect of pH which may affect uptake of NO₃. It might have been that application of buffer defined higher nitrate content in the 50%-vermiliquer treatment in experiment 7 than in the 100%-vermiliquer treatment. High nitrate level in vegetables raises concern with respect to the application of nitric acid as a pH buffer for hydroponically-grown plants. The similar concern about nitrate concentrations in leaves of plants that are consumed fresh is well reflected in publications and some ways to reduce nitrate content without affecting yield are suggested (Santamaria et al., 1998, 2001).

3) Nitrate concentrations of the vermiliquer itself, without nitric acid input, appears to be an adequate source of nitrogen for hydroponically-grown plants. For example, the off-line (batch) unbuffered vermiliquer treatment in experiment 8 accumulated nitrate in concentrations comparable to that in the control treatment in experiment 4 or the 50%-vermiliquer treatment in experiment 9, both buffered with nitric acid.
4) Ability to accumulate nitrate in shoot tissues apparently depends to some extent on growth per se (Buwalda and Warmenhoven, 1999; Behr and Wiebe, 1992). The most ‘unsuccessful’ – severely chlorotic with the lowest yield and stunted growth – vermiliquer treatment buffered with orthophosphoric acid in experiment 3, showed the lowest nitrate concentration in shoot tissues across experiments 3 to 9.

5) These data disagree with the data published by Reinink et al. (1987) who found a negative relationship between shoot nitrate content and shoot dry matter content and between shoot nitrate content and shoot organic-N content (see 5.3.3 Harvest parameters, Table 5.17).

6) My findings agree with reports that the Brassica species tend to have a high nitrogen content, up to approximately 6% (Reuter and Robinson, 1986) as compared to 1.5% considered to be adequate for a typical plant (Salisbury and Ross, 1992). A recent report on nitrate concentration in Brassica species (EFSA, 2008) showed that most of the vegetables in the Brassica group had median nitrate concentrations in the dry tissues of approximately 40 to 200 mg/kg. The maximum recorded nitrate level was 4900 mg/kg in ordinary cabbage. Nitrate concentration in Chinese cabbage and kohlrabi was around 900 mg/kg.

Phosphorus:

1) Phosphorus concentration in the shoot tissues in vermiliquer treatments from different experiments, excluding most unsuccessful ones, was very similar: 0.5-0.8%, which is exactly the suggested average range of phosphorus concentration for several crops (Table 5.13). Phosphorus concentration in vermiliquer in different experiments did not vary too much either and ranged from 36 to 52 mg/L (Table 3.2) – quite comparable with the recommended values for inorganic hydroponic fertilisers. It is assumed that the vermiliquer provided a reliable supply of phosphorus for the hydroponically-grown plants.
2) Point 1 above is supported by the finding that in most experiments (excluding experiment 3), all 100%-vermiliquer treatments showed higher phosphorus content in the tissues than in the control. In experiment 3 phosphorus content in the control treatment was slightly higher than in the 100%-vermiliquer treatment, but it still appears that vermiliquer is an adequate source of phosphorus for hydroponically-grown plants.

3) It could be assumed that phosphorus content in the plant tissues depends on the availability of the element in the nutrient solution. For example, in experiment 9, phosphorus content in the 100%-vermiliquer treatment was naturally higher than in the 50%-vermiliquer treatment, which reflects availability of the element for the plant. However, in experiment 10, phosphorus content in both 100% and 50%-vermiliquer treatments was essentially the same, with a slight tendency for plants in the NFT system to accumulate more phosphorus in plant tissues than in the pot system. Furthermore, in experiment 7 phosphorus concentration was similar in the 100% and 50%-vermiliquer treatments.

4) At the same time, uptake of phosphorus from the nutrient solution could also be greatly dependent on other factors too. I assume that the pH of the nutrient solution may affect uptake of elements from the nutrient solution, including phosphorus. For example, between two identical vermiliquer treatments maintained at a different pH in experiment 3, phosphorus concentration in plants in the treatment at pH 5.5 was 50% higher that in those in the treatment at pH 7.0.

5) High phosphorus content was evident in the treatments with severely stunted growth and poor plant development. For example, two treatments that performed worst of all – the vermiliquer treatment buffered with orthophosphoric acid in experiment 4 and the batch unbuffered vermiliquer treatment in experiment 8 – showed the highest phosphorus content in tissues across all experiments. This may be related to a simple concentration effect and amended nutrient uptake and distribution of the element in plant tissues.
Potassium:

1) Potassium content in the plant tissues in vermiliquer treatments in most experiments was lower than that in the control, which is not surprising considering that vermiliquer solutions contained less (Table 3.2). In experiment 11 potassium concentration in the nutrient solution in the vege-liquer treatment (with kitchen waste) was comparable to the control at all stages of the experiment and potassium in the shoot tissues in that treatment was also identical to the control. These findings support the assertion that potassium content in the shoot tissues and sap depends at least in part on availability of the element in the nutrient solution.

2) Potassium concentration in vermiliquer (in the nutrient solution) in different experiments varied greatly: from 51 mg/L in experiment 5 to 236 mg/L in experiment 3 (Table 3.2). Potassium content in the shoot tissues varied but to a far lesser extent (usually less than two times). For example, in experiment 7 potassium content in the shoot tissues in the 50%- vermiliquer treatment was only slightly lower than that in the 100%- vermiliquer treatment, which was not proportional to the dilution rate of the vermiliquer. That indicates the ability of plants to successfully recover the element from the potassium-deficient solution or that potassium in the 100%- vermiliquer was way above optimal concentration in the nutrient solution.

3) Point 2 above is also supported by the fact that after two-three weeks of most experiments with batch vermiliquer, potassium concentration in the nutrient solution in the 100%- vermiliquer treatments was very low, and in the 50%- vermiliquer treatments potassium was negligible, and, literally speaking, absent.

4) The highest potassium concentration in shoot tissues across all experiments was in the in-line vege-liquer treatment (with kitchen waste) in experiment 12, which suggests that potassium content in plant tissues depends on total amount of the element in the nutrient solution (500 L tank for the in-line treatments) and not so much on its concentration in the solution. I can assume that the plant can effectively absorb the element even from a solution with a low concentration of potassium.
5) Some of the data do not coincide with finding 4. For example, in the same experiment 12 the other in-line vermiliquer treatment with vermicomposted paunch had a higher yield and chlorophyll content (SPAD readings) than the one with the kitchen waste, but the paunch treatment showed one of the lowest potassium concentrations in plant tissues across all experiments. Similarly, potassium content in the shoot tissues in the batch unbuffered vermiliquer treatment in experiment 8 was higher than in the in-line treatment and much higher than in the most ‘successful’ buffered batch treatment.

6) The above finding 5 suggests that potassium content in the shoot tissues, while naturally dependent on availability of the element in the nutrient solution, is also greatly affected by other factors.

7) One of the factors that may affect potassium absorption from the nutrient solution could be the pH of the nutrient solution and/or rates of absorption of other elements. In experiment 3, potassium content in the lowest yielding vermiliquer treatment buffered to pH 7.0 was higher than in the higher yielding vermiliquer treatment buffered to pH 5.5.

8) Poor plant growth and low chlorophyll (as evidenced by SPAD readings) can also affect potassium uptake. To compare two of the most unsuccessful treatments in this study, the vermiliquer treatment buffered with orthophosphoric acid in experiment 3 had less potassium in plant tissues than the vermiliquer treatment buffered with nitric acid, while the batch unbuffered vermiliquer treatment in experiment 8 and the in-line vege-liquer (with kitchen waste) in the experiment 12 had the highest potassium content across all experiments.

9) Results from experiment 10 indicate the tendency for the potassium content in the shoot tissues to be higher in the pot system than in the NFT, especially with commercial hydroponic nutrients. This result also agrees with the data on potassium concentrations in the sap of plants. With limited potassium in the solution and the higher yield in the NFT system, the result can be interpreted as simple re-distribution and dilution of potassium within the tissues of the same plant rather than any other balances.
10) Potassium concentration in the shoot tissues in most of the experiments was ‘just adequate’ and in some experiments (experiments 9 and 10) was lower than the published average potassium concentration for several crops (Table 5.13).

11) Taking into consideration the high mobility of potassium within plant tissues and the lack of potassium deficiency symptoms in the experiments, it may be assumed that low potassium is not an issue for hydroponic plant production using vermilique. It may be related to the plant physiology and the major role of potassium in osmosis. In the recirculating hydroponic culture, in other words in the conditions of a continuous water supply, a high potassium concentration in the nutrient solution is not as critical as in soil culture. That also suggests that conventional N:P:K ratios established (i.e. recommended) for soil cultures should be revised when applied to hydroponics.

Sodium:

1) Concentration of sodium in vermilique varied over the range 380-520 mg/L among experiments. In most, the sodium content in the nutrient solutions of control treatments was significantly lower than in any vermilique treatment. The control was run on RO water, while vermilique naturally accumulated sodium from the composted materials and the tap water used for irrigation of worm pits. Average sodium concentration in the town water in Rockhampton is 30 mg/L (information from the Rockhampton City Council) and the sodium content in the shoot tissues generally corresponded to the sodium concentrations in the nutrient solution. In support of this, sodium concentration in the 100%- vermilique treatments was higher than in the corresponding 50%-vermilique treatments.

2) In experiments 11 and 12 conducted on vermilique obtained from different sources, plants grown on the paunch vermilique had double the sodium content in the shoot tissues compared with those grown on the kitchen waste. This may indicate higher original sodium content in the paunch material.
3) Of interest, in experiment 3, sodium content in the shoot tissues in the vermiliquer treatment maintained at pH 5.5 exceeded by nine times that in the vermiliquer treatment maintained at pH 7.0. The reason for such a difference between the treatments operated on the same source of vermiliquer is not known.

Calcium:

1) Concentration of calcium in the shoot tissues in the vermiliquer treatments was comparable to the control. Generally, calcium concentration in the shoot tissues in most experiments was within the published average range between 1.0 and 2.0% for several crops (Table 5.13), although treatments in experiments 10 and 11 slightly exceeded 2%. Maximum calcium content in the shoots across all experiments was observed in the vermiliquer treatment run on the kitchen waste in experiment 11 (i.e. 3.07% Ca compared to 2.32% for paunch vermiliquer). This may indicate the higher original calcium content in kitchen waste, than in the paunch material).

2) There was no consistent difference between calcium content in the 100% or 50% batch vermiliquer treatments or the in-line treatments. The least was registered in experiment 3 in the lowest yielding vermiliquer treatment. This was buffered with orthophosphoric acid, which may be related to the general poor plant development. Concentration of calcium in the vermiliquer was comparable across experiments between 40 and 80 mg/L (Table 3.2). It may be assumed that vermiliquer can serve as a reliable and adequate source of calcium for hydroponically-grown plants even at 50%-dilution rate.

3) In experiment 10, and consistently for all treatments, plants in the NFT system had a higher calcium content in the shoot tissues than plants in the pot system.

4) Comparison between the same experiments 11 and 12 shows that both in-line vermiliquer treatments in experiment 12 contained less calcium in the shoots than the corresponding batch treatments with managed pH in synchronous experiment 11. This indicates that overall susceptibility to stress may reduce calcium uptake in plants.
Magnesium:

1) Concentration of magnesium in the shoot tissues in vermiliquer treatments was comparable to the control, although values in the control were invariably slightly greater. Magnesium content in the shoot tissues was within the published average range for several crops (Table 5.13), with exception of the in-line vermiliquer treatments in which magnesium was low.

2) There was no consistent difference between magnesium content in the shoot tissues in the 100% or 50%- vermiliquer treatments. In experiment 10, for example, content of magnesium in the shoots was higher in the 50%- vermiliquer treatment than in the 100%- vermiliquer treatment. That suggests that even when diluted, vermiliquer appeared to provide an adequate source of magnesium for hydroponically-grown plants. Of note, concentration of magnesium in the solution varied from 12 to 26 mg/L in different experiments (Table 3.2).

3) The lowest magnesium content was registered in the shoots in the in-line vermiliquer treatments in experiments 6 and 8, the in-line paunch vermiliquer in experiment 12, and in experiment 3 for the vermiliquer treatment buffered with orthophosphoric acid. The treatments could be characterised as ‘the least successful across all experiments’, but in fact there is no evidence to relate low magnesium content to any specific factor such as a low concentration of magnesium in the nutrient solution, or solution pH, to the general poor plant development. For example, in experiment 8, magnesium in the severely stunted batch unbuffered vermiliquer treatment was much higher than that in the in-line vermiliquer treatment that performed better. Likewise, in experiment 12, the in-line vege-liquor (with kitchen waste) with the exceptionally stunted growth and ‘zero’ SPAD-chlorophyll, showed the highest magnesium across all experiments. I may only conclude that for some reason absorption of magnesium from vermiliquer in the in-line experiments was not as efficient as from the batch vermiliquer.

4) In experiments 11 and 12 conducted on vermiliquer obtained from different sources, plants grown with the kitchen waste vermiliquer had significantly higher magnesium
content in the shoot tissues compared with those grown on the paunch vermiliquer. This may indicate higher original magnesium concentration in the kitchen waste, than in the paunch material.

Chlorine:

1) Chlorine content, as for sodium, in the shoot tissues generally reflected availability of the element in the nutrient solution. However, the ability of a plant to accumulate chlorine in the shoot tissues did not always correlate with the concentration of the element in the nutrient solution (Table 3.2). For example, in experiment 7 the diluted 50%- vermiliquer treatment accumulated twice as much chlorine in the shoots as the 100%- vermiliquer treatment, and in experiment 9 the values for the chlorine in shoot tissues were the same in both 100% and 50%- vermiliquer treatments.

2) Plants showed a tendency to take-up more chlorine than required for development. In support of this, the in-line vermiliquer treatment in experiment 6 showed one of the highest chlorine content in the shoot tissues across all experiments. This agrees with the published data that plants tend to uptake up to 100 times their chlorine requirements without adverse effects (Salisbury and Ross, 1992)

3) It also appears that plants tended to accumulate more chlorine (or were simply less efficient in accumulating other elements) under conditions that stunted growth (i.e. the treatments with the lowest yield in these studies). In experiment 3, chlorine content was twice as high in the vermiliquer treatment buffered with orthophosphoric acid as in the other two treatments. In experiment 8, the value was considerably higher in the batch unbuffered treatment than in the other comparable treatments.

Sulphur

1) In all experiments, sulphur content in the shoot tissues in the vermiliquer treatments was comparable or slightly lower than that in the control. Sulphur percentage in the 100%-vermiliquer treatment was higher than in the 50%- vermiliquer treatment.
2) Results from experiment 10 indicate that the NFT plants may have a potential to accumulate more sulphur in the shoot tissues than plants in the pot system, although the trend was not very strong.

3) In experiments 11 and 12, the vege-liquer treatment with kitchen waste led to notably higher sulphur content than the vermiliquer treatment with the paunch material.

Copper:

1) In all experiments, copper content in the shoot tissues in the vermiliquer treatments was comparable or slightly higher than that in the control. I assume that copper concentration depends on the element availability in the nutrient solution.

2) It is interesting that copper concentration in the shoot tissues in most the experiments (from 4 to 10) was lower and in the other experiments ‘just adequate’ (experiments 3 and 11) than the published average range of 5-10 mg/L for several crops (Table 5.13).

3) In experiment 12, the vermiliquer treatment with the paunch material contained nearly three times less copper than the in-line vege-liquer treatment with the kitchen waste. It is interesting that copper content in the shoots in the paunch vermiliquer treatment was the lowest across all experiments.

4) In most cases, the copper in the shoots in the 100%-vermiliquer treatment did not significantly differ from the 50%-vermiliquer. This indicates that plants did not lack available copper.

Zinc:

1) Zinc concentration in the shoot tissues varied greatly (up to 7 times) from experiment to experiment. In most cases, the lowest zinc was in the control treatment, but in experiment 3 the control treatment showed the maximum zinc across all experiments and exceeded maximum permitted concentrations of the metal in food (Table 5.14). Compared with the published data on the average zinc concentration in leaves in tomatoes and cucumbers (Table 5.13) at between 25 and 75 mg/L, the zinc concentration in pak choi in most treatments in the present study was far higher.
2) High content and great variations in the content of zinc in shoots may be related to the zinc concentration in the water and worm feed materials, and also might be due to the high element content in pieces of the equipment such as plastics and pumps. In most comparisons, the zinc in the shoots in the 100%-vermiliquer treatment did not significantly differ from the 50%-vermiliquer treatment, with exceptions discussed below.

3) In experiment 10, the tendency for the NFT plants to accumulate more zinc in the shoot tissues than the pot plants was quite strong: 43 mg/kg versus 33 mg/kg in the control treatment, 133 mg/kg versus 90 mg/kg in the 100%-vermiliquer and 174 mg/kg versus 97 mg/kg in the 50%-vermiliquer treatments.

4) Notably in experiment 12 the in-line vege-liquor with kitchen waste accumulated more zinc than the in-line vermiliquer on paunch material, while in the synchronous experiment 11 the same off-line (batch) vermiliquer treatments showed the opposite pattern. This may possibly be related to the effect of pH on the mechanism of zinc accumulation (higher pH reduced uptake).

Manganese:

1) Table 5.13 shows the average range of manganese content for tomatoes and cucumbers is between 50 and 200 mg/L. In most these experiment it was lower or barely adequate. However, the results fall within the published values for manganese in a cultivar of *Brassica rapa* var. *italica* in the range between 25 and 150 mg/kg (Reuter and Robinson, 1986).

2) There was no particular link between dilution of the vermiliquer and the accumulation of manganese in the shoot tissues. For example, in experiment 7 manganese content in the shoots in the 50%-vermiliquer was a third more, and in experiment 9 it was one third less than that in the 100%-vermiliquer treatment. In experiment 10, manganese content in the 50%-vermiliquer treatment was four times less than in the 100%-vermiliquer, which did not correspond to the dilution rate.
3) As with zinc, there was a tendency for manganese to be accumulated at higher concentrations in the NFT system plants than in those in the pot system.

4) Quantities of manganese in the shoot tissues also varied across experiments in the control treatment. For example, in experiments 4 and 10 it was about 15 mg/kg, the lowest content of manganese across all experiments, while in experiment 11 it was c. 70 mg/kg, one of the highest across all experiments.

Iron:

1) The concentration of iron varied greatly (up to 20 times) from 56 mg/kg in the vermiliquer treatment buffered with orthophosphoric acid in experiment 4 to 1000 mg/kg in the vermiliquer treatment maintained with nitric acid at pH 7.0 in experiment 3. On the whole, iron concentration in the shoot tissues in this study was within the published average range of 60-250 mg/L for several crops (Table 5.13), with the only exception of experiment 3, in which vermiliquer treatments showed three to four times higher content of iron.

2) From results of synchronous experiments 11 and 12, both in-line and batch vege-liquer treatments with kitchen waste contained higher iron than the corresponding vermiliquer treatments with paunch material.

3) Quantities of iron in the shoots in the control treatments varied across experiments. For example, in experiment 4 it was about 70 mg/kg (one of the lowest concentrations) while in experiment 11 it was 194 mg/kg, which was three times greater.

Boron:

Plants across all experiments showed comparable boron concentration in plant tissues, with some tendency for the NFT plants to accumulate more boron than the pot plants (in experiment 10). Comparison with the published average range of boron concentration in leaves for several crops (Table 5.13) indicates that boron content in the shoots in this study was adequate, barely adequate or slightly lower (vermiliquer treatments in experiments 3 and 4) than the suggested range.
Heavy metals - potential contaminants:

Analysis for selected heavy metals contents in the shoot tissues was undertaken for the treatments in experiment 11 (Table 5.12). Results of the analysis indicated that the content of lead (Pb), chromium (Cr), nickel (Ni) and cadmium (Cd) was similar in the control and the vermiliquer treatments. Chromium and nickel are likely to have leached from the hydroponic equipment including plastics and pumps. Nevertheless, the heavy metals in this experiment were within Australian and Queensland Food Standards (Rayment, 1991) and did not exceed MPC (maximum permitted concentrations) (Table 5.14 and Table 5.15), with only one exception. This was for the concentration of arsenic: the highest in the control, 25% less in the vermiliquer (paunch) treatment and significantly (four times lower than in the control) in the vege-liquer treatment (with kitchen waste). The MPC for arsenic is 1 mg/kg (Table 5.14 and Table 5.15). The content of arsenic in the control treatment was double that of MPC, and in the 100%-vermiliquer treatment was 1.5 times higher than MPC. The arsenic in the vege-liquer with kitchen waste was within the allowed standards.

*Differences in nutrient accumulation in the shoot tissues between the NFT and pot systems.*

Comparisons between experiments either with the NFT or pots are confounded by factors such as the source of vermiliquer, weather and age of plants. This study did not indicate that there were any consistent differences between the NFT and pot systems in the accumulation in the shoot tissues of nitrogen (N) and phosphorus (P). Only potassium (K) was consistently higher in the NFT system, that with the potassium-deficient solution may reflect mere re-distribution of the element within the NFT plants having higher biomass compared with the pot system. Uptake of B, Ca, Mg, Mn, S and Zn was, apparently, higher in the NFT system across all treatments.
5.3 Growth parameters

5.3.1 Chlorophyll estimation (arbitrary SPAD values)

In most experiments the highest chlorophyll (estimated by SPAD readings) at the beginning of each experiment was in the control treatment. Changes in chlorophyll across treatments were a good indicator of plant growth because declining levels of chlorophyll was noted from the SPAD readings before any visual signs of chlorosis.

For example, in experiment 4 (Figure 5.36) the highest chlorophyll level occurred in the control treatment in the second week after transplanting (17.12.08). At this time the vermiculique treatment buffered with orthophosphoric acid had the lowest level and the vermiculique treatment buffered with nitric acid was intermediate to these two. With time, chlorophyll concentration in the control treatment steadily declined and at the end of the experiment was the lowest across all treatments, while in the vermiculique treatment buffered with nitric acid it remained high throughout the experiment. The initially low chlorophyll in the vermiculique treatment buffered with orthophosphoric acid remained at the same level until the middle of the experiment and decreased after that, and by the end of the experiment was not different than the control.

![SPAD readings in experiment 4](image)

Figure 5.36. SPAD readings (arbitrary units) in experiment 4 for the control, vermiculique treatment buffered with orthophosphoric acid (10% HPO₄) and vermiculique treatment buffered with nitric acid (10% HNO₃).

The data are consistent with the appearance of the plants throughout the experiment (Figure 5.37) but not with final yields. At the end of the experiment plants in the vermiculique treatment...
buffered with nitric acid were emerald-green, compared to yellowish plants in the control treatment and visually chlorotic yellow plants in the vermiliquer treatment buffered with orthophosphoric treatment.

Figure 5.37. Plants at the end of experiment 4. From left to right: control, vermiliquer treatment buffered with orthophosphoric acid (10%-$\text{HPO}_4^{2-}$), and vermiliquer treatment buffered with nitric acid (10%-$\text{HNO}_3$).

Chlorophyll in all in-line treatments was lower than in the control, as illustrated in Figure 5.38.

Figure 5.38. SPAD readings (arbitrary units) in experiment 6, which compared directly-linked vermiliquer with the control.

Chlorophyll content in the control treatment increased in the second week (between 07.02.09 and 14.02.09) and declined in the third week. A downward trend of chlorophyll in the control
was an indicator of developing nutrient deficiencies. After a spike of 20% Boxsell hydroponic nutrients added to all units of the control treatment on 20.02.09 there was an immediate increase in chlorophyll.

Considering the large volume of vermiliquer tank (500 L compared to 100 L for the control), nutrient deficiencies in the in-line treatment (Figure 5.39) most likely resulted from the inability of plants to take up required elements (such as iron) in the highly alkaline environment.

![Figure 5.39. Appearance of plants at the end of experiment 6 (05.03.09)](image)

The effect of pH on chlorophyll concentration (a possible indicator of functionality of photosynthetic mechanisms) was demonstrated in experiment 8. The off-line (batch) vermiliquer treatment, buffered and unbuffered, was compared with the in-line vermiliquer treatment (Figure 5.40).
Figure 5.40. SPAD readings (arbitrary units) in the in-line and the buffered and unbuffered off-line vermiliquer treatments in experiment 8.

After one week (on 03.04.09) the highest chlorophyll levels were in the in-line and the buffered batch vermiliquer treatments, and the unbuffered batch vermiliquer treatment showed the lowest. Over time (across all three sample dates) chlorophyll concentration in the in-line treatment remained the same but increased in both batch treatments. At the end of the experiment (on 21.04.09) the buffered batch vermiliquer treatment showed significantly higher chlorophyll concentration than the other two – the unbuffered batch (pH 8.62) and the unbuffered in-line (pH 8.66) treatments.

However pH did not seem to be the only factor affecting SPAD readings in the in-line treatments. For example, experiment 12 was run under the same pH (c. pH 8.0) for vermiliquer obtained from green kitchen waste and standard (as for other experiments) paunch material (Figure 5.41).
Figure 5.41. SPAD readings (arbitrary units) in the vege-liquer (with kitchen waste) and the liquer (paunch) treatments in experiment 12.

Figure 5.41 shows that during the experiment chlorophyll in the liquer treatment (with paunch material) was stable. In the vege-liquer treatment (with kitchen waste) it decreased steadily and at the end of the experiment was almost undetectable - the plants were severely stunted (Figure 5.42).

Figure 5.42. Plants in the liquer (paunch material) and the vege-liquer (kitchen waste) treatments in experiment 12 (19.09.09).

In contrast to the in-line vermiliquer treatments, buffered batch vermiliquer treatments showed significantly higher SPAD readings in all experiments.

In experiment 3, where vermiliquer treatments maintained at pH 5.5 and 7.0 were compared with the control, SPAD values in all treatments were relatively high and stable, but showed different temporal dynamics: chlorophyll in the control and the vermiliquer pH 5.5 treatment
somewhat decreased, and increased over time in the vermiliquer pH 7.0 treatment (Figure 5.43).

In experiment 5, SPAD values in vermiliquer treatments were the same as in the control treatment and did not differ significantly during the experiment (Figure 5.44).

![Figure 5.43. SPAD readings (arbitrary units) in the control and the vermiliquer treatments maintained at pH 7.0 and 5.5 in experiment 3.](image)

![Figure 5.44. SPAD readings (arbitrary units) in the control, 100% and 50% vermiliquer treatments in experiment 5.](image)

Experiment 5 was one of the first where an interesting observation was noticed for the vermiliquer treatments. The plants in these showed stable chlorophyll during first two-three weeks, after which chlorophyll increased (Figure 5.44). Initially the 50%-vermiliquer treatment had lower chlorophyll, but at the end of the experiment it matched that of the 100%- vermiliquer treatment.

As for other experiments, chlorophyll in the control was stable for the first two weeks. With the reduction of nutrients in solution chlorophyll concentration decreased, except when it increased...
following the 20%-Boxsell hydroponics nutrient spike applied to all control units of experiment 5 to replenish the treatment and avoid complete nutrient depletion.

An increase in chlorophyll in the vermiliquer treatments after three weeks also occurred in experiment 7 (Figure 5.45).

![SPAD-readings in experiment 7](image)

**Figure 5.45.** SPAD readings (arbitrary units) in the control, 100% and 50%- vermiliquer treatments in experiment 7.

At the first sampling both vermiliquer treatments showed significantly lower concentrations of chlorophyll than in the control, with the lowest SPAD readings in the 50%- vermiliquer treatment.

During the two following weeks chlorophyll remained stable in all treatments. Thereafter, in the control treatment it remained the same, but increased in both vermiliquer treatments to the extent that all treatments showed high chlorophyll, with no significant difference among them, by the end of experiment.

The dynamics of chlorophyll concentration with the vermiliquer treatments calls for special attention, because the initially low values observed in experiments 5, 7, 9 and 11 suggests that an unknown factor affects the vermiliquer treatments for the first two-three weeks, and is then gradually overcome, and by the third/fourth week (closer to the harvest) is completely released, so that the treatments were characterised by a visual improvement in colour and a greater chlorophyll concentration. To the best of my knowledge, this phenomenon has never been described or discussed in the literature.
Some hypotheses to explain these results relate to the chemical and biological nature of vermiliquer. The presence of a live microbiota may initially deplete the concentration of certain organic substances needed for plant growth, or may produce substances that inhibit it.

Data from experiment 9 support the latter 'inhibition' hypothesis (Figure 5.46). A few assumptions allow for the interpretation of the total picture of dynamics of chlorophyll during the experiment. Initially, the control treatment gained a certain advantage of easily-available nutrients while the nutrient solution in both vermiliquer treatments either did not provide required nutrients (nutrient deficiency), provided too much of some nutrients (nutrient toxicity) or contained a growth inhibitor. Lower SPAD values for the 100%-vermiliquer treatment than for the 50%-vermiliquer treatment suggest that the 100%-vermiliquer treatment was affected to a greater extent than the diluted 50%-vermiliquer treatment. Also, plants in the open seemed better able to cope with the stress than plants in the shade, although eventually signs of chlorosis appeared in the open as well. So, after two weeks into the experiment, chlorophyll content in the open fell too. By that time, nutrients in the control treatment were significantly reduced as a result of the intensive plant uptake.

By the third week of the experiment it appeared that the unknown inhibiting factor for the vermiliquer treatments was overcome and by the fourth week (closer to the harvest) completely negated so that both vermiliquer treatments showed a greater chlorophyll concentration.

![Figure 5.46. SPAD readings (arbitrary units) in the control, 100% and 50%-vermiliquer treatments in experiment 9.](image-url)
Differences between the values of photosynthetic activity and SPAD readings.

The treatment values for the photosynthetic activity measured together with other leaf gas exchange parameters twice during experiment 9, on 04.06.09 and 09.06.09, did not show the same trend as SPAD readings. There was no significant difference between the treatments on 04.06.09. However, on the second date, 09.06.09, photosynthetic activity was significantly higher in the control treatment than in the 50%-vermiliquer treatment \( (p = 0.048) \), with the values for the 100%-vermiliquer treatment being between the two and not significantly different from either of them (with means 15.63 \( \mu \text{mol/m}^2/\text{s} \) for the control treatment, 13.68 \( \mu \text{mol/m}^2/\text{s} \) for the 100%-vermiliquer treatment and 12.66 \( \mu \text{mol/m}^2/\text{s} \) for the 50%-vermiliquer treatment, LSD for the treatment factor = 2.224 \( \mu \text{mol/m}^2/\text{s} \)).

Figure 5.47 and Figure 5.48 illustrate the data from Figure 5.46 with the visual appearance of the treatments in the middle of experiment 9 (on 29.05.09) and one week later (on 03.06.09).

![Figure 5.47. Plants in the middle of experiment 9 (29.05.09).](image1)

![Figure 5.48. One week later in experiment 9 (03.06.09).](image2)
The same result of a delayed increase in chlorophyll was registered not only in vermiliquer of different degrees of dilution, but also in vermiliquer obtained from different sources of waste. For example, in experiment 11 (Figure 5.49) vermiliquer batch treatments with kitchen waste and paunch material vermiliquer were compared with the control. All treatments were maintained at pH 5.5–6.0.

![SPAD readings in experiment 11](image)

**Figure 5.49.** SPAD readings (arbitrary units) in the control and the off-line vege-liquier (with kitchen waste) and the liquer (paunch) treatments in experiment 11.

To illustrate Figure 5.49, visual appearance of plants is shown in Figure 5.50 for the middle of experiment 11 (on 10.09.09) and in Figure 5.51 for the end of the experiment (on 17.09.09). On the 10.09.09 the vege-liquier treatment (with kitchen waste) showed considerable chlorosis, the control showed some chlorosis, and the liquer-treatment (with paunch) was emerald green. One week later, on the 17.09.09, the control had developed chlorosis, but both vermiliquer treatments were green.

Figure 5.49 provides an example when after four weeks, before the final harvest, the vege-liquier (with kitchen waste) treatment showed a dramatic increase in chlorophyll and finished within the highest chlorophyll concentration across all treatments, including the paunch vermiliquer treatment that demonstrated a high chlorophyll concentration during the entire experiment.
In conclusion, it is not understood if this effect, which occurs during the first three weeks from the start of experiment, is the result of a change in the microbiota population or due to the chemical decomposition of organic compounds. The dynamics of uptake of nutrients in vermiliquer treatments may be a result of a combined effect of direct action of humic substances on plant growth and indirect effect of microbial metabolism and population changes (i.e. through competition for nutrients between the plants and microbiota (Kay and Hart, 1997)) on the availability of nutrients for plants. It certainly requires further investigation.

5.3.2 Leaf size and total leaf area

Dynamics in total plant leaf area with time reflects plant growth. Total leaf area per plant was measured periodically in experiment 10. In the other experiments leaf size of a youngest fully expanded leaf was used as a surrogate growth parameter (the leaf was removed for petiole analysis). On each subsequent sampling date in most experiments leaf size was larger than on the previous one, with the exception of the treatments manifesting severely stunted growth or extreme nutrient deficiencies such as vermiliquer treatment buffered with orthophosphoric acid.
in experiment 2 (Figure 5.52), or both in-line vermiliquer treatments in experiment 12 (Figure 5.53). Plants in these treatments had significantly smaller leaves (and, naturally, yield parameters) than all other treatments across experiments.

In general, area per youngest fully expanded leaf was linked to the yield of leafy vegetables. For example, in experiment 4 (Table 5.16), leaf size in vermiliquer treatment buffered with nitric acid was less in each sampling occasion by about 20% than in the control treatment (Table 5.16), while the vermiliquer treatment buffered with orthophosphoric acid did not show any increase in area per youngest fully expanded leaf during the experiment, suggesting severely stunted growth in that treatment. This correlates well with the harvest parameters in this experiment (see section 5.3.3. Harvest Parameters).

Table 5.16. Leaf area (cm²) per youngest fully expanded leaf in experiment 4 (means followed by the same letter do not differ at p ≤ 0.05).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>116.12ᵃ</td>
<td>148.34ᵃ</td>
</tr>
<tr>
<td>Vermiliquer buffered with HNO₃</td>
<td>114.16ᵇ</td>
<td>139.57ᵇ</td>
</tr>
<tr>
<td>Vermiliquer buffered with HPO₄</td>
<td>49.25ᵇ</td>
<td>47.95ᵇ</td>
</tr>
</tbody>
</table>

Dynamics of leaf size also reflect availability of nutrients and nutrient deficiencies. For example, in experiment 2, the vermiliquer treatment buffered with orthophosphoric acid was the most ‘unsuccessful’ treatment in that experiment. It showed slow growth in the first two weeks, but three days after that leaf area decreased indicating severely constrained growth (Figure 5.52).

Figure 5.52. Leaf size (cm²) of youngest fully expanded leaf in experiment 2.
A post-harvest spike of control nutrient solution to all treatments (on 30.08.08) resulted in an increase in leaf area. The NFT vermilion treatment with orthophosphoric acid also showed the increase in leaf area, although it was not as marked as in other treatments, suggesting a limited ability to recover from long exposure to a stress-factor.

Figure 5.53 shows leaf area dynamics in experiment 12. In this experiment, involving two in-line vermilion treatments obtained from different sources of waste, plants with 'standard' paunch material and vege-liquor showed no difference in leaf size. Again these final values correspond closely to the harvest parameters. A slow increase, or no change in leaf size with time, suggested stunted growth in both treatments.

![Leaf size in experiment 12](image)

**Figure 5.53. Leaf size (cm²) of youngest fully expanded leaf in experiment 12.**

Of interest, leaf area dynamics in experiment 11 (Figure 5.54), which involved the off-line (batch) vermilion treatments derived from different sources of waste, showed a slower start for the 'vege-liquor' treatment (with kitchen waste) but with a steady consistent increase. This was in contrast to the control treatment and the 'liquor' treatment (with paunch material), which showed rapid development until the middle of experiment with subsequent slowing down in leaf size. At the end of the experiment leaf size in the control and the vege-liquor treatments was the highest. However, yield in the liquor treatment was the same as that of the vege-liquor treatment (see section 5.3.3. Harvest Parameters).
Figure 5.54. Leaf size (cm$^2$) of youngest fully expanded leaf in experiment 11.

Figure 5.55 shows the dynamics of leaf area in the pot and NFT systems. Results from experiment 10 suggest that, all other conditions being equal, yield and leaf area in the NFT system was significantly higher than in the pot system across all treatments.

Figure 5.55. Total leaf area (cm$^2$/plant) in experiment 10.
### 5.3.3 Harvest parameters

#### 5.3.3.1 Summary of harvest parameters throughout the experiments

Table 5.17. Summary of harvest parameters (g per plant). Means within a column within an experiment followed by the same letter do not differ at $p \leq 0.05$.

<table>
<thead>
<tr>
<th>Exp No.</th>
<th>Period</th>
<th>Days</th>
<th>Hydr. system</th>
<th>Treatment</th>
<th>Fresh weight</th>
<th>Dry weight</th>
<th>Total weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Shoots</td>
<td>Roots</td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>% of control</td>
</tr>
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<tr>
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<td>vermiliquer - pH 5.5</td>
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<td>Control</td>
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<td>100% - vermiliquer</td>
<td>414.80</td>
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</table>
In experiment 2, the NFT and pot trials were run on separate hydroponic units and, consequently, on different nutrient solutions. In experiment 10, each hydroponic unit comprised the NFT and pot section and, consequently, the NFT and pot setups were run on the identical nutrient solution.

<table>
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<th>Exp</th>
<th>Date</th>
<th>Type</th>
<th>Control</th>
<th>In-line vermiliquer</th>
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<th>100% - vermiliquer</th>
<th>Batch vermi, buffered</th>
<th>Batch vermi, unbuffered</th>
<th>Control</th>
<th>50% - vermiliquer</th>
<th>100% - vermiliquer</th>
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<td></td>
<td></td>
<td>81.00b</td>
<td>16.20b</td>
<td>97.19b</td>
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<td>7.36b</td>
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<td></td>
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<td>8.72b</td>
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<td>58%</td>
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<td>25.58b</td>
<td>363.50c</td>
<td>8.55b</td>
<td>3.70b</td>
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<td></td>
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<td>26.00b</td>
<td>198.08a</td>
<td>4.65a</td>
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<td>6.01e</td>
<td>3.07b</td>
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<td>367.30b</td>
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<td>418.80a</td>
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<td>12</td>
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<td>7.10a</td>
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</tr>
</tbody>
</table>

1 - in experiment 2, the NFT and pot trials were run on separate hydroponic units and, consequently, on different nutrient solutions.

2 - in experiment 10, each hydroponic unit comprised the NFT and pot section and, consequently, the NFT and pot setups were run on the identical nutrient solution.
5.3.3.2 Comparison between vermiliquer treatments and the inorganic control

Even though yield parameters for the most successful vermiliquer treatments in most experiments were less than those in the control treatment, these results improve upon those of the majority of previous publications of hydroponic plant production using organic fertilisers (e.g. Anderson and Schmidt, 2001).

Taking into consideration that the nutrient content of the vermiliquer treatments was not amended, apart from the supplementation of pH buffer (nitric acid in most experiments), a comparable yield in vermiliquer treatments with the control treatment (using a perfectly balanced but unsustainable inorganic fertiliser) highlights the great practical and commercial potential of this research.

Total fresh weight in the batch buffered undiluted vermiliquer treatments in different experiments ranged from 63 to 100% of the weight in the control treatments (Table 5.17), depending on the origin of vermiliquer, climatic conditions and the system design (NFT or pot setup).

For example, total fresh weight of plants in the 100%- vermiliquer treatment buffered with nitric acid to pH 5.5 in the pot setup in experiment 3 was 98% that of the control. The other vermiliquer treatment in the same experiment maintained at pH 7.0 resulted in 82% of the total fresh weight in the control treatment.

In experiment 4 the 100%- vermiliquer treatment buffered with nitric acid resulted in 87% of total fresh weight of the control treatment.

Total fresh weight in the 100%- vermiliquer treatment in experiment 5 exceeded the control (102% of the control treatment), although the reason for that was the consequence of the exceptionally wet season, when all treatments were effectively running on a half dilution. The yield, therefore, reflected comparative performance under conditions of restricted nutrient supply. The 50%- vermiliquer treatment (effectively only 25%- vermiliquer) resulted in 71% of the control treatment yield.
The same treatments were repeated in experiment 7. However, the vermiliquer on which the experiment was conducted was not the same as in the previous experiments (Table 3.4). The vermiliquer for experiment 7 was produced with similar pre-composted paunch material of plant origin but after the re-setting of the worm pits. Even though the plants in the 100%-vermiliquer treatment did not show any signs of nutrient deficiencies, total fresh yield was only 68% of that in the control. Total fresh weight in the 50%-vermiliquer treatment was only one half of that in the control treatment.

Experiment 9 aimed to repeat experiments 5 and 7, but in the NFT setup. The vermiliquer for this experiment was produced after another re-setting of the worm pits and so its nutrient content was not the same as in the previous experiments. The fresh weight of plants in the 100% and 50%-vermiliquer treatments was only 63% and 55% of the fresh weight in the control treatment. Of interest, total dry weight in the 50%-vermiliquer treatment was higher than that in the 100%-vermiliquer treatment. Reduced total dry weight in the 100%-vermiliquer treatment was linked to the reduced root mass, because dry weight of shoots was still higher than in the half-diluted vermiliquer. Root development might be affected by electrical conductivity, microbiota and plant-regulating substances, and also by different rates and mechanisms of nutrient uptake in the vermiliquer treatments in the NFT hydroponic setup.

In experiment 10 the same vermiliquer as in experiment 9 was used. Treatments as in previous experiments 5, 7 and 9 were arranged in the combined NFT/pot setup. Total fresh weight in the 100%-vermiliquer treatment was 77% (in the pot system) and 84% (in the NFT-system) of that of the control. Fresh weight in the 50%-vermiliquer equalled 54% and 55% (in the pot and NFT setup respectively) of fresh weight in the control treatment.

Experiment 11 was run on vermiliquer from different waste sources. Plants grown with vermiliquer obtained from kitchen waste reached 70% of fresh weight in the control treatment, while those on the 'standard' vermiliquer, used in most experiments, obtained from vermicomposted paunch reached 80% of the fresh weight in the control treatment.

To sum up the results, excluding experiments 7 and 9 where 100%-vermiliquer treatments reached only 63% and 68% of the control fresh weight respectively, in all other experiments,
carried out in different times of year, fresh weight in the off-line vermiliquer treatment buffered with nitric acid was more than 80% of the control.

Total dry weight varied to a greater extent. In different experiments dry weight of the 100% buffered vermiliquer treatment ranged from 58% to 90% of that of the control.

5.3.3.3 Comparison among vermiliquer treatments - factors that affect the yield

These experiments underpin the importance of good management practices affecting plant development in hydroponic systems operated on vermiliquer. It is well known that the ability of plants to take up nutrients (especially iron and manganese) depends on the pH of the nutrient solution. However, plant growth may be limited due to the greatly reduced amount of all available nutrients. Initial results of ‘unmanaged’ vermiliquer were not impressive in terms of yield: plants showed stunted growth, severe chlorosis and leaf discoloration, and poor root structure.

Poor shoot development is always associated with stunted roots and root system damage (small roots, a senesced taproot, lack of fibrous roots, massive decaying old roots). The focus of this research was to identify an optimal nutrient solution regime to allow better root system development as a key for a healthy crop (Figure 5.56 and Figure 5.57).

Figure 5.56. Initial results. Root systems in the control and vermiliquer plants in experiment 2.

Figure 5.57. Improved results. Root systems in the control and vermiliquer plants in experiment 9.
**pH of the nutrient solution.** The data show that pH of the nutrient solution has a crucial role in plant performance. All experiments where pH was not manipulated, including experiments on direct linkage between hydroponics and vermiculture (experiments 6, 8 and 12), resulted in severely retarded growth.

As expected, data from experiment 8 showed that the buffered vermiliquer (maintained at pH 5.5-6.5) out-yielded the unbuffered vermiliquer (at pH > 8.0): five times in fresh weight and four times in dry weight (Table 5.17).

In experiment 3, plants grown on vermiliquer maintained at pH 5.5 out-yielded the plants maintained at pH 7.0 by 16% in the fresh weight (Table 5.17), although dry weight in both treatments was the same.

Of interest and against common beliefs (Moore et al., 1998) pak choi plants grew well under acidic conditions (pH ranged from 3.0-4.0 for the first two weeks, and was under pH 5.0 for the rest of the experiment) in the 100%-vermiliquer treatments in experiments 10 and 11. The acidic environment was a result of a one-step pH buffer application (see sections 5.1.1. pH and 5.1.1.1. Buffer application).

Thus, the data provide evidence that vermiliquer can be used for hydroponic pak choi production over a wide pH range, although pH 5.0-7.0 is considered to be optimal.

**Choice of buffer.** As discussed in section 5.1.1.1. Buffer Application, choice of buffer had a significant effect on the yield of vermiliquer treatments. In experiment 4 all parameters measured at harvest for the 100%-vermiliquer treatment buffered with nitric acid were four times higher than for the one buffered with orthophosphoric acid. In experiment 2, the total dry weight in the 100%-vermiliquer treatment buffered with orthophosphoric acid was ten times lower than in the control for the NFT system and two times lower in the pot system.

**Dilution.** Dilution of the vermiliquer aimed to reduce the amount of fertiliser used for hydroponic plant production and the concentration of phyto-toxic substances that might suppress plant growth. In all experiments the half-diluted vermiliquer resulted in reduced fresh and dry weight of shoots compared to 100% -vermiliquer, although not to the proportion of the
dilution (70% of the comparative undiluted vermiliquer treatment in experiments 5 and 10, and over 80% in all other experiments with dilution).

**Off-line (batch) vermiliquer / in-line linkage.** Direct linkage of hydroponic units to the vermiliquer collecting tanks with ‘live’ vermiliquer, recirculating through worm beds, resulted in the least amount of flexibility to manipulate nutrient solution parameters. There is always a risk that management for hydroponic plant production (e.g. maintaining a pH < 6.0) will affect worms, and there are obvious restrictions on application of sprays against plant pests and diseases. The only practical option to regulate the system would be through adjustments in the worm feeding cycle.

The yield in the in-line vermiliquer varied between experiments. For example, average fresh weight of shoots in experiment 8 (Figure 5.59) was 143 g compared with 81 g in experiment 6 (Figure 5.58). The proportion was similar for the dry weights too.

![Figure 5.58. The control and the in-line vermiliquer treatments in experiment 6.](image1)

![Figure 5.59. The in-line vermiliquer treatment in experiment 8.](image2)

Running the hydroponic system on batch vermiliquer had the advantage that it was possible to manipulate such parameters as nutrient solution pH (through buffering) and electrical conductivity (through dilution), although the latter would be possible for in-line setups too.

**Source of vermiliquer.** With a limited number of replications and due to a high variability in plant biomass within a replicate differences in yield between different sources of organic waste were not found to be statistically significant although the treatment operated with vermiliquer obtained from paunch material apparently out-performed the other one with kitchen waste in
both experiments 11 and 12 involving the different waste sources (Table 5.17). In experiment 11 both vermiliquer treatments produced less biomass than the control treatment (c. 80% in the vermiliquer with paunch material and c. 70% in the vermiliquer with kitchen waste compared to that of the control). Likewise, in experiment 12, despite both fresh and dry weights in the in-line vermiliquer treatment with kitchen waste reaching only c. 56% of that with the paunch material the difference was not statistically significant. The visual differences between the treatments were supported with apparent differences in SPAD values (Figure 5.41) and nutrient accumulation (Figure 4.21 and Figure 5.34). However, in the absence of statistically confirmed difference (with only one exception for root dry weight in experiment 11), the results of last two experiments are not sufficient to conclude that the source of organic waste significantly affected the yield. With an increase in the number of replications differences in yield may well become apparent between different sources of organic waste.

5.3.3.4 Comparison between NFT and pot setup

In these experiments, the NFT setup appeared to amplify both the positive or negative effects of environmental conditions when performance was compared with that of the pot system. In experiment 2, the pot and NFT system were separate setups and therefore could not be compared directly. The systems had the same capacity of 12 plants per channel. Of interest, the “successful” control treatment in the NFT setup produced 20% more biomass than in the pot setup, while the ‘unsuccessful’ vermiliquer treatment buffered with orthophosphoric acid yielded more in the pot system, producing double the biomass of the same treatment in the NFT setup. Signs of chlorosis/nutrient deficiencies in this treatment in the pot system were not apparent until day 18, while the same treatment in the NFT system showed chlorosis in the first week of the experiment (Figure 4.2).

In experiment 10, the NFT and pot setups were combined within one hydroponic channel so that nutrient solution was identical in both systems. In that experiment values for fresh and dry
weights per plant produced in the NFT setup were consistently higher than in the pot setup (Table 5.17).

Figure 5.60. The 50%- vermiliquer treatment in experiment 10 shows developed chlorosis in the NFT and only first signs of chlorosis in the pot section of the same hydroponic channel (14.07.09, 15th day after transplanting).

Figure 5.60 illustrates apparent differences in the 50%- vermiliquer treatment between the NFT and the pot sections of the same hydroponic channel in experiment 10 (14.07.09, 15th day after transplanting). The plants in the pot section of the channel had just showed the first signs of interveinal chlorosis, yet by that time all plants in the NFT section of the same channel were clearly chlorotic.

Direct comparison between the yield per plant in the NFT and the pot systems in experiment 10 was confounded by plant spacing. I had to compare production of one plant in an orifice of the NFT system with two-three plants, grown in one pot in the pot system. Production per plant in the pot-system was naturally restricted by the density of plants and the ‘effective area’ available per plant. Nevertheless, the yield per pot within the same treatment (experiments 4, 5 and 7) was consistent despite high variability of individual weights of plants.
It is not difficult to estimate ‘effective area’ per plant in the two systems. However, to correctly compare the NFT and pot systems, I would have to have the same number of plants per unit area. With the obvious limitations of the experimental design in these studies, this was not possible.

For example, in the combined NFT/pot experiment 10, pots bearing three plants were arranged in a ‘chess’ order – placed in every second orifice in one channel with the similar order, but with one orifice shift in the neighbouring channels (illustrated in Figure 3.9).

There were a few ways to compare ‘effective area’ per plant in the combined NFT and pot system in this experiment (Figure 5.61, Figure 5.63 and Figure 5.62).

A simplified approach to estimate the ‘effective leaf area’ in the NFT/pot setup was by dividing total area under the NFT/pot setup by the number of NFT/pot plants respectively (Figure 5.61).

Figure 5.61. An approach to estimate the ‘effective area’ in the NFT by dividing the total area under the NFT setup by the number of plants.
Another simplified approach to compare the ‘effective area' between the NFT and the pot setup was via comparison of the number of plants per orifice (Figure 5.62).

Figure 5.62. An approach to estimate the ‘effective area’ in the NFT and the pot sections in experiment 10.

The mathematical outcome of both approaches was the same: density of plants in the pot system in experiment 10 with 3 plants in one pot in every second orifice was expected to be 50% higher than in the NFT system and, thus, expected productivity per plant in the pot system was two thirds that in the NFT system. The results of the experiment were as follows: fresh weight per plant of shoots in the NFT system out-yielded the pot system: in the control treatment and the 50%-vermilique by 40%, and in the 100%-vermilikiqer treatment by 55%.
There was an approach to estimate the ‘effective area’ in the pot setup as the area of a ‘cell’ (Figure 5.63) available for the plants growing in one pot without interception with the other ‘cells’.

Figure 5.63. An approach to estimate the ‘effective area’ in the pot sections in the pot setup, dividing the ‘cell’ area by the number of plants in the pot.

However, the disadvantage of all estimations was that the plants did not expand to cover the whole area of the hydroponic system available between the NFT plants or pots, while the self-shading effect of a few plants in one pot naturally restricted individual plant growth.

In conclusion, direct comparison between the NFT and pot systems was not possible. The NFT system apparently enhanced productivity under favourable conditions (there was less inter-plant competition), while the pot system helped to compensate for stress-factors such as nutrient deficiencies, high temperatures and interrupted supply of the nutrient solution. Economically, the NFT and pot system represent two options: a high-risk investment with a higher potential profits versus a low-risk investment with a potentially lower outcome.
Comparison between synchronous experiments

Numerous factors such as climatic and seasonal conditions made comparison between the experiments difficult and inappropriate. For example, for final yield the number of days elapsing before harvest can reduce/increase yields considerably.

Comparison between the experiments that were commenced and harvested at the same time gives a better idea about comparative performance of different treatments under the same climatic conditions. The major interest in this comparison was to investigate if, despite spatial difference, the independent hydroponic systems could be used as blocks for a larger hydroponic experiment and that the other treatments in both experiments could confidently be compared to each other.

The pairs of experiments 5 and 6, 7 and 8 and 10 and 11 were carried out in similar hydroponic systems – the batch and the in-line systems (Figure 3.19) – with different disposition (perpendicular to each other and so differently sun-oriented), separated by approximately 30 metres.

The hypothesis was that the yield in the identical treatments used in the synchronous experiments would indicate how the location factors (such as disposition to the sun/shade/exposure to pest populations) may affect the yield and determine whether the direct comparison between the experiments is possible at all.

In the synchronous experiments 5 and 6 one identical treatment in both experiments was the control treatment and in the synchronous experiments 7 and 8 the identical treatment was the off-line (batch) 100%-vermiliquer buffered with nitric acid.

Comparison of the yield parameters (leaf area on two sampling dates; fresh/dry weights) in the control treatment in experiments 5 and 6 showed that the differences between respective control treatments were not statistically significant (Table 5.18), although absolute values for each parameter were greater in the batch system in experiment 5 than in the in-line system in experiment 6.
Comparison between the identical batch 100%-vermiliquer treatment buffered with nitric acid in the synchronous experiments 7 and 8, showed that again in absolute values the 100%-vermiliquer treatment in one experiment (experiment 7) outperformed the same treatment in experiment 8 in each parameter, but statistical analysis confirmed significant difference only for leaf area on both sampling dates (Table 5.19).

The results suggest that direct comparison between the experiments is possible, however, due to great variability of parameters between individual plants resulting in treatments with large LSD, the two systems were used separately in further experiments.
5.3.3.6 Comparative yield in two blocks of six hydroponic units used in experiments 3-5, 7, 9-11

The batch hydroponic system, as illustrated in Figure 3.19, comprised two blocks, each containing six NFT-channels. To quantify the effect of shading and polyhouse microclimatic conditions, during experiments 9, 10 and 11, a polyhouse was installed over one block. Thus, in experiments 9, 10 and 11 the blocks are described as ‘the sun’ and ‘the shade’.

Table 5.20 summarises fresh shoot production for each block in the batch system. It shows that despite some qualitative differences in treatments between the blocks, overall productivity of the systems was not apparently block or season dependant in different experiments, and varied within 10% between the blocks (maximal 25% difference was observed in experiment 7) before and after the polyhouse was installed over one block.

Table 5.20. Fresh shoot weights in the two blocks of the off-line (batch) hydroponic system (g per plant, and expressed as a % of the higher yield).

<table>
<thead>
<tr>
<th></th>
<th>Exp.3</th>
<th>Exp.4</th>
<th>Exp.5</th>
<th>Exp.7</th>
<th>Exp. 9</th>
<th>Exp.10</th>
<th>Exp.11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block 1</td>
<td>284.6</td>
<td>205.8</td>
<td>356.4</td>
<td>367.5</td>
<td>180.2</td>
<td>356.5</td>
<td>368.1</td>
</tr>
<tr>
<td>(NFT channels 1-6)</td>
<td>91%</td>
<td>92%</td>
<td>98%</td>
<td>100%</td>
<td>89%</td>
<td>100%</td>
<td>90%</td>
</tr>
<tr>
<td>Block 2</td>
<td>311.2</td>
<td>224.2</td>
<td>364.2</td>
<td>279.9</td>
<td>203.2</td>
<td>335.4</td>
<td>407.6</td>
</tr>
<tr>
<td>(NFT channels 7-12)</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>76%</td>
<td>100%</td>
<td>94%</td>
<td>100%</td>
</tr>
<tr>
<td>Season</td>
<td>spring</td>
<td>summer</td>
<td>autumn</td>
<td>autumn</td>
<td>winter</td>
<td>winter</td>
<td>spring</td>
</tr>
<tr>
<td></td>
<td>open sun</td>
<td>polyhouse</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It appears that in the tropical conditions, solar radiation was not a limiting factor, and even under conditions of reduced light in a polyhouse it was sufficient for the plants to achieve maximum photosynthesis. Without proper replication (which could not be achieved within these experiments), the effect of shade on pak choi grown hydroponically on vermiliquer remains an issue for further investigation.
5.3.3.7 Comparison between the open and the shaded polyhouse used in experiments 9, 10 and 11 – shade effect and greenhouse microclimatic conditions

As mentioned above, for the final three experiments (9, 10 and 11), one set of six hydroponic units was placed under clear polyethylene cover, thus creating a shading polyhouse/greenhouse effect. Under the limitations of the experimental setup with no replicates for the shade treatments, the effect of polyhouse was superimposed on natural differences related to the location of trial blocks (including different exposure to the sun during the day, and to wind and pest populations).

*Light intensity.* The amount and spectrum of solar radiation is greatly influenced by time of day, time of year, latitude and the condition of the earth atmosphere such as ozone, water vapour and carbon dioxide. Light, or photosynthetic quantum flux density (0.4-0.7 μm), is essential for plant growth although it covers only a small range of wavelengths of the total electromagnetic spectrum of solar radiation (Brenner, 1996). Table 5.21 shows comparative light intensity (photosynthetically active radiation) in the polyhouse, and in the open, measured with LI-COR radiometer.

**Table 5.21. Photosynthetically active radiation (PAR) measured on a cloudless day (21.05.09).**

<table>
<thead>
<tr>
<th></th>
<th>9:00</th>
<th>10:00</th>
<th>11:00</th>
<th>12:30</th>
<th>13:30</th>
</tr>
</thead>
<tbody>
<tr>
<td>In the polyhouse</td>
<td>126.6</td>
<td>724.8</td>
<td>1062.5</td>
<td>1228.2</td>
<td>1123.5</td>
</tr>
<tr>
<td>In the open</td>
<td>917.2</td>
<td>1224.1</td>
<td>1457.2</td>
<td>1508.1</td>
<td>1439.5</td>
</tr>
<tr>
<td>Percentage (%) of PAR received in the polyhouse compared to that in the open</td>
<td>13.80%</td>
<td>59.21%</td>
<td>72.91%</td>
<td>77.69%</td>
<td>78.05%</td>
</tr>
</tbody>
</table>

Light intensity was markedly higher in the open than in the polyhouse. It is assumed that the polyethylene cover reduced the sun light by approximately 35% compared to that in the open.

These data agree with mean values of solar radiation measured during quantification of leaf gas exchange with IRGA (ADC BioScientific Lci Analyser) on a cloudless days of 4th of July 2009 between 12:00 and 16:00 (in the polyhouse - 1146 PAR, in the open – 1727 PAR, approx. 34%
more than in the polyhouse) and 9th of July between 11:00 and 13:00 (in the polyhouse – 1359 PAR, in the open – 1865 PAR, approximately 38% more than in the polyhouse).

To meet some key performance requirements in greenhouses, it is generally recommended that covering allows solar radiation transmission at minimum of 75% to 80% PAR (Connellan, 2009). The polyethylene covering we used during this study to create a ‘greenhouse’ effect marginally suited the requirement. However, as discussed later, measurements of photosynthetic rate with an IRGA gas exchange meter did not vary significantly between the shade and the open, and so it can be assumed that solar radiation was sufficient for the plants to achieve their maximum photosynthesis.

Besides light intensity, other microclimatic conditions varied between the polyhouse and the open.

Temperature and humidity. Two shielded sensors (data loggers) installed in the middle of the open and the shaded block registered ambient temperature and relative humidity (RH) every hour during the experiments.

Ambient temperature was closely linked with the time of day. To illustrate this, Figure 5.64 combines the time/temperature data from 04.12.09 to 08.06.09 reflecting summer conditions in Rockhampton.

![Ambient temperature in the shade and in the open (summer)](image)

Figure 5.64. Fluctuations in the ambient air temperature in the open and in the shade (04-08 December 2009).

Figure 5.64 shows that the midday temperature in the polyhouse was on average 5-10 degrees higher than in the open. The night temperatures did not differ. I may conclude that, apart from reduction in sunlight, a major source of difference in plant growth between the open and the
shaded polyhouse could be the difference in temperature conditions, particularly the warmer temperature in the shade being due to the poor ventilation therein.

Figure 5.65 shows that RH in midday hours was higher in the open. Figure 5.66 shows the relationship between ambient temperature and RH in the sun and shade. There is considerable overlap between the values for open and shade conditions.

![Relative humidity in the shade and in the open (summer)](image)

**Figure 5.65.** Relative humidity in the shade and in the open (04-08 December 2009, summer).

![Relative humidity/temperature relationship in the shade and in the open](image)

**Figure 5.66.** Relative humidity/temperature relationship in the shade and in the open (04-08 December 2009, summer).

Regression analysis confirmed strong inverse relationship between the RH and ambient temperature. The RH strongly related to the particular hour of day and was higher (p < 0.001) in the open than within the polyhouse.
IRGA measurements.

IRGA measurements taken on 09.06.09 during experiment 9 (tropical winter) (Figure 5.67, Figure 5.68, Figure 5.69 and Figure 5.70) show plant responses to the different environmental conditions in the shade and in the open.

Figure 5.67. Light intensity.  
Figure 5.68. Leaf surface temperature.  
Figure 5.69. Stomatal conductance.  
Figure 5.70. Transpiration rate.
The light intensity was significantly higher in the open compared with the shaded polyhouse (Figure 5.67), which is consistent with the data in Table 5.21. It is interesting that the leaf temperature was higher in the open (Figure 5.68), although the midday air temperature was higher in the shade (Figure 5.64 and Figure 5.66). Other publications support the finding that temperature of leaves, having small mass and large exposure to the sun, could differ significantly from the air temperature depending on the air flow and humidity (Connellan, 2009). In contrast, transpiration rate and stomatal conductance were higher in plants in the shade (Figure 5.69 and Figure 5.70). Transpiration rate might indicate how plants adapted to the reduced light and higher midday ambient temperature at lower relative humidity in the polyhouse, as compared with the open. A lower transpiration rate and greater leaf temperature in the open might result from stomata being more closed outside.

Of great interest, IRGA measurements did not show a significant difference in photosynthetic activity between plants in the shade and in the open (see section 5.3.1. Chlorophyll estimation). These findings may indicate that the reduced light in the shaded polyhouse was still sufficient to saturate the photosynthetic mechanisms in plants, or that the higher leaf temperature in the open suppressed photosynthesis, or that photo-inhibition occurred in the open, or any combination of these three mechanisms resulted in similar rates of photosynthesis outside and within the polyhouse.

In conclusion, in experiments where a polyhouse was trialled, the light intensity was higher in the open sun, but temperature during daytime hours was higher and humidity lower in the polyhouse, thus creating environmental conditions where more than one factor was different. However, there were no significant differences in photosynthetic activity between the blocks with or without polyethylene shade. Therefore, despite the reduced light and other varying factors, plants were apparently able to achieve maximum photosynthesis.
5.4 Water use efficiency of the integrated system

Knowledge of water use efficiency (WUE) of a system is necessary for the selection of equipment of the correct capacity and to estimate the water budget of the system for a specific crop and season.

Water consumption depends on a number of factors including plant species, its phenological stage and climate (especially temperature and relative humidity).

Table 5.22 shows water use efficiency (WUE) for four experiments. It is important to note that the calculated WUE index is an approximation only. Ideally, WUE is calculated as total dry weight per unit of accumulated water use by transpiration. For these experiments WUE was calculated as total dry weight (g) produced by all replicates of each treatment divided by total losses in volume of nutrient solution (L) in all reservoirs of each treatment. In the absence of leakages, water losses in a closed system occur both through transpiration by plants and evaporation from the open surfaces. The exact amounts of water lost by transpiration and evaporation are not known and, therefore, all water losses throughout experiments were assigned to transpiration and included in the WUE.

Due to some minor recognised leakages that occurred during the first trials, experiments from 1 to 4 were excluded from the analysis. With the greater experience in operating practices and technical improvements (including better sealing and pipe connections of the system) obvious leakages did not occur in further experiments. Experiment 5 coincided with an exceptionally wet season when the nutrient solution was diluted with rain water, the exact amount of which was not known, so WUE was not calculated for this experiment. All in-line trials were omitted from WUE analysis due to obvious reasons of high complexity of the system involving direct linkage to the verminpits.

Thus, the values should only be interpreted as indicative. Although incomplete, the data provide a good indication of the relative water consumption of the integrated system, allow for a simple analysis of the plant need for water, and can be used for simple economic analyses and commercial applications.
Table 5.22. Water use efficiency (WUE), calculated as total dry weight (root and shoot) per unit of accumulated water use by transpiration.

<table>
<thead>
<tr>
<th>Exp No.</th>
<th>Period</th>
<th>Days</th>
<th>Hydr. system</th>
<th>Treatment</th>
<th>WUE (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp 7</td>
<td>26/03/09-27/04/09</td>
<td>33</td>
<td>Pot</td>
<td>Control</td>
<td>3.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50%-vermi</td>
<td>2.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100% - vermi</td>
<td>2.31</td>
</tr>
<tr>
<td>Exp 8</td>
<td>26/03/09-27/04/09</td>
<td>33</td>
<td>Pot</td>
<td>Batch vermi, buffered</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Batch vermi, unbuffered</td>
<td>0.87</td>
</tr>
<tr>
<td>Exp 10</td>
<td>26/06/09-31/07/09</td>
<td>32</td>
<td>Pot/NFT</td>
<td>Control</td>
<td>2.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50%-vermi</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100% - vermi</td>
<td>1.87</td>
</tr>
<tr>
<td>Exp 11</td>
<td>22/08/09-19/09/09</td>
<td>29</td>
<td>NFT</td>
<td>Control</td>
<td>2.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Vege-liquor (kitchen waste)</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Liquor (paunch)</td>
<td>2.25</td>
</tr>
</tbody>
</table>

WUE in these experiments was comparable with the published data for hydroponic systems (Bhattarai et al., 2008).

Table 5.22 shows that the highest WUE was in the control treatment compared with the vermiliquer treatments (experiments 7, 10, 11). Comparing the full-strength (100%) vermiliquer with half diluted (50%) vermiliquer treatments, WUE in the former was higher than in the latter (experiments 7, 10). Half-diluted vermiliquer treatments used almost as much water as full-strength ones, but yield was considerably lower in the former. The treatment run with vermiliquer sourced from the kitchen waste appeared to be less water-efficient than vermiliquer obtained from the paunch material (experiment 11). In experiment 8, the WUE in the unbuffered vermiliquer treatment was half that in the buffered vermiliquer treatment.

Direct comparison between the experiments, carried out in different seasons and on different experimental setup with the crops of slightly different maturity, is not appropriate but comparison between the treatments within each experiment was quite indicative. It was evident that variation in crop yield (Table 5.17), rather than in water consumption, was responsible for the observed treatment effects on WUE. As a rule, WUE of the treatments corresponded to the comparative yield in the treatment. For example, among other treatments, in experiment 7 the control treatment showed the highest yield and the highest WUE and in experiment 8 the unbuffered vermiliquer treatment showed the lowest yield and the least WUE.
5.5 Pests and diseases

During the lifespan of these experiments there were no problems with any soil-borne diseases. I did not implement any sedimentation or mechanical filtration of nutrient solution, except for thorough washing of the system and additional treatment of the media with 0.1%-chlorine between the experiments.

At the same time, my experience shows that pests can have a substantial effect on the yield. It has been reported that annual crop losses due to insects and plant diseases can exceed 10 to 15 percent of total yields a year worldwide (Hopkins and Huner, 2004). Minimizing pests and diseases during all stages of growth is especially important in tropical climates where many pest species occur year round, and in ‘pure’ organic systems or in direct-linkage systems where pest control is in-operable.

Plants in experiment 6, which involved an in-line vermiliquer treatment, were not treated against pests because the chemicals might harm the worms. As a result, plants in this experiment were heavily affected by pests (caterpillars), especially the control treatment (Figure 5.71). Plants, treated with chemicals in the parallel experiment 7 were less affected.

Pest-tolerance can be considered as a treatment-related factor and for this reason plants affected by pests were not excluded from statistical analysis.

Figure 5.71. Harvested plants in the control treatment affected by pests in experiment 6 (27.04.09).
Research on pests and dynamics of their population was beyond the scope of this study, but they can certainly become an important factor defining crop yield in organic and in-line linkage systems.

Periodically pest-control measures were undertaken in experiments with batch vermiliquer: once or twice during experiments plants were sprayed with 0.1% pyrethrum and seedlings in experiment 7 and 10 were treated with pyrethrum powder.

Direct linkage to the worm beds restricted application of chemicals that might harm worms. Different pests occurred in different experiments, presumably because weather conditions and seasonal factors determined pest population dynamics.

For example, aphids were one of the major crop-deteriorating factors in experiment 3 (spring) (Figure 5.72). Aphids also affected the in-line experiment 8 (autumn) and were noticed on a few plants in experiments 10, 11 and 12 (winter-spring).

In the wet weather there were practically no pests recorded except for occasional grasshoppers (Figure 5.73). In the drier seasons the major pests were caterpillars (the white butterfly Pieris brassicae and Pieris rapae larvae). Heavy attacks of caterpillars resulted in crop damage in experiments 5, 7 and 8 (Figure 5.74).
In most experiments, randomised distribution of the pests over the plants across the treatments did not reveal any specific susceptibility of any of the treatments to the pests, or the pests’ selective preferences to any of these treatments.

However, one overall weakness of treatment was expressed in a higher susceptibility to pests. For example, in experiment 4 the ‘weakest’ vermiliquer treatment buffered with orthophosphoric acid was more affected by the white moth caterpillars than the other treatments (Figure 5.75). This may indicate suppressed natural defensive mechanisms against pests in these plants.

Figure 5.74. White butterfly caterpillars in experiment 7.

Figure 5.75. Some meristems were terminally damaged by white butterfly larvae in experiment 4.

During the studies plants were affected by pests at different stages of growth. In experiment 7 some seedlings were found to be infested with ‘loopers’ (white butterfly larvae) before transplanting into the hydroponic system. The seedlings were treated with pyrethrum and no pests were registered throughout the experiment until the last week before the harvest. It was observed that even two days were enough for the pests to cause rapid losses in biomass in some plants (Figure 5.74).
Occasional viral problems in plants did not significantly affect the yield (Figure 5.76).

Figure 5.76. Viral disease in experiment 9.
6. Conclusions

This study has shown that the production of the Asian vegetable pak choi is possible based upon the use of vermiliquer as the nutrient source derived from the culture of worms fed composted abattoir paunch material and food waste.

The only addition shown to be important was a buffer material for the hydroponics; currently nitric acid has been found to be suitable.

In this research plant performance in the buffered off-line (batch) system was significantly better than in the in-line system (with direct linkage between vermiculture and hydroponics). The in-line linkage is unlikely to be successful unless the natural pH of the vermiliquer is adjusted to become slightly acidic.

In vermiliquer, complex biological, chemical and physical interactions between its organic and inorganic components and its richness in micro-biota are barely understood.

This study provides extensive information on the use of vermiliquer to sustain plant food production. In this small-scale commercial version of hydroponics it has been shown that vermiliquer can be used as an alternative to inorganic fertilisers for hydroponic production of pak choi. Results from the experiments across varying seasonal and other factors, indicate that plant production is likely to be improved through manipulation of growth factors. This is the case where targeting seemingly small issues can provide a big response.

The research has demonstrated that the integration of hydroponics and vermiculture is not only possible but has all the prospects to become commercially viable.
7. Summary

Integrated to operate as a closed-cycle system, hydroponics and vermiculture has shown great potential to take advantage of nutrient-rich waste, and, rather than dispose of them, to convert them into food production.

This study has shown that it is possible to successfully grow the Asian vegetable pak choi in hydroponic system with vermiliquer (leachate from vermicomposted organic waste).

The value and importance of recycling organic ‘wastes’ for further food production will influence the adoption of this technology. Economic potential, and long-term environmental benefits plus efficient use of urban space and wise water-use are certain to ensure success of this innovative technology. Issues of public acceptance such as certification of the end product as organic have yet to be addressed. Further research must support the success of the integration.

*Pak choi growing at the Centre for Plant and Water Science, CQU*
8. List of references and websites


Accessed November 2009


