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Hydroponics Removal of Wastewater's Contaminants for the Generation of Commercially Valuable Plants and Environmentally Sound Effluent for The Dead Sea Communities

Abdellah Rababah [1)]

1) German Jordanian University, Water Engineering & Management, P.O.Box 35247, Postal Code 11180, Amman, Jordan, Tel: +962 6 5300666 EXT 245, Fax; 5300672. Email:abdellah.rababah@gju.edu.jo

ABSTRACT

The purpose of this article is to investigate the applications of hydroponic wastewater management systems (HWMS) as wastewater treatment facilities for the Dead Sea vicinity. In addition, it aims at managing the wastewater through generating commercially valuable plants using a proposed HWMS.

A commercial hydroponic system was adapted for studying the potential heavy metals removal from primary treated municipal sewage effluent. The system consisted of five plastic gullies, 3 meters long by 100 mm wide. Primary treated effluent was used to irrigate lettuce in one series, and a commercial nutrient solution was used to irrigate the same type of lettuce in another series as a control, both by Nutrient Film Technique (NFT). Lettuces accumulated heavy metals in leaf tissues at concentrations higher than the maximum recommended levels (As = 6.5, Cd = 3.8, Pb = 20 mg kg^{-1}).

The hypothetical hydroponic systems may be suitable for the Dead Sea specific conditions where the plentiful salt tolerant plant species may be utilized to manage effluent that would not be safely applied for crop irrigation.

Keywords: Dead Sea, Salt Tolerant Plants, Heavy Metals' Removal, On-site Hydroponic Wastewater Management.

INTRODUCTION

Virtually every terrestrial plant appears to be capable of growing in some form of hydroponic system (Jewell, 1990; Cooper, 1996).

Jordan is suffering the effect of climate changes, which is increasing strain on its already exhausted water resources. Desalination plants are energy-guzzling systems that would increase Jordan's contribution to climate changes; hence, are one of the country's least favoured water supply options. Furthermore, the high building, operational and maintenance cost involved in desalination plants requires careful considerations.

Site assessment of Dead Sea area revealed that major discharges into the Dead Sea water may primarily be released from on-shore hotels and tourist resorts located at maximum of 100 meters from the shore.

OHWMS may be constructed by common contractors under the supervision of onsite wastewater designers with components that differ significantly depending on the nature and size of the activity under consideration. Consequently, design and configuration of the Hydroponic Zone is determined after careful site consideration.

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Table 1: Agricultural reuse categories* use in different countries (Levine *et al.*, 1997).

Countries	No exposure	Forest/ restricted areas	Cotton sugar beets, cereals, dry fodder seeds	Green fodder orchards	Deciduous fruits, vegetables cooked or peeled, pastures	Sport fields and golf courses	Parks and lawns	Unrestricted crops and vegetables, eaten raw
Australia	I	II			III			
France	I	II				III		
Israel	I			II	III			IV
Kuwait	I							II
California	I				II			III
WHO	I	II				III		

*Category I is the least stringent and IV is the most stringent.

Onsite hydroponic wastewater management systems (OHWMS) may be accepted as long term wastewater treatment systems as alternative option to the centralized wastewater treatment systems in the Dead Sea area. The system will save the cost of construction infra-structure for sewage transport and wastewater management facilities that would have an ongoing elevated operational and maintenance cost. Fuel to run air-blowers through diffusers for aerated biological treatment units is of high cost. Moreover, blowers are known for their high maintenance cost (Jewell, 1994).

Furthermore, the generation of massive quantities of sludge needs further costly management prior to safe disposal (Asano, 1987; Ayaz and Sagin, 1996). However, the current lack of public understanding of OHWMS as adequate treatment and dispersal facilities of wastewater has been a major drawback in achieving specific performance outcomes.

Many communities have very limited capacity of surface water bodies. In addition, many surface waters can not be used for any purpose due to contamination by effluent discharged with high levels of pollutants. In some parts of the world, farmers use such effluent for plant production for human consumption, resulting in serious health and social problems. The common reasons for the high levels of pollutants in industrial municipal effluents are the difficulties and unaffordable cost of operation and maintenance of necessary treatment facilities. A major part of the operating cost is due to energy used to transfer oxygen to the aerobic bacteria in order to oxidize organic matter to carbon dioxide, water and new cells. Moreover, operating and maintaining a conventional Sewage Treatment Plant (STP) requires skilled people. Hence, it is clear that alternative or more advanced sewage treatment methods have to be adopted for a safer environment and yet allowing development.

Work in Japan demonstrated hydroponic system utilizing channels in porous blocks of concrete, for the treatment of a small polluted municipal river and for the production of tomatoes (Ohta et al., 1993). Their system removed more than 99% of total organic carbon (TOC). Nevertheless, none of the above authors developed models for their hydroponic systems, which could have be used for general design considerations.

When wastewater effluents are used for crop irrigation, the concentration of trace elements in general is not high enough to cause any short-term (acute) harmful effects (Pettygrove and Asano, 1985). Since most trace elements tend to accumulate in the soil, the trace-element contents of the receiving soil could be substantially elevated by the long-term use of the wastewater. Subsequently, the ground water quality may deteriorate. Hydroponic applications of wastewater for irrigation will not have such effects as long as plant biomass is utilized appropriately.

Table 2: Recommended maximum concentrations of metals and salts in irrigation water used continuously on various soil types.

Metal	Australia[1] on all soils (mg L^{-1})	California/USA on Sandy soil[2] (mg L^{-1})
Al	5.0	5
As	0.1	0.1
B	3.0	0.75
Cd	0.01	0.01
Co	0.05	0.05
Cr	0.1	0.1
Cu	0.2	0.2
Fe	1.0	NGR[3]
Hg	NGR	0.01
Li	2.5	2.5
Mg	NGR	NGR
Mn	0.2	0.2
Mo	0.01	0.01
Se	0.02	0.02
Be	0.1	0.1
Ni	0.02	0.2
Pb	0.2	5.0
Zn	0.20	1.0

[1] (NSW RWCC, 1993; NSW EPA, 1995; NH&MRC, 1996).

[2] (Chang *et al.,* 1996).

3 NGR = no guidelines recommended.

GUIDELINES AND FOOD QUALITY

Levine et al. (1997) attempted to identify different risk levels in wastewater reuse guidelines for different countries (Table 1). These different risk categories varied between I and IV, where IV is the most stringent. In some countries, such as Australia, III is the most stringent which is for crops eaten raw to those eaten cooked. Categories in Table (1) are not clearly identified for each country and hence the relationship between categories of different countries was not identified.

The discharged effluent which is planned to be considered as an alternative resource of non-potable water used for irrigation and the commercially valuable plants produced should comply with the standards outlined below.

Table (2) outlines highest levels of metals for the utilization of reclaimed water in irrigation. Metals in excess of plant requirements may lead to adverse long term environmental effects from accumulation of salts in soil.

Table 3: Australian food standards for food crops.

Metal	Food guidelines* for vegetables (mg kg^{-1})
As	1.0
Cd	1.25
Cu	10.0
Pb	0.5
Zn	150

*(ANZFA, 1995).

The Australia and New Zealand Food Authority (ANZFA) guidelines of selected heavy metals for food are outlined in Table (3).

The ions of most concern in wastewater are sodium, chloride and boron. The most prevalent phytotoxicity from the use of reclaimed municipal wastewater is from boron (Kirk, 1987). The source of boron is usually household detergents or discharge from industrial plants. Salt toxicities are generally reduced at neutral or pH > 6 (Pettygrove and Asano, 1985).

Trace elements are effectively removed from the effluent by removal of suspended solids (Pettygrove and Asano, 1985), whereas salinity is not easily removed, but requires exchange resins and/or Reverse Osmosis (RO).

Elemental Uptake by Plants

The factors affecting the amounts of metal absorbed by plants are those controlling (Shariatpanahi and Anderson, 1986; Gardiner et al., 1990):

(i) the concentrations and speciation of the metal in the solution;
(ii) the movement of the metal from the solution to the root surface;
(iii) the transport of the metal from the root surface into the root; and
(iv) its translocation from the root to the shoot.

In the case of the strongly adsorbed ions, adsorption is more dependent upon the surface area of root available (Nye and Marriot, 1969; Noggle and Fritz, 1983). Mycorrhizae are symbiotic fungi which effectively increase the absorptive area of the root and can assist in the uptake of nutrient ions, such as orthophosphates and micronutrients (Lüttge and Pitman, 1976). Roots also posses a significant Cation Exchange Capacity (CEC), due largely to the presence of carboxyl groups, and this may form part of the mechanism of moving ions through the outer part of the root to the plasmalemma where active absorption occurs (Robb and Pierpoint, 1983).

Absorption of metals by plant roots can be by both passive and active (metabolic) processes (Broom et al., 1994). Passive (non-metabolic) uptake involves diffusion of ions in the solution into the root endodermis. On the other hand, active uptake takes place against a concentration gradient but requires metabolic energy and can therefore be inhibited by toxins (Enoch et al., 1994). The mechanisms appear to differ between metals; for instance, Pb uptake is generally considered to be passive while that of Cu, Mo and Zn, is thought to be either active metabolic uptake or a combination of both active and passive uptake (Robb and Pierpoint, 1983).

Relative differences in the uptake of metal ions between plant species and cultivars is genetically controlled and can be due to various factors including: surface area of the root, root exudates and the rate of evapotranspiration. The latter mechanism affects the mass flow of the solution in the vicinity of the root and thus the movement of ions to the root absorbing surface (Waisel et al., 1996).

EXPERIMENTAL METHODOLOGY

Criteria for the selection of the plant type to be tested with the NFT wastewater treatment system included:

1. Plants grown commonly with NFT hydroponics system to minimize systems modification;
2. Concentration on a species requiring large nitrogen and phosphorous inputs;
3. Plants able to tolerate the wastewater physical and chemical characteristics;
4. Plants able to grow using growing lights and having a short growth cycle (e.g. 8-10 weeks); and
5. Plants with a commercial value.

Table 4: Average concentrations (n=3) of nutrients and other elements in effluent compared to accent hydroponics final nutrient solution and standard deviations.

Parameter	Primary effluent Concentration ± standard deviation (mg L^{-1})	*Nutrient Solution Concentration (mg L^{-1})
Nitrogen (Total as N)	56 ± 6	208**
TP (as P)	4.4 ± 0.8	62
K	30.7±3.15	332
Ca	41.4 ± 28	168
Mg	15.4 ± 3.9	49
S	NM**	65
Fe	1.97 ± 1.14	5.6
Mn	0.03 ± 0.01	2.2
B	2.7±0.96	0.3
Cu	1.29±0.79	0.06
Zn	0.18± 0.12	0.06
Conductivity(μs.cm^{-1})	1325 ± 215	2850 ± 320
pH	6.2 ± 0.8	6.9 ± 1.1

* (Accent Hydroponics PTY, LTD, 1994),**Nitrate as (N), NM = Not measured.

Lettuce *(Lactuca sativa* L.*)* with an annual output value of £31 million was the third most important crop under protected cultivation in the United Kingdom. An area of approximately 1200 hectares of glass and plastic-film structures is used for cultivation of lettuce in the UK during the period from September to early June (Rose and Edwards, 1981).

After some consultation, the project was initiated with a local variety, Mignonette Green Lettuce (Accent Hydroponics PTY, LTD, Sydney). Moreover, lettuce is a common crop, which is eaten raw. The physiology of the plant also makes it one of the worst cases, i.e., pathogens and heavy metals taken up by the root are directly translocated to the edible part.

Two series of commercial hydroponic Nutrient Film Technique (NFT) systems (Cat-2530 Accent Hydroponics PTY, LTD, Sydney) were modified to study the removal of heavy metals from primary treated municipal sewage effluent to produce commercial plants.

Wastewater Plot

The system consisted of the following components and is illustrated in Figure (1).

Feed Recirculating Tank: A cylindrical 1 m^3 plastic tank was chosen to be the circulating tank of the primary effluent.

Table 5: Average concentrations of nutrients and heavy metals in the leaves of lettuce grown on wastewater NFT compared with typical values in foliage plants along with food standards for vegetables.

Metal	Measured concentration in NFT fully grown lettuce leaves± standard deviation (mg kg^{-1})(n=15)	Typical values* in leaves of foliage plants (mg kg^{-1})	Food standards** for vegetables (mg kg^{-1})
As[1]	6.5 ± 1.2	0.1-5 [1]	1.0
B	85 ± 78	15-100	NA
Ca	23 338 ± 2 870	10 000-50 000	NA
Cd	3.8 ± 0.96	1-5	1.25
Co	2.8 ± 0.4	0.2-29	NA
Cr	3 ± 0.07	0.5-1	NA
Cu	12 ± 1.7	5-15	10.0
Fe	647 ± 154	50-300	NA
K	120 049 ± 16 837	15 000-50 000	NA
Mg	12 819 ± 687	2500-10 000	NA
Mn	1 454 ± 219	25-250	NA
Na	33 983 ± 7 032	200-2000	NA
Ni	47 ± 18.8	8-14	NA
Pb	20 ± 15	4-6	0.5
Zn	2 042 ± 378	15-75	150

* From Robb and Pierpoint (1983).

** Douch (1997).

1 From Pettygrove and Asano (1985). NA = not available.

Supply Pipe Line: A light 10 mm in diameter PVC pipe (Accent Hydroponics PTY, LTD, Sydney) was selected to transmit the primary effluent from the circulating tank to the plants.

Pump: A Little Giant submersible pump (Model NK1, Trans World Traders Pty, Ltd, Sydney) was used to pump from the circulating tank to the head of the NFT channels where the plants were grown bare-rooted. The suitable flow rate of effluent in the supply pipe was 8 L.min^{-1}.

NFT Channels: Two series consisting of five plastic rectangular NFT channels measuring 3 meters in length, 100 mm in width and 700 mm in height were used. Primary treated effluent was used to irrigate lettuce in one series (effluent plot). Each NFT channel was a hollow rectangular plastic tube with 10 holes of 75 mm in diameter drilled in the top side of the channel.

Growing Pots: White coloured plastic re-useable growing pots (Cat-39505; Accent Hydroponics PTY, LTD, Sydney) (75 mm x 46mm dia) with a perforated base were used to hold the plants in the NFT channels. The perforated base ensured capillary action to draw water in and a way out for the growing roots.

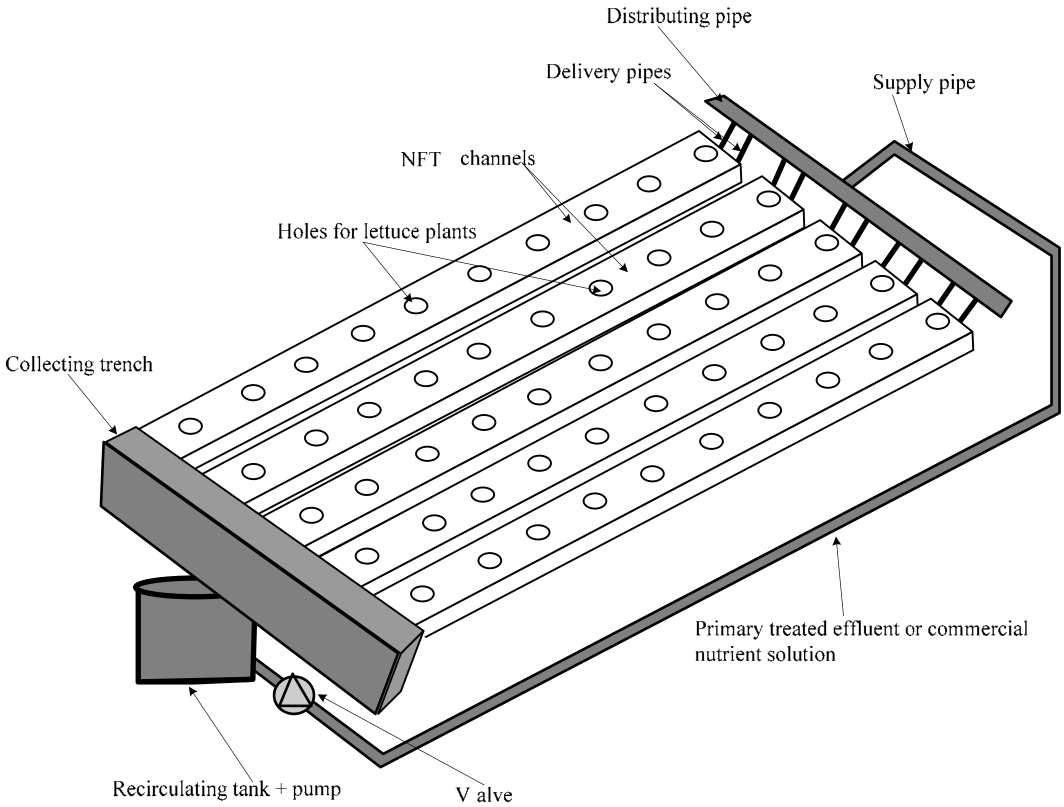

Figure 1: Commercial hydroponic system (Accent Hydroponics PTY, LTD, Sydney) after modifications to suit the experimental design. Two of these systems were used for the experiment: one as a control and one for the effluent.

Growing Medium: Perlite and Vermiculite were used as support media for seedlings in the growing pots. A ratio of two parts perlite to one part vermiculite (v/v) was utilized. The vermiculite kept the medium moist while the perlite helped in aeration.

Growing Lights: Lighting systems were used to control light dosage to both plots described in section 4.2.1. Six; 400 W halide lights (Accent Hydroponics PTY, LTD, Sydney) with a light intensity of 450 μW m^{-2} and a wavelength of around 500 nm were installed overhead of the hydroponics plots. A 400 Watt light suits an area of 1 m^2, which accommodated 10 plants for this project. The lights were kept 300 mm over the plants. Initially, the lights were operating for 18 hours until the plants reached 4 weeks of age, then the lights were timed for up to 16 hours per day. This was partly to save energy and reduce the possibility of plants being affected by the light heat as they grew closer to the light.

Wastewater: Primary settled municipal wastewater free from bulk objects to avoid clogging of the effluent distribution system within the pilot plant was utilized in this study. Moreover, the selected effluents were primarily settled without chemical treatment of nutrients that are essential for plants growth. Every batch of wastewater was analyzed in the laboratory before being used for growing plants. Bondi (South of Sydney) sewage treatment plant primary effluent was utilized.

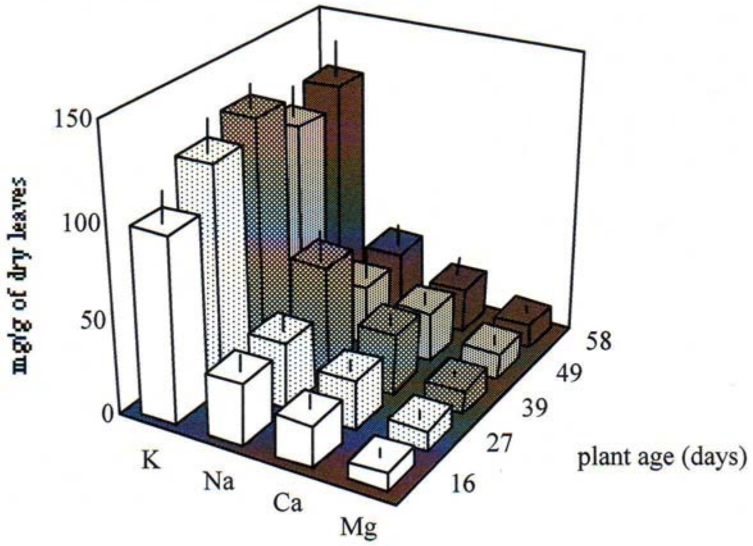

Figure 2: Concentration of different macro elements at different growth stages in the leaves of lettuce plants grown in an NFT utilizing primary effluent (n=15, error bar = 1 SD).

Control Plot

The control plot was in principle the same hydroponic system used as the test. It consisted of a 60 L recirculation tank for nutrient solution storage, a small submersible pump (10 litres at 1.4 m head) and the same NFT channels. The pump was the same as for the standard and quality required for the use in hydroponics, i.e. able to tolerate nutrient solution salt levels without causing contamination of nutrients or rapid deterioration of the pump itself. A plastic by-pass valve was used to control the quantity of water being pumped to the plants. Table (4) shows the concentrations of macronutrients and micronutrients in the final nutrient solution that was added to the circulating tank of the control plot as compared to concentrations in the utilized effluent.

The Hydroponic Pilot Plant Set Up

Plants were grown initially with 18 hours of light per day for the first 5 weeks, then they were grown with 16 hours of light per day.

Wastewater Plot

The effluent was pumped from the primary settling tank into a mobile fibreglass tank and transported to the experimental pilot plant. This tank was fixed onto a trailer, along with a petrol driven pump. The mobile system was specially designed and manufactured for the project. From the mobile fibreglass tank, four hundred liters of effluent were transferred into a 1 m^3 plastic tank (the recirculating tank) from which the effluent was pumped to the lead of the NFT channels for gravity feed via the lettuce plants in a closed-loop hydroponic-NFT configuration.

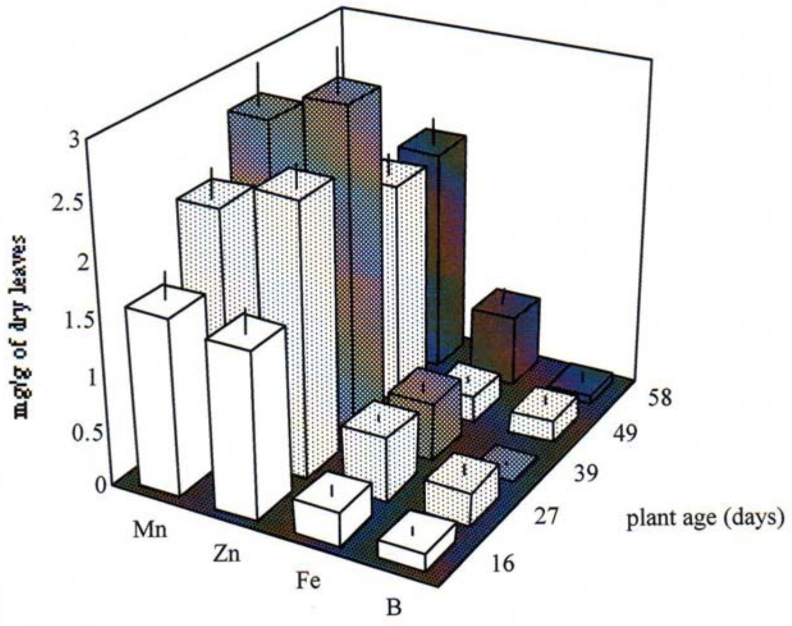

Figure 3: Concentration of different trace elements at different growth stages in the leaves of lettuce plants grown in an NFT utilizing primary effluent (n=15, error bar = 1SD).

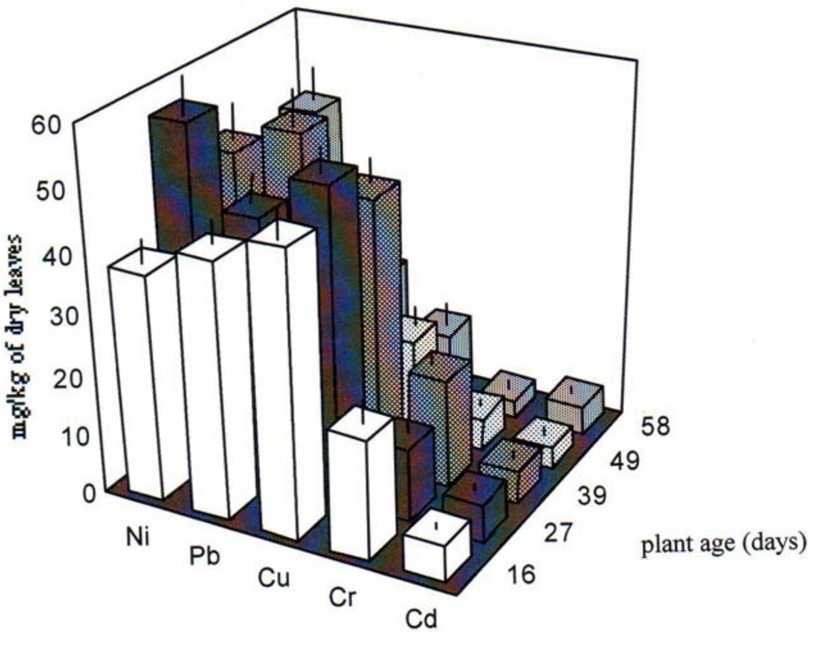

Figure 4: Concentration of different heavy metals at different growth stages in the leaves of lettuce plants grown in an NFT system with primary effluent (n=15, error bar = 1 SD).

Control Plot

Parallel with the wastewater plot, a commercial hydroponic system was operated which utilizes a commercial nutrient solution dissolved in tap water. This solution was pumped from a 60-liter tank to the plants in a similar hydroponic system to those of the wastewater plot at 8 L min^{-1}. The utilized solution flowed back to the 60-liter plastic tank by gravity.

The hydroponic NFT system was moved to a glasshouse belonging to the School of Biological Sciences (UNSW, Sydney) with a controlled temperature of 22-26 °C, where the primary light source was natural light during the months of May to June. The glasshouse provided a controlled environment to grow plants in the adapted hydroponic system at any time of the year under natural light. The growing lights, however, were installed and used to give uniform lighting through the experiment for 16 hours a day.

Laboratory Analysis

Trace elements and phosphorus* were determined by Inductively Coupled Plasma-AES (ICP-AES) as detailed below (Anderson, 1996):

1. Immediately after harvesting, tissue samples were washed with P-free detergent (extrain 300, BDH, Sydney) and rinsed with milli-Q water to remove dust particle residues. The risk involved in washing plant tissues, however, is that some nutrients (for example potassium) may be leached out of the tissue (Noggle and Fritz, 1983).

Roots were further washed with 0.06M $CaCl_2$ for fifteen minutes, then rinsed with milli-Q water. This technique excluded any adsorption contribution to the absorbed phosphorus, but rinsings were collected for analysis.

2. To express the element composition of plant tissues in terms of dry rather than fresh weight, the tissues were dried in a forced draft oven at a temperature of 70°C.
3. The dried tissue was subsequently ground to powder using a ceramic pestle and mortar.
4. After weighing the total mass of powdered tissue, a known weight (50-100 mg) of plant powder was added to a digestion vessel, mixed with 2 ml of 70% nitric acid (HNO_3) and digested at 150°C for three hours.
5. After cooling to room temperature, the digest was diluted to form a 2% HNO_3 final solution (prepared sample).
6. Two mL of the prepared sample were analyzed via a fully calibrated ICP-AES according to standard methods for metals by the Inductively Coupled Plasma Method (APHA, 1995).

Effluent samples were digested with nitric acid according to the 3030 E Nitric Acid Digestion Method for Metals according to (APHA, 1995). The digested sample was then analyzed via a fully calibrated ICP-AES according to standard methods for wastewater (APHA, 1995).

RESULTS AND DISCUSSION

Growth rate of the NFT lettuces, wastewater treatment efficiency and heavy metal concentrations in the NFT lettuces are discussed below.

Metal Accumulations in Lettuce

Theoretically, roots of the plants in the NFT channels are exposed to different levels of macronutrients and trace elements depending on their location within the NFT channels. Hence, the experimental trial in the glasshouse was conducted to investigate element concentrations in each plant grown in the system. In addition to effluent quality indications along the channels, the obtained concentrations will aid in the final design of the hydroponic treatment farm, i.e. distributing plants of different ages within the proposed full-scale treatment farm based on the plant content of the measured elements. Trace element concentrations were also used to observe metal accumulation in the plant tissues for health risk assessment.

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* Phosphorus in plant samples was determined by ICP-AES only for Bondi STP trials, otherwise by Hach (1992).

Table 6: Recommended maximum concentrations of metals in irrigation water used continuously on all soil types and in Bondi effluent before and after one week's recirculation in the NFT pilot plant.

Metal	Initial Concentration and Standard Deviation (mg L^{-1})	Final Concentration and Standard Deviation (mg L^{-1})	Recommended Maximum Concentration in Irrigation Waters* (mg L^{-1})
Al	NM**	NM	5.0
As	0.435 ± 0.439	0.403 ± 0.278	0.1
B	2.7 ± 0.96	1.28 ± 1.14	3.00
Cd	0.061 ± 0.067	0.045 ± 0.06	0.01
Co	<0.002	<0.002	0.05
Cr	0.026 ± 0.018	<0.002	0.1
Cu	1.29 ± 0.79	1.022 ± 0.464	0.2
Ni	2.02 ± 1.38	0.4 ± 0.28	0.02
Pb	0.214 ± 0.102	0.12 ± 0.15	0.2
Zn	0.18 ± 0.12	0.1608 ± 0.063	0.20

* (NSW EPA, 1995). **not measured.

The primary objective of using lettuce in this hydroponic wastewater treatment system was not to remove or concentrate metals from the wastewater but to produce a crop which is both commercially valuable and primarily capable of removing the nutrients nitrogen and phosphorus for acceptable effluent discharge. Nevertheless, excessive heavy metals content would obviously preclude the use of these crops as fodder for animals or humans.

Figures (2) through (4) summarize the results obtained from the ICP analysis conducted on the lettuce plants at various stages in their growth cycle. The numbers represented composite averages from sacrificing fifteen plants per sampling period.

In Figure (2), concentrations of four macroelements are represented. The average concentrations in mature plants and average standard deviations were about: K, $1.2x10^5 \pm 1.6x10^4$ mg kg^{-1}; Na, $3.4x10^4 \pm 7.0x10^3$ mg kg^{-1}; Ca, $2.3x10^4 \pm 2.8x10^3$ mg kg^{-1}; Mg, $1.2x10^4 \pm 687$ mg kg^{-1}. Lettuce plants at 39 days of age seem to show greater difference for Na and Ca than at other ages. The significant difference between the means of K and Na concentrations in plants of different ages was tested according to the null hypothesis tests (Student's T-test, Miller and Miller, 1993). The means of the two macroelements were significantly different ($p<0.05$). However, following the same approach, the means of Mg and Na were not significantly different ($p > 0.05$).

Concentrations of another group of different trace elements are presented in Figure (3).

B, Fe, Mn and Zn, were all below 3,000 mg kg^{-1}. The Mn and Zn concentrations followed a similar pattern, but at 58 days concentrations were 1.454 ± 219 and 2.042 ± 378 mg kg^{-1}, respectively. At 58 days the concentrations of Fe and B were 647 ± 154 mg kg^{-1} and 85 ± 78 mg kg^{-1}, respectively. Neither of the differences between means of Mn and Zn, nor between those of Fe and B were significant ($p > 0.05$).

Figure (4) shows concentrations of the heavy metals Ni, Pb, Cu, Cr and Cd.

Concentration and standard deviation of Ni in mature lettuce plants was 46.6 ± 18.8 mg kg^{-1}; lead 20 ± 8.2 mg kg^{-1}; copper 12 ± 2.5 mg kg^{-1}; chromium 3.1 ± 0.4 mg kg^{-1}; cadmium 4.8 ± 0.96 mg kg^{-1}. The average concentration of Cd was lower than the average concentration of either Ni, Pb or Cu (i.e. the average concentration of Cd was signicantly different compared to either Ni, Pb or Cu, $p \leq 0.05$). Similarly, the average concentration of Cr compared to average concentration of either Ni, Pb or Cu differs significantly (for $p \leq 0.05$) (average Cr concentration < average concentration of either Ni, Pb or Cu). However, when compared to the average concentration of either Cu or Pb, the average concentration of Ni in plant tissues did not differ significantly ($p > 0.05$).

The concentrations of the five metals (Ni, Pb, Cu, Cr and Cd) in the plants generally decreased after 39 days of age. Consultations with Dr Barrow (CSIRO, WA, 1997) concluded that the decrease in concentration with plant age was due to the fact that these concentrations were diluted by the faster rate of mass increase than the rate of absorption. Furthermore, young plants have greater capacity to take up nutrient per unit of root growth than older plants.

Average levels of trace elements found in the edible part of plants grown in the NFT system are listed in Table (5). In column 3, typical values of these elements in market plants are also listed. Four values for heavy metals were found in the reports of Australia and New Zealand Food Authority (1995), as guidelines for the acceptable levels of metals in vegetable plants.

Looking at Table (5), one can notice the concentrations of nutrients and heavy metals in lettuce leaves.

The plants grown in the NFT experimental set up contained As, Cd, Cu, Pb and Zn in excess to what may be considered an acceptable level even though some (e.g. Zn) were within limits set for irrigation. This is one of the main reasons to recommend the use of non-edible plants such as flowers or pyrethrum as value added crops for the proposed system. Below is a summary discussion related to results of selected elements.

Arsenic

Arsenic concentrations in primary effluent exceeded the recommended levels for irrigation waters (Table 6). The As content of lettuce plants grown in the experimental NFT pilot plant was also well over the recommended value.

Boron

Primary effluent is suitable for growing lettuce, because the plant can tolerate boron level which is higher than the concentration found in effluent (Table 6). Primary effluent, however, would not be suitable for many plants such as tomatos or even apples (Leeper, 1978).

Cadmium

Lettuce plants grown in the NFT experimental pilot plant accumulated Cd in their leaf tissues at concentrations typical for leaves of foliage plants (Table 5).

Copper

Lettuce plants grown in the adapted hydroponic system accumulated Cu at concentrations higher than the recommended value (Table 5).

Lead

Australia and New Zealand Food Authority (ANZFA, 1995) does not allow more than 0.5mg kg^{-1} of Pb in food (Table 6). About 20 mg kg^{-1} of Pb was accumulated in the leaves of the lettuce plants grown in the experimental NFT pilot plant with Bondi effluent containing 0.2 mg L^{-1} of Pb. Though, the maximum recommended concentration of Pb in irrigation water is 0.2 mg L^{-1}, which is equal to the concentration in the utilized effluent (Table 6). The grown lettuce in the NFT system do not comply with the food standard.

Nickel

About 47 mg kg^{-1} of Ni was accumulated in the leaves of lettuce grown in the NFT channels irrigated with primary effluent. Typical plant content of Ni is between 8 and 14 mg kg^{-1}. Nickel concentration in primary effluent was about 2.0 mg L^{-1} which is higher than the recommended maximum concentration for irrigation waters.

Zinc

Lettuce plants accumulated about 2.042 mg kg^{-1} of Zn which is over an order of magnitude higher than the maximum recommended concentration for crops (150 mg kg^{-1}). The Zn concentration in primary effluent averaged 0.18 mg L^{-1}, being less than the maximum recommended concentration for irrigation water which is 0.2 mg L^{-1}.

CONCLUSION

The results showed that lettuce plants grew well in a modified hydroponic system (best in the glasshouse) and would be further improved by suitable distribution of plants of different ages along the NFT channels in the proposed full-scale NFT treatment plant. Furthermore, heavy metals (As, Cd, Cu, Pb) in NFT plants may cause health problems if consumed by humans or animals. Alternative plants (i.e. flowers) of minimum health risk are therefore recommended for an NFT system utilizing a mixed industrial and/or domestic effluent. Edible plants, however, may be recommended if As, Cd, Cu and Pb are reduced and the effluent is disinfected.

REFERENCES

Anderson, K.A. 1996. Micro-digestion and ICP-AES Analysis for the Determination of Macro and Micro Elements in Plant Tissues. *Atomic Spectroscopy,* 17 (1): 30-33.

ANZFA. 1995. Australia and New Zealand Food Authority, Standards Development Group, Product Standards and Labelling, Canberra, Australia.

APHA. 1995. Standard Methods for the Examination of Water and Wastewater. 18th Edition. Eaton, A., Clesceri, L. and Greenberg, A. (*eds*). American Public Health Association, American Water Works Association and Water Environment Federation. Washington DC, USA.

Arar, A. 1991. Wastewater Reuse for Irrigation in the Near East Region. *Wat. Sci. Tech.,* 23 (10-12): 2127-2134.

Asano, T. 1987. Irrigation with Reclaim Municipal Wastewater. *Geojournal*, 15 (3): 273-282.

Ayaz, S.C. and Sagin, O. 1996. Hydroponic Tertiary Treatment. *Wat. Res.,* 30 (5): 1295-1298.

Broom, G., Squires, R., Simpson, M. and Martin, I. 1994. Treatment of Heavy Metal Effluents by Crossflow Microfiltration. *J. Membrane Sci*., 87 (1-2): 219-230.

Cooper, A. 1996. The ABC of NFT. Casper Publications Pty, Ltd., Narrabeen, Australia.

CSIRO. 1997. Division of Human Nutrition, Adelaide, Australia, Personal Communications.

Enoch, G., Van-Ven Broeke, W. and Spiering, W. 1994. Removal of Heavy Metals and Suspended Solids from Wastewater from Wet Lime (Stone)-Gypsum Flue Gas Desulphurization Plants by Means of Hydrophobic and Hydrophilic Crossflow Microfiltration Membranes. *J. Membrane Sci.*, 87 (1-2): 191-198.

Fazil, A.A. and Haas, C.N. 1996. A Quantitative Risk Assessment Model for *Salmonella*. *Proc. AWWA Ann. Conv.,* 23-27 August 1996, Toronto. Am. Wat. Wor. Assoc., Denver.

Jewell, W. 1990. Energy and Biomass Recovery from Wastewater: Piloting Resource Recovery Wastewater Treatment. Gas Research Institute, Chicago, Il.

Jewell, W. 1994. Resource-recovery Wastewater Treatment (Combined Anaerobic Treatment of Primary Sewage with Hydroponic Secondary Tertiary Treatment). *Am. Scient.*, 82: 366-375.

Gardiner, D., Christensen, N. and Myrold, D. 1990. Comparison Method for Estimating Phosphorus Uptake Kinetics under Steady State Conditions. *J. Pl. Nutri.,* 13 (9): 1079-1093.

Kirk, P. 1987. In: Heavy Metals in Wastewater and Sludge Treatment Processes, Volume II: Treatment and

Disposal; Leaster, J. (*ed*), CRC Press, Inc., Boca Raton, Florida, USA.

Leeper, G. 1978. Managing the Heavy Metals on the Land. Marcel Dekker, Inc., New York, USA.

Levine, B., Lazarova, J. and Suffet, I. 1997. Wastewater Reuse in Mediterranean Regions: Need for Guidelines. Conference Proceedings, *Beneficial Reuse of Water and Biosolids*, Marbella, Malaga, Spain.Water Environ. Fed., 13/59-13/72.

Lüttge, U. and Pitman, M. (*eds*). 1976. Encyclopedia of Plant Physiology Transport in Plants, II, Part B: Tissues and Organs. Springer-Verlag, Berlin, Heidelberg, New York, USA.

Miller, J. and Miller, J. 1993. Statistics for Analytical Chemistry. Ellis Horwood, Ltd., Chichester, West Sussex, England.

Noggle, G. and Fritz, G. 1983. Introductory to Plant Physiology, Prentice Hall, Inc., Englewood Cliffs, New Jersey, USA.

Nye, P. and Marriot, F. 1969. Theoretical Study of the Distribution of Substances Around Roots Resulting from Simultaneous Diffusion and Mass Flow. *Pl. Soil,* 3: 459-472.

Ohta, K., Ito, N., Hosoki, T., Endo, J. and Kajikawa, O. 1993. Influence of the Nutrient Solution Concentrations on Cracking of Cherry Tomato Fruit Grown Hydroponically. *J. Jpn. Soc. Hortic. Sci*., 62 (2): 407-412.

Pettygrove, G. and Asano, T. (*eds*). 1985. Irrigation with Reclaimed Municipal Wastewater: A Guidance Manual. Lewis Publishers, Chelsea, MI, USA.

Rababah, A. 1998. Innovative Nutrient Film Technique Treatment of Municipal Wastewater Generating Commercially Valuable-Plants and Environmentally Sound Effluent. PhD Thesis, School of Civil and Environmental Engineering, University of New South Wales, Australia.

Rababah, A., Rengel, Z., Ashbolt, N. and Boyden, B. 1997. Modelling Phosphorus Removal in a Nutrient Film Hydroponic System Utilzing Municipal Wastewater. Conference Proceedings, *Beneficial Reuse of Water and Biosolids*, Marbella, Malaga, Spain.Water Environ. Fed., 11/27-11/38.

Rababah, A. 1998. Hydroponic Treatment of Wastewater. PhD Thesis, University of New South Wales, Sydney, Australia.

Rababah, A., Boyden, B. and Ashbolt, N. 1995. Removal of Nutrients from Municipal Wastewater to Produce Vegetable Crops Hydroponically. *AWWA Annual Conference, 16th Federal Convention,* Sydney, Artarmon, Australia, Australia Water and Wastewater Association, 2: 1031-1036.

Robb, D. and Pierpoint, W. (*eds*). 1983. Metals and Micronutrients Uptake and Utilization by Plants. Acadamic Press Pty, Ltd., London, UK.

Rose, J.B., Haas, C.N. and Regli, S.J. 1991. Risk Assessment and Control of Waterborne Giardiasis, *Am. J. Public Health*, 81: 709-713.

Rose, D. and Edwards, D. (*eds*). 1981. Mathematics and Plant Physiology. Acadamic Press Pty, Ltd., London, UK.

Shariatpanahi, M. and Anderson, A. 1986. Accumulation of Cadmium, Mercury and Lead by Vegetables Following Long-Term Land Application of Wastewater. *Sci. Total Environ.,* 52 (1-2): 41-47.

Shuval, I. 1987. Development of Water Reuse in Israel. *Ambio*, 16 (4): 186-190.

Waisel, Y., Eshel, A. and Kafkafi, U. (*eds*). 1996. Plant Roots, the Hidden Half. Marcel Dekker, Inc., New York, USA.

WEF and ASCE. 1992. Design of Wastewater Treatment Plants. American Society of Civil Engineers, New York, USA.

Williams, R. 1946. The Physiology of Plant Growth with Special Reference to the Concept of Net Assimilation Rate. *Ann. Bot*., 10:41-72.

Wong, A., Shipway, J., Chapman, A. and Ball, A. 1994. Enumeration of *Clostridium Prefringens* from Environmental and Wastewaters by Membrane Filtration. *Annual General Meeting of the Australian Society for Microbiology*, Australian Society for Microbiology, Canberra, Australia.