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Urban agriculture, using sustainable practices that involve the reuse of wastewater and solid waste

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ABSTRACT

This study proposes a safe method for the disinfection of wastewater destined for reuse in urban agriculture. It also discusses the year-round production of fresh vegetables in confined urban spaces, using sustainable practices that involve the recycling and reuse of waste while at the same time saving water. To address the aforementioned problems, this study aimed to determine the efficiency of applying organoponic techniques to urban crops, using selected organic compounds and recyclable solid waste products, plus home-made organic fertilizers and treated wastewater. The results obtained demonstrate that in addition to disinfecting the wastewater, ozone contributes oxygen and nutrients to the soil, thereby reducing the need for chemical fertilizers. Ozone also reduces the risk of infection by eliminating highly pathogenic micro-organisms, and increases the rate of plant growth such as: radishes (*Raphanus sativus L.*), tomatoes (*Lycopersicum esculentum*), spearmint (*Mentha piperita*), camomile (*Matricaria recutita*), Romaine lettuce (*Lactuca sativa*) and Chinese cabbage (*Brassica rapa*). Great benefits can therefore be derived from employing these urban agriculture techniques because, in addition to putting to good use waste products that are generated by the ton, these techniques also produce quality food plants that are 100% organic.

1. Introduction

Agriculture is not normally one of our daily activities especially if we are town-dwellers, even though food production is directly related to agriculture, and we all know something about what agriculture involves. Current trends in today's society tend to distance us even further from producing our own food, but some agriculture programmes are now striving to reverse these trends in Modern Cities (Cervantes and Juárez, 2005).

It is a fact that all the world's cities produce huge amounts of solid waste, and that drinking water is becoming progressively scarcer while we continue generating ever more wastewater (Carrasco and Turner, 2006).

Mexico City produces a daily total of 13,401 tons of municipal solid waste (INEGI, 2008), comprising 50% organic residues from the domestic sector and 34% recyclable wastes. The problem is, however, that we do not know how to make good use of it. Similarly, there seems to be little interest in the city to save water. After the People's Republic of China, Mexico is the world's second biggest user of wastewater in agricultural activities; and in Latin America, Mexico is the country with the greatest number of hectares irrigated with recycled but untreated wastewaters (Almanza Garza Victoriano, 2000; Rojas-Valencia et al., 2007).

The CNA (Mexico's National Water Commission, initials in Spanish) estimates that over the whole country about 350,000 hectares are being irrigated with municipal wastewater, at a rate of about 160 m^3/s. Some of this municipal wastewater is mixed with industrial wastewater, some with surface waters, and some with well-water. The impact of this on health is reflected in the rise of gastro-intestinal diseases and acute respiratory infections (Carrasco and Turner, 2006).

Wastewater is known to pollute rivers and lakes, and when wastewater is used in irrigation it pollutes the soil as well. The problem is common to both urban and rural environments. There is therefore an urgent need to apply effective treatment to help reduce water and soil contamination at source, and to ensure that wastewater from the domestic sector does not become mixed with industrial waste, because the types of contaminant transported in industrial effluents are often highly toxic, and in many cases cannot be removed by conventional wastewater treatment alone.

According to the International Development Research Centre in Ottawa, Canada, only 5% of private homes and multi-occupied dwellings in Latin America and the Caribbean remain unconnected to sewage treatment systems. To date, however, the vast majority of these treatment systems only operate primary sedimentation to eliminate suspended solids (Looker, 2005).

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This Project set out to treat wastewaters originating from the domestic sector. The purpose of this project, therefore, was two-fold. Firstly, it set out to test feasible methods for treating wastewater with ozone, destined for reuse in agriculture. Secondly, it suggests a strategy for cultivating different types of fresh vegetables in confined urban spaces such as terraces, roof-gardens, back-yards, balconies and small gardens, without the use of pesticides or chemical fertilizers but re-using waste products, and without affecting public health and to determine the efficiency of applying organoponic techniques to urban crop-growing, utilizing selected organic compounds and recyclable solid waste products.

2. Methods

The methodology was divided into five parts, described soon after with detail.

2.1. Preparation for planting and cultivation

The first part was to collect (a) organic wastes such as: fallen leaves, fruit and vegetable waste, wooden crates, egg boxes and liquid organic fertilizer, for use in the cultivation; and (b) recyclable solid waste such as: plastic packaging materials, used tyres, and disposable soft-drinks cans and bottles, to serve as plant pots and watering cans.

A heavy-duty cutter was used to slice the side off a used tyre, leaving a ring which was then turned inside out. The tyre was then lined with waste plastic packaging material. The plant pot thus constructed was filled with compacted dead leaves (40%) and finely chopped fruit and vegetable waste (20%), with a thin layer of soil sprinkled on top which covered the whole container to a depth of 40%, as can be seen in Fig. 1. Previously germinated seedlings were then transplanted into the containers, or, in the case of some vegetables such as radishes, the seed was sown directly into this prepared soil mixture.

Through this method, plants for human consumption are produced and compost is generated. The modules have to be oriented as to receive sun most of the day.

2.2. Multiple-species cultivation

Bio-tests were conducted on commercially viable and fast-growing crop plants such as: radishes (*Raphanus sativus L.*), tomatoes (*Lycopersicum esculentum*), spearmint (*Mentha piperita*), camomile (*Matricaria recutita*), Romaine lettuce (*Lactuca sativa*) and Chinese cabbage (*Brassica rapa*), as can be seen in Fig. 2. Care was taken to appropriately combine or associate cultivations of several species (in order to promote mutual benefits for vegetables sowed together, such as optimum use of nutrients and sowing space).

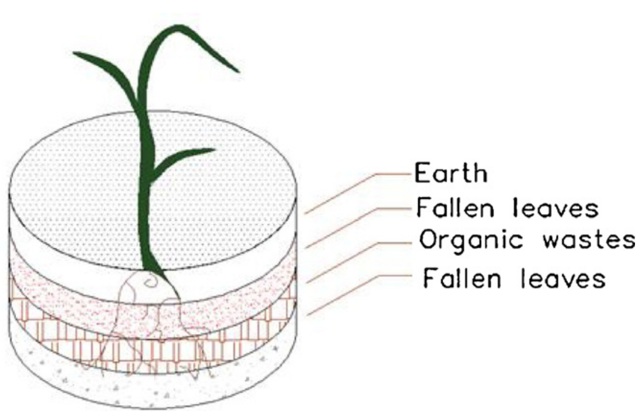

Fig. 1. Preparation of experimental modules.

Fig. 2. Experimental modules with multiple species cultivation.

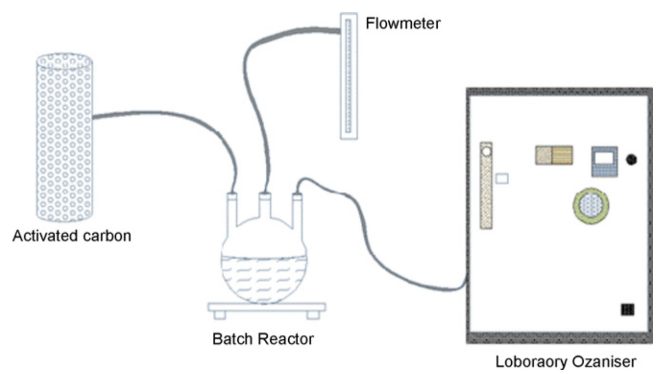

Fig. 3. Wastewater treated in the laboratory ozoniser.

Pest-control was maintained by sowing aromatic plants in the containers to act as a natural repellent. Recommended small size aromatic plants such as thyme, chamomile, or roses were sowed.

2.3. Wastewater treated

This project set out to treat wastewaters originating from the domestic sector, in particular from a typical multi-occupied residential dwelling.

Both organic and inorganic suspended solids were removed during primary treatment of the wastewater, and all floating matter was removed prior to secondary treatment.

The treatment type involved the use of ozone (O_3)-treated wastewater (O_3). A 5-L reactor was used to produce the ozone (flow 1 L/min) gas-phase ozone was applied to the base of the reactor, for a period of one hour as can be seen in Fig. 3, ozone was generated with a Laboratory Ozoniser type Labo 76 (Emery-Trailigaz Co. Cincinnati, OH, USA) using oxygen enriched air as input gas. At pH 7 and a temperature of 23 °C, the concentration of ozone dissolved in the liquid phase averaged 7.36 mg/L. (These parameters were previously determined as optimum for this study). Under these conditions, pathogens were removed, but the nutrients present in water were retained. (Rojas-Valencia et al., 2004; Orta de Velásquez et al., 2006, 2008). Dissolved ozone was measured through the indigo method (Bader and Hoigné, 1981).

Two comparative experiments were also set up. In one, the plants were watered with totally untreated raw wastewater

(5 L/week), and in the other the plants were watered with drinking water (5 L/week), which was the control experiment.

Determination of the following physical–chemical parameters related to the disinfection process, were made for all the treatment types: alkalinity (pH), Biochemical Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), and organic Nitrogen, all were determined according to *Standard Methods for the Examination of Water and Wastewater* (Clesceri et al., 1998).

To ascertain the micro-biological quality of the cultivated plants, tests were carried out to detect the presence of pathogenic agents such as: Helminth eggs and bacteria. *Faecal coliforms* were determined according to NMX-AA-113-SCFI-1999 and NMX-AA-102-SCFI-2006, respectively.

Each set of experimental conditions was tested in quintuplicate, and all the modules were irrigated for a period of 6 months.

2.4. Toxicity study

In this study, toxicological tests were conducted using commonly standardized plants, such as lettuce *Lactuca sativa*, as test organisms.

To determine the possible toxicity of the treatment types (drinking water, wastewaters, treated wastewaters), different dilutions of the raw and treated wastewaters (50%, 75%, 100%, v/v) were prepared in aliquots of 20 mL. The different dilutions were then poured onto 45 mm Millipore Pads that had previously been laid over Petri dishes measuring 60 mm × 15 mm, until the Millipore Pads were totally soaked through. Then 10 seeds per dish per concentration of each treatment type were sprinkled on each Millipore Pad, the seeds being arranged in 4 rows of 3 seeds per row. The same procedure was followed with the control sample, which simply used drinking water, making a total of 75 dishes in all. The dishes were then covered and placed in a humidified incubator set at 24 °C, for a period of 5 days. The results were subjected to a Kruskal–Wallis test analysis.

2.5. Analysis of soil in the plant beds generated by transformation of initial compost mixture during the growth process

After harvesting, the soil produced was analyzed to study its physico-chemical composition, its nutritional quality and microbiological content. All were determined according to *Standard Methods for the Examination of Water and Wastewater* (Clesceri et al., 1998).

3. Results and discussion

3.1. Water quality results

Table 1 gives the water quality results for drinking water, raw wastewater, and ozone-treated wastewater. As was expected, no contaminant showed up in drinking water while raw wastewater showed high SST concentration, turbidity, COD and microorganisms such as faecal coliforms and helminth eggs. When ozone was applied, good BOD_5 removal was observed 87%, and COD removal was 93%. The N and P were preserved.

The fact that the N and P originally found in wastewaters were preserved ensured that the nutrients were available for the large nitrogen consumers such as Chinese cabbage. Said results can promote the acceptation of wastewater by farmers.

3.2. Results of the toxicity study

The percentage of seeds that germinated in each box is set out in the last column of Table 1. On the fifth day, five seedlings were selected from the seeds that had germinated in each Petri dish, and their length was measured. An average length was calculated per dish, and these values are set out in the germination column of Table 2. The statistical analysis was conducted on the basis of said germination percentages and average lengths. A statistical diagram (Fig. 4) shows the average length of the five seedlings selected from each dish of each treatment type.

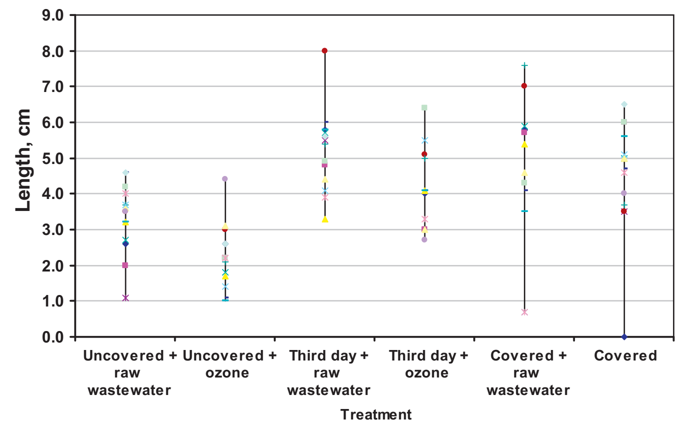

Fig. 4. Range of germination length on the fifth day.

As can be seen in Table 3, the lettuce seedlings grew to a maximum average length when watered with ozone-treated wastewater (6.02 cm). The smallest average growth was observed in the seedlings irrigated with drinking water (5.39 cm); and the next smallest average was seen in the seedlings irrigated with raw wastewater (5.47 cm). If we remember that drinking water is free from plant nutrients, the result makes sense. In the case of raw wastewater, on the other hand, it may be due either to an excess of nutrients, or to the presence of some pollutant that inhibits growth. The standard deviation for the average length of the seedlings was approximately 0.6 cm, regardless of the treatment applied.

The lowest germination percentages were observed in plants in the Petri dishes irrigated with raw wastewater and drinking water. In these cases, 10 of the 15 Petri dishes (66.67%) irrigated with raw wastewater, and 7 of the 15 Petri dishes (46.67%) irrigated with drinking water gave a percentage of seeds germinated that was less than 80%. By contrast, in the case of watering with ozone-treated wastewater the percentage of germination was greater or equal to 90%.

According to the Kruskal–Wallis test analysis, said means are significantly different (test statistic = 24.156, 4 degrees of freedom and n.s. = 0.0001).

The variance analysis resulted in the existence of a significant difference in the average length of the seedlings watered with different types of water (n.s. = 0.0103, F = 3.58, with 4 *y* 70 degrees of freedom in the numerator and denominator, respectively). Two treatments were considered different when the absolute value of the difference between their means was greater than 0.44 cm. It was thus determined that the average length of the seedlings watered with drinking water and raw water is similar (5.39 and 5.47 cm, respectively) and the length of the seedlings watered with ozone-treated wastewater is greater (6.02 cm).

3.3. Results of the multiple-species cultivation

The growth of all the different types of plant used in the multiple-species cultivation, namely: lettuce (*Lactuca sativa)*, radish *(Raphanus sativus L.*), spearmint (*Mentha piperita*), tomato (*Lycopersicum esculentum*), camomile (*Matricaria recutita*) and Chinese cabbage (*Brassica rapa*), evidenced good plant development with all the wastewater treatment types as can be seen in Fig. 5.

Table 1
Characteristics of the untreated wastewater and treated wastewater whit ozone used for irrigation.

Parameters	Drinking water	Raw wastewater	Ozone-treated wastewater
pH	7	8	6
Turbidity (NTU)	ND	127	82
SST (mg/L)	ND	112	85
Total N (mg/L)	2	530	575
P (mg/L)	ND	6.4	5
Ammoniacal nitrogen (mg/L)	ND	4	3
Nitrates (mg/L)	ND	0.2	0.1
COD (mg/L)	ND	378	25
BOD_5 (mg/L)	ND	32	4
FC (CFU/100 mL)	ND	1.2×10^5	ND
Helminth eggs (He/L)	ND	15	ND

SST: Suspended solids totals, ND: Non detectable, FC: Faecal coliform.

Table 2
Average length of the seedlings.

Number	Code	Treatment	Boxes	Length (cm)	Germination (%)	Number	Code	Treatment	Boxes	Length (cm)	Germination (%)
1	101	1	1	5.26	90	39	309	3	9	6	90
2	102	1	2	5.4	70	40	310	3	10	5.14	80
3	103	1	3	6.1	100	41	311	3	11	5.14	100
4	104	1	4	6.66	80	42	312	3	12	4.92	80
5	105	1	5	5.98	100	43	313	3	13	5.94	80
6	106	1	6	5.98	90	44	314	3	14	5.88	80
7	107	1	7	5.4	90	45	315	3	15	5.46	70
8	108	1	8	5.74	100	46	401	4	1	5.56	80
9	109	1	9	6.84	100	47	402	4	2	5.4	80
10	110	1	10	6.94	90	48	403	4	3	5.04	80
11	111	1	11	5.92	90	49	404	4	4	6.64	80
12	112	1	12	6.7	90	50	405	4	5	4.3	70
13	113	1	13	6	80	51	406	4	6	5.54	90
14	114	1	14	5.3	100	52	407	4	7	5.88	70
15	115	1	15	6	90	53	408	4	8	4.9	80
16	201	2	1	7.2	90	54	409	4	9	5.46	90
17	202	2	2	6.34	100	55	410	4	10	5.94	80
18	203	2	3	5.54	100	56	411	4	11	4.5	80
19	204	2	4	5.08	100	57	412	4	12	5.9	90
20	205	2	5	6.86	100	58	413	4	13	6.12	80
21	206	2	6	6.08	100	59	414	4	14	5.04	80
22	207	2	7	6.6	100	60	415	4	15	5.78	80
23	208	2	8	6.54	100	61	501	5	1	6.302	100
24	209	2	9	5.9	70	62	502	5	2	6.16	90
25	210	2	10	5.52	90	63	503	5	3	5.82	90
26	211	2	11	5.86	90	64	504	5	4	6.12	100
27	212	2	12	5.96	90	65	505	5	5	5.08	100
28	213	2	13	5.44	100	66	506	5	6	5.56	100
29	214	2	14	6.14	90	67	507	5	7	4.98	90
30	215	2	15	5.18	100	68	508	5	8	6.2	100
31	301	3	1	6.12	80	69	509	5	9	4.84	90
32	302	3	2	4.1	80	70	510	5	10	5.58	100
33	303	3	3	5.1	80	71	511	5	11	5.82	80
34	304	3	4	5.42	90	72	512	5	12	4.92	70
35	305	3	5	4.42	100	73	513	5	13	6.48	90
36	306	3	6	6.06	90	74	514	5	14	6.9	90
37	307	3	7	5.38	90	75	515	5	15	6.26	90
38	308	3	8	5.8	90						

Table 3
Average maximum length.

Treatment	Boxes	Half statistic	Standard deviation	Minimum	Maximum
Drinking water	15	5.39	604	4.1	6.1
Raw wastewater	15	5.47	626	4.3	6.6
Ozone-treated wastewater	15	6.02	614	5.1	7.2

However, the overall maximum growth was seen in the module irrigated with wastewater treated with O_3 (see Table 4).

Radish harvest period started at 30 days, lettuce began its main development and harvest started at 60 days just when tomato production began. Said three cultivations did not compete between them during most of the cycle and thus the area could be used optimally concluding with Chinese cabbage that was harvested at four months.

In the modules prepared for this study, it was observed that, because their growth and development, a good association between the cultivated plants was reached. In this case it was seen that rice, radish and leaf vegetables, such as lettuce, extract different quan-

Table 4
Growth register for the multiple-species cultivation.

Plant	Treatment		
	Raw wastewater	Ozone-treated wastewater	Drinking water
Romaine lettuce (cm)	9	12	5
Tomatoes (cm)	7	19	6
Radishes (cm)	15	15	11
Spearmint (cm)	15	18.5	13
Camomile (cm)	17	26	15
Chinese cabbage (cm)	39	48	32
Chinese cabbage (gr)	790	1117	705

tities and types of nutrients. Moreover, it was observed that the first ones extract their nutrients from the lower layers of the soil while lettuce and tomato extract nutrients from the upper layer. After harvesting them, there is sufficient nitrogen in the soil so that Chinese cabbage, a large nitrogen consumer, can satisfactorily grow.

The Chinese cabbage was the last plant to be harvested. The longest growth (48 cm) and greatest weight (1117 g) were observed in the plants irrigated with ozone-treated wastewater. A similar behaviour pattern was seen in the case of the other vegetables.

The association of the other plants with chamomile helped control pests. Another advantage is that the organoponic module can be used independently of the weather and physical conditions because the small size of the cultivation surfaces helps control adverse conditions.

None of the plants died in any of the treatments.

3.4. Results from analyzing the soil generated by transformation of the initial compost mixture during the growth process

3.4.1. Soil analysis results

The growing process itself transformed the initial compost into a type of soil. During cultivation, the soil was irrigated with three different types of water: drinking water, raw wastewater and ozone-treated wastewater. After harvest, the average depth of soil remaining was 30 cm. In the case of modules (tyres) irrigated with drinking water, the soil showed a deficiency in nutrients. By contrast the concentrations of macro and micro-nutrients still remaining in the soil in the modules irrigated with ozone-treated wastewater showed that this soil was still fertile and could be reused for another crop cycle without any difficulty.

After the second harvest, the module was disassembled to collect the compost generated and remaining at the bottom. It is relevant to emphasize that compost or organic substrate has a great water and nutrient storage capacity compared to plain soil.

Soils irrigated with untreated wastewater showed an increase in concentrations of macronutrients N, P, K, and micronutrients such as Ca, Mg, Na, Fe, Mn, Zn, Cu, Pb, Ni and Cd, as can be seen in Table 5. All these elements are necessary for building plant tissues and performing developmental functions. In a natural environment, plants obtain said elements directly from the soil; in our case, it is supplied through treated water, in the form of organic fertilizers. Food is free of chemical fertilizers and pesticides and thus healthy crops with a higher nutritional level are obtained.

Since in an organoponic module or system the substrate is formed by soil and leaves, it was necessary to complement the nutrients through a liquid medium such as treated wastewater.

Previous studies (Orta de Velásquez et al., 2006) have reported that an overabundance of nutrients can be as much of an impediment to plant growth as insufficient nutrients, and that the smaller vegetables harvested from land irrigated with wastewaters treatment are indeed the product of soils too rich in nutrient content. Other papers confirm the same paradox: Huett and Dettmann (1991) report that nutrients in excess are as detrimental to the growth of vegetables as are too few nutrients; Walworth et al. (1994) found that over-rich soils produced lower yields at harvest; and Hochmuth et al. (1994) describe how too much nitrogen decreases lettuce quality, sometimes even to the point of rotting an entire crop.

On the other hand when treatment was by ozone alone, Raub et al. (2001) found that agricultural irrigation using this wastewater could in fact increase oxygenation of the soil, thereby improving harvests, decreasing the threat of pests, and eliminating much of the need for chemical fertilization. Theoretically at any rate, by oxygenating the soil, it appears that ozone acts to promote nitrification and the uptake of nutrients.

The results of this study also show that ozone-treated wastewater meets current Mexican Regulations with regard to the following

Fig. 5. Results of experimental modules with multiple species cultivation.

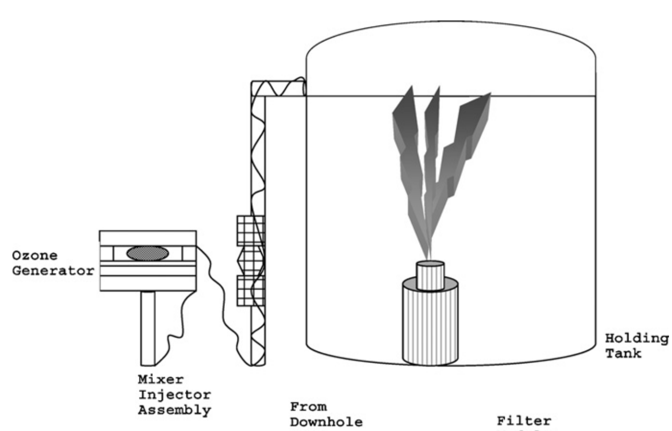

Fig. 6. Ozone equipment in a PVC tank and running the ozonation system.

Table 5
Average physical–chemical and microbiological results of laboratory analysis of soil (30 cm) irrigated with three different types of water.

Parameters	Drinking water	Raw wastewater	Ozone-treated wastewater
pH (soil-water)	7	7	6
Total N (mg/kg)	1063	1923	1613
Total P (mg/kg)	214.7	502	276
Ammoniacal nitrogen (mg/kg)	60	147	130
Nitrates(mg/kg)	20	714	222
K(mg/kg)	38.5	397	286
Ca(mg/kg)	16	19.4	18.4
Mg(mg/kg)	1	1.05	0.1
Na(mg/kg)	0.21	0.46	0.3
Fe(mg/kg)	0.15	0.30	0.2
Mn(mg/kg)	2.4	4.02	3
Zn(mg/kg)	3.08	3.8	3.5
Cu (mg/kg)	1.9	2.6	2
Pb (mg/kg)	ND	0.2	0.1
Ni (mg/kg)	ND	0.4	0.17
Cd (mg/kg)	ND	0.2	0.1
FC (CFU/100 mL)	ND	1.2×10^5	ND
Helminth eggs (He/L)	ND	12	ND

ND: Non detectable, FC: Faecal coliforms.

micro-organisms: pathogenic agents such as Helminth eggs and faecal coliforms (NOM-001-SEMARNAT-1997).

These results report experiments in a laboratory setting. In any full-scale application of the treatment process, this study recommends installing ozone equipment in a PVC tank and running the ozonation system 24 h a day to ensure production of treated wastewater that is suitable for the various uses mentioned elsewhere. Drawing only 55 W of power (usual US cost about $3 per month), units are available in worldwide voltages: 230 V–50 Hz and 230 V–60 Hz. One example as can be seen in Fig. 6.

4. Conclusions

The results obtained in this research work lead to the following conclusions:

Applying at raw wastewater one hour of treatment with ozone, at a concentration of 7.36 mg O_3/L, the removal of BOD_5 and COD were 87% and 93%, respectively. Nutrients were not removed but pathogen microorganisms were destroyed. It can thus be used for crop watering purposes.

The results of the toxicity analysis showed that the average length of the seedlings watered with drinking water and raw wastewater was similar (5.39 cm and 5.47 cm, while germination was 46.7% and 66.7%, respectively). This may be due to a lack or excess of nutrients, while the length reached by seeds watered with ozone-treated wastewater was greater (6.02 cm) and germination reached 90%.

The Chinese cabbage was the last plant to be harvested. The longest growth (48 cm) and greatest weight (1117 g) were observed in the plants irrigated with ozone-treated wastewater. The lesser growth seen in the case of this plant occurred in the cultivations watered with drinking water, possibly because of the lack of nutrients, particularly nitrogen which is essential for Chinese cabbage.

Soils watered with raw and treated wastewater showed an increase in the concentration of macronutrients such as N, P, K and micronutrients such as Fe, Zn and Cu. The highest concentrations occurred in soils watered with raw wastewaters.

The presence of microorganisms was observed neither in soils watered with ozone-treated wastewater nor in plants, and thus the consumption of the harvested products does not represent a health risk.

Enormous advantages were noted in the practice of these urban agriculture techniques, because they lead to the selective recycling of waste materials that are generated by the ton, in the production of high quality 100% organic food, despite only having access to confined spaces.

As long as wastewater from residential dwellings does not become mixed with industrial wastewater, it can be made reusable for such needs as watering parks and gardens, washing cars, floors and lavatories, and for agricultural irrigation, simply by sedimentation and disinfection with ozone.

This document provides guidelines and advice on the formulation and implementation of urban agriculture programmes that incorporate the use of wastewater plus the use of organic compounds and recyclable solid waste products.

5. Recommendations

More study and validation is required of the technique of putting solid wastes to good use in urban agriculture together with the reuse of treated wastewaters; and there is an urgent need to educate and encourage the general population in techniques of reuse and recycling.

The production of Organic Solid Wastes (OSW) in Latin America and the Caribbean varies between 30% and 60%, and they can be used in Urban Agriculture (UA). There is still much disinformation and lack of participation among the inhabitants and local authorities with regard to the implementation of OSW recycling and utilization systems. It is thus necessary to promote environmental education and citizens' participation and to develop appropriate technologies to foster their treatment and use.

Techniques to use solid wastes in UA must be improved and validated; urban farmers have to be trained in recycling and utilization techniques; the community must be instructed at source selection (formal and informal education); and regulations have to be fostered at local and national government levels in order to promote and standardize this activity.

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