The reuse of treated wastewater for agricultural purposes in Nicaragua; Central America

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Abstract The first subsurface flow wetland (SSFW) system for about 1,000 PE, was constructed in Nicaragua in 1996 to apply this technology in the form of an integral project, combining the treatment of domestic wastewater with its reuse for crop production in small and medium size communities. The SSFW-effluent meets all standards established in the national regulations for wastewater reuse in agriculture, except for faecal coliforms, existent at an average concentration of $7 \times 10^4$ MPN/100 ml. A conventional surface irrigation method was used to irrigate different crop species selected to establish their risk of contamination. To judge the potential health risk for consumers and farmers, samples of vegetables and fruits harvested in the dry seasons of the years 1997 to 2002, were analyzed for the presence of pathogenic microorganisms like faecal coliforms, salmonella and shigella. In addition, a yield comparison between crops irrigated with well water using chemical fertilizers, and crops irrigated with the effluent of the SSFW-system was made, to analyze the economical benefits of the wastewater reuse.

Keywords Crop production; economical yield comparison; effluent reuse; health risk; subsurface flow wetland system

Introduction

With the current growth of world population and an increasing water demand per person, the need for this vital liquid is growing rapidly. On the other hand, the available amount of freshwater is limited and is in serious danger from environmental contamination. Worldwide, average freshwater extraction is growing by some 2.5 to 3% annually since 1940, primarily due to the demand for irrigated crop production. Population has been growing meanwhile at between 1.5 and 2%. But in developing countries water reclamation increased in the same period between 4 to 8% annually (Hinrichsen et al., 1998). One means of reducing pressure on the drinking water supply of mankind is to use wastewater for the irrigation of agricultural crops. Often it is possible to reduce the application of chemical fertilizer because of macronutrient concentration existing in domestic wastewater, but there has to be special care taken due to the presence of pathogenic microorganisms that can endanger human health.

In a tropical country like Nicaragua, where agriculture is the main support of a weak economy, only a few farmers have the financial capacity to carry out intensive crop production all year long, because of the need for irrigation water, at least through the six months of dry season. In the Pacific region, where about 80% of the main crops are cultivated, there is a potential irrigation water demand of 978 million cubic metres per year (MARENA, 2001). However, at the present time, actual demand is far less due to the high installation and operating costs of these systems, because there is a lack of sufficient surface water and the usual water table depth lies between 30 and 150 m.

At present, about 20 centralized wastewater treatment plants (stabilization ponds, anaerobic filters, SSFW-systems) to pre-treat or treat 17.33% of the municipal effluents are operating in Nicaragua at several cities located in the interior of the country (ENACAL, 2002).
But a lot of cities, including the capital city Managua, discharge their raw wastewater directly into rivers or lakes, contributing greatly to the pollution levels of these water bodies. At the same time, it has been noted that crops are frequently irrigated with raw wastewater, including crops that are eaten crude. To offer a viable solution to this problem, the first SSFW-system for a suburb of the city of Masaya was built 7 years ago. It is located amongst agricultural fields, to combine an extensive and efficient wastewater treatment technique with an agricultural irrigation project, using the system’s effluent. The effluent reuse is controlled by an accurate monitoring program for the microbial quality of water and crops, including restrictions on the place and method of wastewater reuse.

**Methods and materials**

**SSFW – system and irrigation project, Masaya**

The pilot plant, financed by the Austrian Development Cooperation, consists of a pre-treatment (manually-cleaned coarse screen and grit removal channel), primary treatment (Imhoff Tank) and secondary treatment stage, comprised of four SSFW-units (total area: 1,300 m²), operating in parallel and independently of each other. The system has the capacity to treat the domestic wastewater generated by 1,000 person equivalent (approximately, 120 m³/d), population of the nearest suburb. The treatment plant was designed to investigate the treatment efficiency and design criteria of this technology in a tropical climate, using different aquatic plants and filter materials. Next to the treatment plant, an agricultural irrigation area was prepared to study the effects of the treated wastewater on the irrigated crops. The water quality was determined based on the required standards for irrigation water. Soil analyses were carried out and a conventional surface irrigation method was applied. Different crop species were selected as follows to establish their risk of contamination: crops growing in the soil (e.g. onion, manioc, peanut); crops growing in contact with the soil (e.g. zucchini, cucumber); crops growing near the soil surface (e.g. tomato, beans, paprika) and crops growing distant from the soil surface (e.g. papaya). A pasture plant that is commonly used in Central America as cattle fodder, the Elephant grass (*Pennisetum purpureum*), was planted directly on the SSFW to determine the possibility of feed production on the surface of the treatment system.

**Ways of crop contamination**

There is a broad spectrum of pathogenic microorganisms, including bacteria, virus, protozoa and helminth eggs present in domestic wastewater, as well as in soils and crops that come in contact with it. After studying the relations between different enteric pathogens and the risk of infection, Shuval et al. (1986) developed a theoretical epidemiological model, which shows that bacterial infections and helminthes diseases, if they are endemic like in most tropical regions, will be transmitted very effectively by crop irrigation with wastewater.

All plants have on their surface a more or less typical microflora, which include germs deposited by water, wind and animals (e.g. birds, insects), that can develop there. Healthy plant tissues are normally sterile in their interior parts, with the exception of the roots of *leguminous* where some nitrogen-binding bacteria (*Rhizobium*) are living in symbiosis with the plant. The natural microflora depend principally on the plant species, but also on climatic and location factors. Stage of plant development and ripeness of the fruit are other important factors influencing their infection by pathogenic microorganisms. Fruit and vegetables growing closer to, or in the soil, are infected more often with germs (Müller, 1988).

To determine sanitary qualification of the agricultural products so obtained, international quality criteria for foods were applied, under which three hygienic quality levels, related principally to the quantity of *E. coli* and *Salmonella* in the food samples are established.
Results and discussion

Chemical and microbiological characteristics of the wastewater

The Masaya SSFW-pilot plant was carefully monitored during the operation period between 1996 and 2002. The quality parameters of the raw wastewater and the plant effluent, presented in Table 1, are average values of consecutive analyses realized on 12-hour pooled samples. The Ministry for Environmental Protection published the first national wastewater standards (MARENA, 2000) in 1995, including those values concerning wastewater reuse for agricultural purposes. An amendment of this standard adds by the way of explanation that the indicated value for faecal coliforms is valid for irrigation of crop products eaten raw. There are also limits established for the concentration of heavy metal and toxic substances in the irrigation water. Nonetheless these parameters are only considered if the wastewater used for crop irrigation originates from commercial or industrial activities.

SSFW-systems present a high removal efficiency of organic matter attributed to anaerobic and aerobic microbial degradation in the filter bed. The combination of aerobic degradation near the plant roots (or rhizosphere) and the anaerobic degradation in the zones distant from the roots, produce an effluent with a very low organic charge. This is important due to putrefaction phenomena in the soil and the negative effects that could be caused on the crops over time by high organic loading. Efficient sedimentation and filtration processes provide the principal mechanisms for suspended solids removal. This opens up the possibility to use alternative and more effective irrigation methods such as drip irrigation, because the low presence of solids avoids the obstruction of tubes and outlet gaps. The detergents and soap residues, detected by the MBAS-method were always less than 3 mg/l.

Helminth eggs, specifically Ascaris lumbricoides (~70% of total), cause a lot of endemic diseases in Central America. Concentrations between 2 and 61 helminth eggs per liter were detected in raw wastewater, while in its effluent this range was between 0 and 1. The results obtained confirm that the helminth egg concentration in wastewater treated by a SSFW is practically zero, because of sedimentation, filtration, natural die-off and predation mechanisms in the filter bed. The national and international standards for faecal coliforms were not met because of the high concentration in the systems affluent and a hydraulic retention time of less than 4 days. It could be detected in other investigations that faecal coliform concentration can be reduced down to the limit of $10^3$ MPN/100 ml with a retention time of more than 6 days. Nevertheless the Masaya SSFW-system effluent was used for crop irrigation, since Salmonella was negative in all samples analyzed.

Crop demand on irrigation water

The analyzed crops were selected for their importance in the national economy and consumption patterns. These crops are cultivated normally by intensive production methods using chemical fertilizers, because they require high amounts of nutrients for good

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Raw wastewater</th>
<th>SSFW-effluent</th>
<th>Max. permitted values</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.8</td>
<td>7.1</td>
<td>6.5 – 8.5</td>
</tr>
<tr>
<td>Conductivity (µs/cm)</td>
<td>2,800</td>
<td>546</td>
<td>2,000</td>
</tr>
<tr>
<td>BOD (mg/l)</td>
<td>273</td>
<td>6</td>
<td>120</td>
</tr>
<tr>
<td>COD (mg/l)</td>
<td>650</td>
<td>35</td>
<td>200</td>
</tr>
<tr>
<td>Total suspended solids (mg/l)</td>
<td>251</td>
<td>7.5</td>
<td>120</td>
</tr>
<tr>
<td>Faecal coliforms (MPN/100 ml)</td>
<td>$1.6 \times 10^7$</td>
<td>$7.0 \times 10^4$</td>
<td>$1.0 \times 10^3$</td>
</tr>
<tr>
<td>Helminth eggs (N/1,000 ml)</td>
<td>23</td>
<td>&lt; 1</td>
<td>1</td>
</tr>
</tbody>
</table>
productivity. The soil analyses showed adequate characteristics for all kind of crops, except for those that require high humidity. Soil was classified as andosol with a pH value of 7.5, humidity of 26.07% and infiltration rate of 10–11 cm/h. The content of available phosphorous is 28.26 ppm, 1.59 g of organic nitrogen/kg dry mass and 0.49 g of available potassium/kg dry mass. The relatively low nutrient content that is typical for agricultural soils in Nicaragua indicates the necessity to utilise some kind of fertilization method to obtain satisfactory crop production levels.

Raw wastewater generally contains nutrients at concentrations that cause negative impacts on the quality and the aquatic life of receiving water bodies, such as toxic effects and eutrophication. SSFW-systems remove about 41% of total nitrogen and 23% of total phosphorous because of nitrification, denitrification, matrix sorption and plant uptake. Although those removal mechanisms reduce the environmental contamination, there is still certain concentration of macro-nutrients in the treated wastewater that can be an important nutrient source to the irrigated crop, leading to savings in the use of chemical fertilizer in comparison with the use of well water (see Table 2).

The theoretical range of nutrient requirement for optimal production referring to the analyzed crop species is 50–180 kg N/ha, 15–30 kg P/ha and 80–170 kg K/ha (Schilling, 1989). The quantities of N-P-K available in the treated wastewater can supply in almost all crops analyzed the nutrients necessity to assure an adequate crop growth, without utilization of chemical fertilizer. Almost all nitrogen is present in the form of ammonia. The well water in the region presented low N and P concentrations, but elevated K values. High chloride concentration can severely affect the irrigated crops, but concentrations of less than 70 mg/l cause very little damage (ÖWWV, 1992).

The salinity value permits the irrigation of crop species with a medium salt tolerance, such as the majority of the analyzed crop species, except beans, which is considered a crop having a low salt tolerance. The Sodium Adsorption Rate (SAR) and salinity were determined to see whether the irrigation water could cause structural and pH problems in the agricultural soil over time. A conductivity within the range of 250–750 µs/cm (see Table 1), and a SAR value of 1.72 mval/l, it was established there is a low sodium risk according to Vipond and Withers (1978); this indicates that the SSFW-effluent does not affect the soil structure and can be used on soils with fine or coarse texture.

Microbiological quality of irrigated vegetables and fruits

To judge the real potential health risks for consumers and farmers, samples of vegetables, basic grain and fruits, harvested in the dry seasons of the years 1997 to 2002, were analyzed for the presence of pathogenic microorganisms like faecal coliforms, Salmonella and Shigella. All this data was used to establish human consumption standards based on international criteria for hygienic food conditions (ICMSF, 1983). Crop irrigation was suspend- ed at least one week before harvest to give greater sanitary security. The microbiological results, shown in Table 3, correspond to random samples taken from the internal parts of the

Table 2 Concentration and mass loading of essential elements in the treated wastewater and well water

<table>
<thead>
<tr>
<th>Elements</th>
<th>Concentration in the treated wastewater (mg/l)</th>
<th>Mass loading rate(^1) (kg/ha)</th>
<th>Concentration in well water (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH(_4^+)-N</td>
<td>22.3</td>
<td>111.5</td>
<td>0.25</td>
</tr>
<tr>
<td>NO(_3^-)-N</td>
<td>0.5</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>PO(_4^{3-})</td>
<td>13.8</td>
<td>69.0</td>
<td>0.1</td>
</tr>
<tr>
<td>K(^+)</td>
<td>28.93</td>
<td>144.7</td>
<td>20.72</td>
</tr>
<tr>
<td>Cl(^-)</td>
<td>36.5</td>
<td>319.1</td>
<td>10.64</td>
</tr>
<tr>
<td>SAR</td>
<td>1.72 mval/l</td>
<td></td>
<td>1.67 mval/l</td>
</tr>
</tbody>
</table>

\(^{1}\) With wastewater irrigation of 500 mm/cycle
vegetables and fruits, after washing their skin with drinking water but without a disinfecting application.

Salmonella and Shigella were absent in all crop samples analyzed. Only beetroot, a vegetable growing in the soil, was unacceptable for human consumption, showing in 83% E. coli concentrations of more than 10 ufc/g. Other vegetables growing under similar conditions, like carrot, manioc and onion, showed a provisional acceptance, like zucchini and cucumber, growing in contact with the soil. However, peanuts had a total acceptance, which can be attributed to the high resistance and impermeability of its shell. Crops growing near to and distant from the soil practically didn’t present E. coli contamination at all, indicating that a possible direct contact between wastewater and irrigated soil mainly determines its faecal contamination. In addition the influence of peeling on the microbiological contamination of the irrigated crops was determined.

It could be noted a reduction of total coliforms from $10^6$ to $10^3$ ufc/g to $10^1$ to $10^3$ ufc/g. E. coli was also eliminated very effectively (~96%), showing that peeling of the vegetables and fruits irrigated with treated wastewater is strongly advised before consumption. Vegetables that showed provisional acceptance are recommended to consume only after cooking.

Microbiological analysis realized on Elephant grass leaves, taken in different areas of the SSFW-surface (inlet, center, outlet zone), didn’t show E. coli presence at all, demonstrating effective vegetative barriers of that fodder plant for pathogens. The concentration of total coliforms was between $10^2$ to $10^5$ ufc/g. Elephant grass leaves couldn’t come in contact with wastewater because of the subsurface flow in the system ($\Delta h > 15$ cm) avoiding secondary contamination.

**Yield comparison**

Crop productivity was established to determine the effect of the SSFW-effluent with a remnant nutrient concentration on plant development. Results obtained in this way were compared with typical crop production methods in the region, using well water and chemical fertilizer. Table 4 summarizes this information.

Beans, sweet corn and sugar cane showed 25 to 35% lower production costs and similar productivity, when they were irrigated with treated wastewater. Due to the high nutrient demand of rice, paprika and tomato, less productivity with the SSFW-effluent was noted, but lower production costs too. In that case, the main criteria for the reuse of treated wastewater in crop production is the conservation of natural water sources.
A yield comparison between Elephant grass planted directly on the SSFW-surface and the irrigation of this cattle fodder with well water was made. In tropical countries Elephant grass has a nutrient demand of about 400-100-200 kg N-P-K/ha,year, to obtain output of 20 t dry mass/ha,year (Cordova and Baldeolmar, 1989). The average productivity on the SSFW-surface was 5 kg fresh mass/m², equivalent of 1.9 kg dry mass/m², revealing an effective fodder production due to an average wastewater nutrient loading of 0.4 kg PO₄³⁻/m²,year; 0.8 kg Ntot/m²,year and 0.9 kg K/m²,year.

Since chemical fertilizer application isn’t necessary for Elephant grass production on the SSFW-surface, fertilizer costs of US$280/ha,year can be saved. So the net yearly income from a periodical harvest (every 3 month) was about US$1.9/m², in base of the actual price of this cattle fodder in Nicaragua. To obtain a similar productivity of Elephant grass during the whole year with a conventional irrigation method, you need to consider the following operational costs:

Energy consumption of pumping equipment 913 kWh/ha,month
(design: 150′, 5 kw, operation: 6 hours/day)
Energy costs ~ US$800/ha,year

On consideration of the sum of operating costs, the net income is reduced about 16% when well water is used for irrigation of Elephant grass.

**Conclusions**

The wastewater treatment technologies used in developing countries of tropical regions have to take special account in design criteria regarding the reduction of faecal coliforms and helminth eggs. Agricultural irrigation with treated wastewater from SSFW-systems constitutes a viable alternative for crop production especially because of the low presence of pathogenic organisms and a remnant macro-nutrient concentration. SSFW-systems also represent an economically-viable technology for the treatment of domestic wastewater in Central America, because of their low investment (50 – 100 US$/PE) and operating costs (~5 US$/PE, year), above all when de costs can be recovered particularly by the commercialization of plants growing on the SSFW-surface.

In general, the risk to human health is greater when the consumed crop is growing in the wastewater irrigated soil or in contact with it. Like the consumers, the farmers can also be affected more frequently of wastewater transmitted diseases when the harvest work is to do directly on the soil surface where pathogenic organisms are persistent.

<table>
<thead>
<tr>
<th>Crop species</th>
<th>Irrigation with treated wastewater (SSFW-effluent)</th>
<th>Irrigation with well water and application of chemical fertilizers 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crop productivity kg/m²</td>
<td>Production costs US$/ha</td>
</tr>
<tr>
<td>Beans</td>
<td>0.12</td>
<td>459.77</td>
</tr>
<tr>
<td>Sweet corn</td>
<td>0.42</td>
<td>405.77</td>
</tr>
<tr>
<td>Rice</td>
<td>0.23</td>
<td>538.42</td>
</tr>
<tr>
<td>Papaya</td>
<td>0.96</td>
<td>792.38</td>
</tr>
<tr>
<td>Paprika</td>
<td>1.40</td>
<td>897.65</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>7.38</td>
<td>981.11</td>
</tr>
</tbody>
</table>

1) Commercial N-P-K fertilizer (18-46-0) and urea (46%)
2) Average crop productivity in the dry seasons 1996–2002, irrigation project Masaya
3) Fruits/tree

**Table 4** Productivity and production costs of selected crops
A SSFW-system with a retention time of more than 6 days is able to completely satisfy the standards for reuse of its effluent for irrigated crop production. A system with a retention time between 3 and 4 days can completely eliminate helminth eggs and salmonella, and leave remaining E. coli at concentrations between $10^3$ and $10^5$ MPN/100 ml. In this case, crop irrigation is recommended under the following restrictions (Silva, 1999).

- Irrigation of vegetables, fruits and basic grains that are subject to washing and peeling, or cooking processes before consumption. According to the results obtained, 90% of the washed and peeled crop samples presented <10 ufc/g of E. coli and there was no exceeding of 100 ufc/g. The cooking process is also important to obtain impeccable hygienic conditions of the foods, considering that the pathogens are not thermoresistant and don’t form sporozoa. They are destroyed completely in temperatures $\geq 60^\circ$C during 12 minutes. Crops in this category that are planted and consumed traditionally in the region are beans, sweet corn, rice and manioc.

- Irrigation of industrial crops, like sugar cane, peanuts and soybeans, that are of economic importance for the Central America countries and pass through a drying, roasting or extraction process, where pathogenic organisms are eliminated effectively.

- Irrigation of fruit trees whose fruit are growing distant from the soil (e.g. papaya), and in the case of citrus plantations such as orange, lemon, mandarin and grapefruit, because their fruits have a thick skin that shields the flesh from mechanical damage and contains natural acids and other substances which inhibit the growth of pathogenic bacteria.

Planting Elephant grass on the SSFW-surface is recommended, because its utility in the wastewater treatment itself was demonstrated and generates at the same time a product that can be used as cattle fodder. The consumption of raw vegetables irrigated with treated wastewater is recommended only if a strict program is adopted to assure the sanitary qualification of the agricultural products, including periodical analyses of the irrigation water, with regard to faecal coliforms, salmonella, shigella and helminths.

References

