Wastewater treatment and biomass production by slow rate systems using different plant species

V.E. Tzanakakis*,**, N.V. Paranychianakis*, S. Kyritsis** and A.N. Angelakis*

* Inst. of Iraklio, National Agric. Res. Foundation, 71307 Iraklio, Greece (E-mail: vasilisj@mailbox.gr)
** Dept. Natural Resources and Agric. Eng., Agric. Univ. of Athens, Iera Odos 75, 11855 Votanikos, Athens, Greece

Abstract Natural treatment systems especially those based on land treatment, remain the only viable choice for wastewater treatment and reuse in small rural communities. In order to develop the appropriate technology required a slow rate (SR) systems were established at Skalani, a small village close to Iracklio, Greece. The SR systems were planted with four plant species eucalyptus, acacia, poplars and reeds to evaluate their effects on wastewater treatment and produced biomass. Systems performance were evaluated by monitoring BOD, COD, TSS, TKN, NH3-N, NO3-N, FC, and TC in soil solution and soil samples taken from the 15, 30 and 60 cm of the soil depth. The SR systems, displayed a good performance as regards COD BOD, TKN, NH3-N and bacteria removal (TC and FC). However, relatively increased values of NO3 were detected in 60 cm. In terms of plant species used, there were no significant differences in treatment efficiency among the four SR systems. Although, significant differences were observed in biomass production with acacia trees producing the greatest amount of biomass followed by reeds, while the lowest one produced by eucalyptous and poplar trees.

Keywords Biomass production; plant species; rural communities; slow rate system; wastewater treatment

Introduction

Increasing population and uncertain climatic changes will pose heavy demands on water resources in the future in most of Mediterranean countries. Holistic approaches and integrated water management principles (in which non conventional resources and especially recycled wastewater must be included) will be necessary for developing sustainable schemes and preventing catastrophes. With technologies that are now available and our understanding of natural treatment systems, in the future emphasis will be on sustainability through wastewater treatment, recycling and reuse.

Land treatment systems are forms of zero discharge and reduce pollution of rivers or other surface waters. They are often operated according to the “out of sight, out of mind” principle, to well engineered and well managed treatment plants and environmentally sound, sustainable reuse projects (Bouwer, 2000). Treatment of domestic wastewater with land treatment systems is appeared as a reliable alternative recommendation to costly conventional plants used in large cities. They are suitable for wastewater treatment and disposal in rural communities or decentralized cluster of homes, due to significant advantages, such as low construction, operation and maintenance costs. SR systems involve treatment, reuse practices, and effluent disposal. Such systems are being investigated currently in various parts of the world, with respect to sustainability of land use, treatment efficiency and plant biomass production (Myers et al., 1995; Duncan et al., 1998).

Plants consist a major component for the planning and performance of SR systems (Metcaf and Eddy, 1991; Crites et al., 2000). Plant species often differ in growth rate and therefore a show a different ability for biomass production. Biomass distribution between various organs (leaves, wood and roots) is an important factor determining the value and the utilization of biomass products (chips, pulp, solid wood products, biomass for fuel, etc.)
(Kuhn and Nuss, 2000). However, biomass not only consists an important output which can offset the costs of installation, operation and maintenance, but also can affect the treatment efficiency of a SR system. Differences have been found among various plant species used in such systems in terms of hydraulic loading rates and nutrient removal (US.EPA, 1981; Hopmans et al., 1990). Nitrogen and phosphorous removal is of particular interest in SR systems because these nutrients often represent a limiting factor for the performance of SR systems and are associated with severe environmental impacts (Correl, 1998; Magesan et al., 1998). Finally, selected plant species defines the required land area. Hydraulic load application in these systems is based on crop water requirements, which have been found to differ among plant species (Allen et al., 1998). Reducing required land area is of major concern because often represent a limiting factor and the major shortcoming of these systems.

The main objectives of the present study were: a) to evaluate and optimize the treatment processes in a SR system and b) to evaluate biomass production quantitatively and qualitatively of the different plant species used in such a system.

Materials and methods

System description

The SR system was established at Skalani, a small rural community adjacent to the city of Iraklio, Greece. One-year old trees of eucalyptus (Eucalyptus camandulensis), acacia (Acacia cyanophylous) and poplar (Populus nigra) were transplanted in October 2000 forming individual SR systems. Each of these systems contained 16 trees planted at distances of 1.00 m in row and 1.00 m between rows and was separated from the next one with a 3.5 m corridor. In addition to those plant species, rhizomes of reeds (Arundo donax) were excavated, cut in small cuttings and transplanted at distances 0.50 m between and within rows in February 2001. The four SR systems were arranged at a randomized complete block design with four replications. Subsequently, plants species allowed to grow without any treatment until June of 2001, when the application of pretreated wastewater began. Soil characteristics of the SR systems are shown in Table 1.

Wastewater pretreatment, application system and hydraulic loading rates

Wastewater pretreatment. Raw domestic wastewater received a pretreatment in a septic tank before applied to SR system. Septic tank was divided in two apartments, with the second apartment equipped with a screen volt. There, after the pretreated wastewater was pumped into a plastic (primary) sedimentation tank (1.5 m$^3$) and it finally was stored in two tanks of 3.5 m$^3$ volume each, before application to SR system.

Application system. Pretreated wastewater applied to the SR systems with a plastic distribution network. Application points were covered with half plastic pipes of 200 mm ID, for odour control and avoidance other undesirable side effects. Lateral pipes of 16 mm ID were connected to the half plastic pipes by spaghetti plastic pipes of 6 mm ID.

Hydraulic loading rate. The hydraulic load rate applied to individual SR systems was equal to the water requirements of each plant species. Water consumption was monitored with the use of tensiometers established at the depths of 30 and 60 cm. Pretreated wastewater was applied in such rates to replenish evapotranspiration (ET) losses from each plant species. Pretreated effluent application began when the soil water tension fall bellow the threshold of 70 kPa.

Sampling, preparation and analyses of samples

Samples of raw and pretreated wastewater and soil solution were regularly collected and
analyzed for BOD$_5$, COD, TSS, TKN, ammonium nitrogen (NH$_3$-N), nitrate nitrogen (NO$_3$-N), electrical conductivity (EC), TP, and TC and FC in order to evaluate performance and the effectiveness of treatment processes. Preparation and analyses of the samples was done according to Standard Methods for Examination of Water and Wastewater (APHA, 1995).

Soil solution was extracted from different soil depths (15, 30 and 60 cm) at mid-irrigation interval with soil water samplers (Soil Moisture Equipment Corp. model 1920F1l24-B0,5M2). Soil solution samplers were installed in August 2001, in the interior two rows of each system and were stabilized with a thin layer of bentonite.

Plant growth and development were determined by measurement of plant height and trunk diameter. In October of 2001, four plants from each experimental treatment were cut off and separated to individual organs: leaves, two-year old and current season’s wood and fresh weights were recorded. Dry weight of plant biomass was assessed after representative subsamples of all plant tissues were dried at 65°C until constant weight.

**Results**

The main results, obtained during the period from July 2001 to July 12, 2002 are following.

**Wastewater pretreatment.** The composition of raw wastewater reaching the septic tank is illustrated in Table 2. It is characterized as relatively strong wastewater with high organic load and nitrogen content. The reduction of COD and BOD in the septic tank approached 40%, while the corresponding reduction for TKN was only 8.65%. TP did not reduce during pretreatment process. TC and FC showed a reduction of about 82%. In general, pretreatment level of the raw wastewater was equivalent of that reported by Metcalf and Eddy (1991) and others.

**Applied hydraulic loadings rates.** In general, water consumption was negligible during the winder when wastewater did not applied and increased from the beginning of spring until late of summer as a result of plant increase, prevailing environmental conditions and increased ET rates (Figure 1). During the period of operation (from 6 June 2001 to 12 July 2002) significant differences were observed in water requirements among plants species used. Reeds displayed the highest water consumption, while the lowest values were observed for the poplar trees.

The total applied hydraulic load until 31 July 2002 was 1,103.5, 1,165.8, 1,060 and 1,265.3 mm for the eucalyptus, acacia, poplars, and reeds respectively.
Wastewater treatment efficiency. The reduction of COD in the SR rate system occurred mainly at the first 15 cm of the soil profile reaching the 91%, while only a slight reduction was detected from this depth until 60 cm (4%) (Figure 2a). In terms of nitrogen forms, TKN followed the general trend observed for COD displaying a high reduction at 15 cm, while a smaller decline was detected at higher depths (Figure 2b). NH$_3$-N although was highly reduced until 15 cm remained fairly constant after that depth (Figure 3a). Although NO$_3$-N were not observed during the pretreated process, they reached 31 mg/L at 15 cm depth and declined to 19 mg/L at 60 cm depth (Figure 3b). Moreover NO$_3$-N concentration in soil solution showed a tendency to increase with season progress (data not presented).

The concentration of TP in soil solution remained stable independently of soil depth and approximated 1 mg/L. The low volumes of soil solution taken from 15 cm due to rapid depletion of soil water at this depth did not allow the determination of TC and FC concentrations at that depth. However, TC and FC concentrations never exceeded 7 CFU/100 ml at 30 and 60 cm. No significant differences were found among plant species in wastewater treatment efficiency of the SR systems; although the significant different hydraulic loads applied. pH decreased from 7.52 at 15 cm to 7.12 at 60 cm soil depth,. An opposite trend was observed for EC. EC increased slightly with increasing soil depth. Also it significantly increased with season progress, reaching 3.1, 3.4, 3.7 dS/m at 15, 30, and 60 cm depths, respectively in June of 2002.

Plant growth and produced biomass. Owing to different patterns of growth among plant species used in this study, growth measurements were focused only on the trees. Poplar

Table 2 The composition of raw and pretreated wastewater and the efficiency of the pretreated method

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Raw wastewater</th>
<th>Pretreated wastewater</th>
<th>Removal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC (dS/m)</td>
<td>1.80</td>
<td>2.15</td>
<td>–</td>
</tr>
<tr>
<td>pH</td>
<td>7.84</td>
<td>7.30</td>
<td>–</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>837</td>
<td>487</td>
<td>41.8</td>
</tr>
<tr>
<td>BOD$_5$ (mg/L)</td>
<td>598</td>
<td>370</td>
<td>38.13</td>
</tr>
<tr>
<td>TKN (mg/L)</td>
<td>104</td>
<td>95</td>
<td>8.65</td>
</tr>
<tr>
<td>NH$_3$-N (mg/L)</td>
<td>45.71</td>
<td>82.73</td>
<td>–</td>
</tr>
<tr>
<td>NO$_3$-N (mg/L)</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>–</td>
</tr>
<tr>
<td>TP (mg/L)</td>
<td>5.69</td>
<td>6.82</td>
<td>–</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td>367.5</td>
<td>171.15</td>
<td>53.43</td>
</tr>
<tr>
<td>TC (CFU/100 ml)</td>
<td>103 x 10$^6$</td>
<td>17.1 x 10$^6$</td>
<td>83.4</td>
</tr>
<tr>
<td>FC (CFU/100 ml)</td>
<td>47.5 x 10$^6$</td>
<td>8.5 x 10$^6$</td>
<td>82.1</td>
</tr>
</tbody>
</table>
trees showed the greatest height (Table 3), while acacia trees the greatest trunk diameter (Table 2). However, the results obtained from growth measurements were not completely consistent with the produced biomass. The highest biomass was produced by acacia trees followed by reeds, while the lowest biomass was produced by eucalyptus and poplars (Table 4).

Table 3  Trees’ height and trunk diameter as affected by plant species during the operation period of 2001

<table>
<thead>
<tr>
<th>Plant species</th>
<th>01/03/2001</th>
<th>06/08/2001</th>
<th>06/10/2001</th>
<th>18/12/2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalyptus</td>
<td>1.22c</td>
<td>2.15c</td>
<td>2.53c</td>
<td>2.67c</td>
</tr>
<tr>
<td>Poplars</td>
<td>1.92a</td>
<td>2.80a</td>
<td>4.03a</td>
<td>4.23a</td>
</tr>
<tr>
<td>Acacia</td>
<td>1.57b</td>
<td>2.48b</td>
<td>3.01b</td>
<td>3.52b</td>
</tr>
<tr>
<td>Eucalyptus</td>
<td>1.17b</td>
<td>2.08b</td>
<td>3.44b</td>
<td>3.90b</td>
</tr>
<tr>
<td>Poplars</td>
<td>1.09b</td>
<td>2.12b</td>
<td>3.56b</td>
<td>3.86b</td>
</tr>
<tr>
<td>Acacia</td>
<td>1.43a</td>
<td>3.23a</td>
<td>4.49a</td>
<td>5.10a</td>
</tr>
</tbody>
</table>

Table 4  Dry weight of produced biomass by different plant species at the end of the 2001

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Trunk</th>
<th>Shoots</th>
<th>Leaves</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalyptus</td>
<td>2.05c</td>
<td>1.02bcd</td>
<td>1.44bcd</td>
<td>4.51b</td>
</tr>
<tr>
<td>Poplars</td>
<td>3.62bc</td>
<td>2.21b</td>
<td>0.17c</td>
<td>6.00b</td>
</tr>
<tr>
<td>Acacia</td>
<td>4.22ab</td>
<td>5.34a</td>
<td>4.35a</td>
<td>13.91a</td>
</tr>
<tr>
<td>Reeds</td>
<td>5.61a</td>
<td>0.44d</td>
<td>2.08b</td>
<td>8.13b</td>
</tr>
</tbody>
</table>
in which soil infiltration followed by subsequent biological reduction and oxidation in the vadose zone, indicated as the basic removal mechanisms of organic matter. Also, no decrease in COD, particularly for that corresponding to insoluble carbon (defined as any organic compound in the soil solution sized larger than 0.45 µm) was measured beyond 2.5 m depth in a loam soil under the application of primary treated wastewater (Angelakis and Rolston, 1985).

The decline in rates of organic matter degradation with increasing soil depth can be attributed to the prevalence of anoxic conditions in soil profile at that depth. In addition, organic load applied in the system was higher of that applied in other SR systems (George et al., 1986; Hosner, 1978); However, it was not appeared to be a limiting factor for the performance of the SR systems due to relatively low COD/TKN ratio (Reed and Crites, 1985; Crites et al., 2000).

Total Kjeldahl nitrogen, nitrates and ammonium nitrogen

TKN was reduced during the pretreatment process as result of sedimentation while anaerobic biodegradation of the organic N resulted an increase of NH₄-N concentration due to ammonification process. Removal rates between 70 to 94% of TKN in various SR systems have been reported (Crites and Tchobanoglous, 1988; Reed et al., 1995). These findings are consistent with those observed in this study. NH₄-N displayed a rapid reduction at the shallow soil profile (Figure 3a) that was followed by corresponding increase in NO₃-N (Figure 3b). This indicates that nitrification process was the dominant mechanism of NH₄-N reduction. In contrast, NO₃-N did not show a significant reduction with increasing soil depth. The negative charge of NO₃⁻ inhibit its absorption to mineral clays and favor leaching to higher depths. The increase in NO₃-N concentration of soil solution with the season progress indicates that applied nitrogen loads exceeded the removal capacity of the plant-soil system due to uptake and losses through denitrification process.

Total phosphorus

The major removal processes of TP during soil application of wastewater are adsorption, uptake from plants and chemical precipitation (Crites et al., 2000). TP in wastewater occurs mainly as orthophosphates which are readily absorbed by clay minerals of the soil matrix. Removal of TP in SR systems occurs rapidly at the first centimetres of the soil depth (Degens et al., 2000). The removal efficiency of TP in this study appeared to be lower than...
the recorded in other systems in which it was exceeded 90% (Crites and Tchobanoglous, 1998). However, this finding do not imply a reduced capacity of the system for the TP removal, but it could be due to pH values observed. Neutral pH values have been reported to favor the solubility of the phosphate compounds in the soil (Bouwer, 1985).

**Coliforms (FC and TC)**

In general, pathogen populations in the soil matrix reduced due to sunlight exposure, oxidation rates, desiccation, and antagonism with the soil microbial fauna (Reed and Crites, 1985). High efficiency of the SR system on TC removal (<7 CFU/100 ml at 60 cm) mainly due to rapid die-off, straining, entrapment, radiation, sedimentation and adsorption (Metcalf and Eddy, 1991). These results are consistent with previously reported findings in which a soil infiltration system in the vadose zone, after 28 weeks of operation, resulted in a depletion of FC at or bellow 10 CFU/100 ml at 60 and 90 cm of soil depths (van Couk et al., 2000). In this study, none FC detected in soil samples beyond 30 cm depth. These results are in agreement with the complete attenuation of pathogen measured in this study on 30 cm soil depth.

**Plant species and biomass production**

Plant species did not have any significant influence on the wastewater treatment performance of SR system; although the hydraulic loading rates differed among plant species. The lack of any effect on the organic load degradation can be justified by the fact that organic load applied did not exceed the capacity of SR systems (Reed et al., 1995). Furthermore, no differences were detected in the soil solution concentration of nutrients among various plant species, despite the diverse water use. Likely, the increased biomass production of plant species consumed the more water compensated for the applied higher nutrient loads. Plant species showed differences in the produced biomass as well as in the main components of it (wood and leaves), suggesting the application of criteria for selecting plant species according to intended use. These differences in the amount of biomass production will be probably differentiated by the time.

**Conclusion**

Based on this study, SR systems can be considered as:

(a) advanced treatment systems of primary treated wastewater effluent – very high reductions of COD, TKN, TP, TC and FC of 95%, 94%, 85%, 99.9%, and 99.9%, respectively, were measured;

(b) ideal technologies for small communities due its low cost for construction, operation, and maintenance, especially in the areas with low land cost;

(c) cost-effective technologies and environmentally sound.

**Acknowledgments**

This work was financed by EU Coretech project: ICA 3-CT 1999-00012. Authors are grateful to: students Mr. M.I. Geniatakis, Ms. E.G. Voumvoulaki, Ms. A.D. Perysinaki, and Mr. G.E. Kladakis, for their contribution in laboratory analysis of samples, and Mr. M. Titakis for his technical support in the field.

**References**


