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Waste Management

Use of Commercial Plant Species in a Hydroponic System to Treat Domestic Wastewaters

Nathalie Vaillant,* Fabien Monnet, Huguette Sallanon, Alain Coudret, and Adnane Hitmi

ABSTRACT

The objectives in this work were to investigate a conceptual layout for an inexpensive and simple system that would treat primary municipal wastewater to discharge standards. A commercial hydroponic system was adapted for this study and the wastewater was used to irrigate wooly digitalis (*Digitalis lanata* Ehrh.) and foxglove (*Digitalis purpurea* L.). These plants are medicinal and produce cardenolide compounds. Influent and effluent samples were collected once a month for six months and analyzed to determine the various parameters relating to water quality. The legal discharge levels for total suspended solids (SS), biochemical oxygen demand (BOD$_5$), and chemical oxygen demand (COD) were reached for the two tested plants after 48 h of wastewater treatment; the removal was 82, 93, and 79%, respectively, for wooly digitalis and 92, 92, and 84%, respectively, for foxglove. Similar results were obtained during a 6-mo period although the sewage composition varied widely. The system tended to be unable to remove N and P to concentrations below regulated levels. Compared with the nutrient solution composition, the wastewater was more concentrated in Na$^+$ and Cl$^-$ and less in N, K$^+$, and Ca^{2+}. These variations can lead to the decline of wooly digitalis plants. Foxglove developed a significant root system to increase mineral absorption wastewater being used as the unique nutritive source. After 10 wk all the wooly digitalis seedlings were dead. Despite this fact, however, the root system remained in place for a significant time ($<$4 mo), thus continuing to filter wastewater and to be used as a bacterial support thus making it possible to have a security period to replace the dead plants.

COLLECTION AND TREATMENT OF WASTEWATER in low population density areas is problematic. Decentralized sewage treatment is usually inevitable for economic reasons, but the currently available technologies for the wastewater treatment from single houses, dwellings, and small communities remain in many aspects unsatisfactory (Rababah and Ashbolt, 2000). The increase in wastewater production in rural areas leads to environment pollution. Nitrification–denitrification and phosphate precipitation are classical methods to fight against the eutrophication of aquatic ecosystems. These treatments are expensive and produce huge quantities of sludge that it will no longer be possible to spread in landfills after 2005 (European Directive 91/271/CEE of 21 May 1991).

There is an increasing need to develop low-cost and energy-saving wastewater treatment systems suited to rural areas. Recently, considerable attention has been directed toward wastewater treatment processes using wetlands consisting of bed filters usually planted with emergent plants due to low cost and ease of operation (Cooper, 1999). The use of constructed wetlands and reed bed treatment systems has gradually developed over the past 20 yr (Huang et al., 2000; Philippi et al., 1999). Compared with conventional wastewater treatment systems, they are relatively inexpensive to construct and maintain and can provide effective and reliable wastewater treatment (Hammer, 1989).

Domestic wastewater has constituents mainly derived from organic matter and contains most of the required nutrients for plant growth, generally in an appropriate ratio (Ayaz and Saygin, 1996). Duckweed (*Lemna* spp.) (Culley and Epps, 1973), water hyacinth [*Eichhornia crassipes* (Mart.) Solms] (Gopal, 1987), cattail (*Typha latifolia* L.) (Stark et al., 1996), and reed [*Phragmites australis* (Cav.) Trin. ex Steud. and *Carex* spp.] (Kadlec and Knight, 1996) are generally planted in wetlands. Studies conducted on the removal of total P and total N (Abe and Ozaki, 1998; Drizo et al., 2000; Fisher and Reddy, 2001) showed a very wide range of treatment effectiveness. These plants enhance biodiversity yet have no other uses for rural communities besides purification. Jewell (1994) has combined anaerobic treatment of primary sewage with a specialized hydroponic (water as a growth medium) secondary or tertiary treatment system that yields biomass.

The aim of this study is to investigate the possibility of using valuable commercial species such as wooly digitalis and foxglove in the treatment system of urban wastewater. These plants are perennial herbaceous Scrophulariaceae plants, and are of commercial importance as horticultural and pharmaceutical plants. These plants of great pharmaceutical importance as most of the cardenolide compounds (cardiac glycosides) used in the treatment of cardiac diseases (e.g., digoxin, lanatoside C, and acetyldigoxin) are still extracted from their leaves (Hoelz et al., 1992).

A raw effluent treatment has been developed using terrestrial species and the nutrient film technique

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Abbreviations: BOD$_5$, biochemical oxygen demand; COD, chemical oxygen demand; NFT, nutrient film technique; SS, suspended solids.

(NFT). We review some of our studies performed to evaluate and compare the survival and the effectiveness of wooly digitalis and foxglove plants for sewage purification.

MATERIALS AND METHODS

Laboratory Pilot Plants

The laboratory pilot plants consisted of PVC channels (4 m long, 0.15 m wide, and 0.10 m deep; Fig. 1). The purification system used the NFT soilless culture (Cooper, 1996) with permanent recirculation of 30 L of wastewater, regulated by an electric pump with a flow rate of 9 L min^{-1}.

Wooly digitalis and foxglove plants were developed initially in individual pots containing a 50:50 mixture of vermiculite and compost. After 90 d of culture, they were transferred to a hydroponic system. They were cultivated for 30 d in a hydroponic system with a nutrient solution. These plants presented an average shoot length of 20 cm. The plants grew bare-rooted in 3 cm of solution flowing by gravity. Five channels were used:

- a channel with 25 plants of wooly digitalis supplied with wastewater (Planted Channel I);
- a channel with 25 plants of foxglove supplied with wastewater (Planted Channel II);
- a channel with 25 plants of wooly digitalis supplied with nutrient solution (control plant channel; Lesaint and Coïc, 1983);
- a channel with 25 plants of foxglove supplied with nutrient solution (control plant channel; Lesaint and Coïc, 1983);
- a plant-free channel supplied with wastewater (unplanted channel) to reveal the role of plants.

These experiments were performed under a glass house at 25 ± 3 and 15 ± 3°C (day–night) and with a natural photoperiod.

The raw effluent was a combined stormwater–sewage wastewater, coming from a representative rural community of 980 people with no industry. The raw effluent was collected weekly and stored at 4°C during the whole experimentation period. Planted and unplanted channels were supplied with 30 L of collected raw effluent, renewed every 72 h. The experiment lasted 6 mo (July to December inclusive); this period includes three different seasons, thus affecting the qualities of wastewater. Wastewater quality was controlled once a month during a 72-h recirculation cycle: in July after 0, 12, 24, 48, and 72 h of treatment and August to December after 0 and 48 h of treatment.

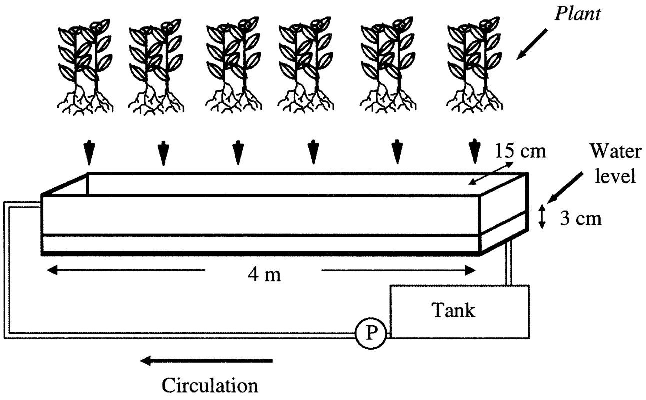

Fig. 1. Wastewater treatment system showing horizontal flow system with plants (wooly digitalis or foxglove) in the channel. The term P denotes the pump.

Growth Measurements

At the beginning and at the end of the experimentation, five plants per treatment were harvested and the fresh weights of shoot and root parts were determined. The dry weights were obtained by drying the plant for 72 h at 85°C. The growth rate is determined by the ratio of dry weight at the end of the experimentation to dry weight at the beginning of the experimentation.

Chlorophyll *a* Fluorescence Measurements

Chlorophyll *a* fluorescence was employed as an indicator of the physiological state of the plants. A wide range of laboratory studies have established that the chlorophyll *a* fluorescence parameter is a sensitive and early indicator of damage to photosynthesis and the plant physiology resulting from environmental stresses (Maxwell and Johnson, 2000). It provides information on the inhibition or damage occurring in the transfer of the electrons throughout Photosystem II and on photochemical quantum yield, and is a sensitive indicator of photoinhibition (Lichtenthaler, 1996). In addition, the measurement of chlorophyll *a* fluorescence is both nondestructive and noninvasive.

Fluorescence parameters were measured on intact leaves of 20 plants of wooly digitalis and foxglove with a pulse amplitude modulation–portable fluorescence monitoring system (PAM–FMS; Hansatech Instruments, Norfolk, UK). The measuring probe of the fluorimeter was placed in the adaxial side in the central part of the leaves. The parameters used to define the yield and quenching mechanisms of chlorophyll *a* fluorescence were those described previously (Genty et al., 1989): $\Delta F/F'_{\mathrm{m}}$, which is the quantum yield of electron flow throughout Photosystem II (ΦPSII), and $F_{\mathrm{v}}/F_{\mathrm{m}}$, the maximal photochemical efficiency of PSII measured in pre-darkened (for 30 min) leaves.

Chlorophyll Content

Total chlorophyll was extracted in an aliquot of 80% acetone and estimated as described by Lichtenthaler and Welburn (1983).

Measurement of Water Quality Parameters

The various samples necessary for the analysis of the physical, chemical, and biological parameters were determined using standard procedures. Five replicates were made for each measurement.

The pH was measured using a glass electrode with a WTW (Ft. Myers, FL) pH 320 pH meter and dissolved oxygen with a WTW OXI 320 portable oximeter. Total suspended solids (SS) were determined after filtration under vacuum, with 47-mm-diameter filters made of glass fiber (Durieux, France) and after drying to constant weight at 105°C. The chemical oxygen demand (COD) was measured and expressed in mg L^{-1}. The biochemical oxygen demand (BOD_5) was determined after 5 d in the dark in a thermostated incubator set at 20°C (LIEBHERRE, Germany) by measuring the oxygen concentration, expressed in mg L^{-1}. Total N concentration in wastewater was measured by spectrophotometric assay (Genesys 5; Thermo Spectronic, Madison, WI) after potassium peroxodisulfate digestion at 120°C, 45 min, and 100 000 Pa. Total P concentration in wastewater was measured by spectrophotometric assay using ascorbic acid and after potassium peroxodisulfate digestion at 120°C, 30 min, and 100 000 Pa.

The anionic and cationic composition was determined by capillary electrophoresis (P/ACE 5000 System Series; Beckman Coulter, Fullerton, CA) equipped with a diode array detector (DAD). The capillary was 60 cm long (54-cm effective length) with a 75-mm i.d. The capillary was thermostated at 25°C. Sample injections were made with pressure mode for 30 s at 3.45 kPa. The detection of NO_3^-, NO_2^-, PO_4^{2-}, SO_4^{2-}, and Cl^- was performed at 254 nm with a bandwidth of 1 nm and with a constant voltage of 20 kV. The carrier buffer was a chromate electrolyte solution of 4.7 m*M* sodium chromate (Fisher Scientific, Hampton, NH), 4 m*M* OFM-OH (Waters, Milford, MA), 10 m*M* CHES (Sigma, St. Louis, MO), and 0.1 m*M* calcium gluconate (Sigma) at pH 9 (Romano and Krol, 1993).

The detection of NH_4^+, K^+, Ca^{2+}, Na^+, and Mg^{2+} was performed at 214 nm and with a constant voltage of 25 kV. The electrolyte contained 65 m*M* 2-hydroxy isobutyric acid (Aldrich, St. Louis, MO), 50 m*M* 4-methyl benzyl amine (Fluka, Buchs, Switzerland), and 20 m*M* 18-crown-6-ether (Sigma).

Statistical Analysis

All data were analyzed using the Mann–Whitney test at the 0.05 probability level.

RESULTS AND DISCUSSION

Plant Behavior

Virtually every terrestrial plant appears to be capable of growing in some form of hydroponic system (Cooper, 1996). To evaluate plant survival, we used the growth rate, the shoot to root ratio, chlorophyll *a* fluorescence, and chlorophyll contents.

The chlorophyll *a* fluorescence of the seedlings of foxglove cultivated on wastewater was not significantly different from those of seedlings cultivated on the nutrient solution (Fig. 2). At the end of a 6-mo period, the chlorophyll contents in leaves of the foxglove plants growing on wastewater were identical to those of the control plants (Table 1).

Contrary to the control plants, wooly digitalis plants developed on wastewater show a decrease in chlorophyll *a* fluorescence after 10 wk of beginning of the experimentation. At the same time, leaf chlorosis appears (data not shown). After 15 wk, chlorophyll *a* fluorescence and chlorophyll content in leaves were nil, thus proving that the plants were highly stressed and probably dying.

Wooly digitalis and foxglove developed correctly when they were both irrigated with the nutrient solution. The irrigation with wastewater did not inhibited the total growth for foxglove, but the shoot to root ratio was modified in favor of the development of the root system (Table 1). The lack of nutritive elements led the plant to develop a more significant root system to increase mineral absorption. This comportment was particularly observed when the medium was low in nitrates (NO_3^-) and phosphates ($H_2PO_4^{2-}$), yet was less distinct with Ca^{2+} or SO_4^{2-} (Sattelmacher et al., 1990). When wastewater was used for irrigating wooly digitalis, plant growth was inhibited and the plants withered.

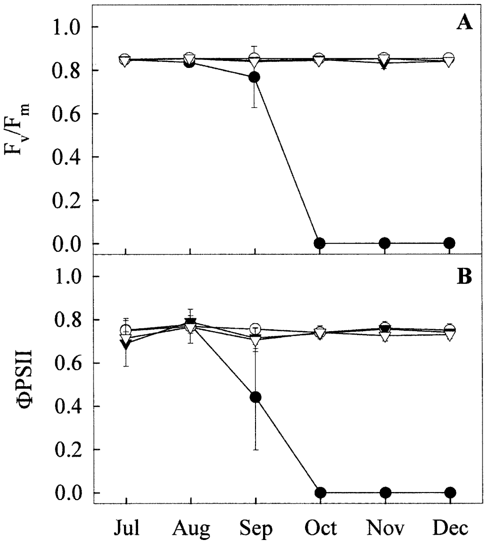

Fig. 2. Chlorophyll *a* fluorescence parameters: (A) ratio of variable (F_v) to maximum (F_m) fluorescence and (B) efficiency of quantum yield of electron flow throughout Photosystem II (ΦPSII) measured on leaves of wooly digitalis cultivated with wastewater (filled circles) and nutrient solution (open circles) and foxglove cultivated with wastewater (filled triangles) and nutrient solution (open triangles). Values are means ± standard deviations; *n* = 20.

Nitrate and ammonium are the major sources of inorganic nitrogen taken up by the roots of higher plants. The nutrient solution brought 196 mg L^{-1} of nitrogen ($NH_4^+ + NO_3^-$) whereas the wastewater only contained on average 36 mg L^{-1} of total nitrogen. Moreover, potassium concentration in the effluents varied from 14.9 mg L^{-1} to 39.1 mg L^{-1}. Whereas the potassium is the mineral nutrient required in the largest amount by plant after nitrogen (Table 2), K^+ was on average 13 times less concentrated in wastewater than in the nutrient solution and K deficiency can induce abnormal permeability, protein synthesis, and enzyme activation. Potassium deficiency can affect various aspects of photosynthesis, including CO_2 fixation (Marschner, 1998). In wastewater, Ca^{2+} was eight times less concentrated than in the nutrient solution (Table 2), which can result in signifi-

Table 1. Growth rate, shoot to root ratio, and chlorophyll contents after 6 mo of culture on wastewater or nutrient solution.

	Wooly digitalis		Foxglove	
Property	**Wastewater**	**Nutrient solution**	**Wastewater**	**Nutrient solution**
Growth rate†	**0.92 ± 0.17‡**	**9.53 ± 1.58**	**4.63 ± 0.57**	**6.52 ± 2.79**
Shoot to root dry weight ratio	**6.05 ± 1.52**	**9.32 ± 2.85**	**3.89 ± 0.28**	**6.64 ± 1.46**
Total chlorophyll, mg g^{-1} dry wt.	**0.04 ± 0.02**	**1.62 ± 0.17**	**1.97 ± 0.16**	**1.37 ± 0.12**
Chlorophyll *a*/*b*	**0.88 ± 0.17**	**2.21 ± 0.22**	**2.00 ± 0.29**	**2.19 ± 0.30**

† Ratio of dry weight at the end of the experimentation to dry weight at the beginning of the experimentation.

‡ Values are means ± standard deviations, *n* = 5.

Table 2. Ionic composition of nutrient solution and wastewater ($n = 25$).

	Nutrient solution	Wastewater		
Ion	Coïc Lessaint	Average	Minimum	Maximum
	mg L^{-1}			
NH_4^+	28	22.7	0	66.8
K^+	202.8	14.9	7.8	39.1
Ca^{2+}	128	15.7	10.3	23.8
Na^+	4.6	41.9	8.2	87.1
Mg^{2+}	18	7.6	3.0	11.9
NO_3^-	168	1.1	0	10.1
PO_4^{2-}	34.1	8.2	2.58	15.7
SO_4^{2-}	24	25.1	10.6	48.3
Cl^-	7.1	35.9	6.7	179.8

cant damage because Ca^{2+} is critical in many physiological processes (such as cellular division), it is a cofactor for some enzymes, and it plays a role in nitrate assimilation.

Salinity level in ground water of high population densities can exceed the allowed limits (Ayaz and Saygin, 1996). The Cl^- and Na^+ concentrations in treated wastewater by NFT system were five times and nine times higher, respectively, than in the standard nutrient solution. Sodium toxicity seems not as widespread as chloride toxicity and in many non-salt-tolerant species, high chloride levels cause growth inhibition and severe leaf chlorosis as well as depression in photosynthesis (Glenn et al., 1999).

Wastewater Purification

The NFT system with wooly digitalis and foxglove significantly reduced the total organic load. Compared with the plant-free channel, the process with plants was very effective in reducing SS, BOD_5, and COD parameters. Those parameters decreased exponentially (Fig. 3) and can be described by the following first-order kinetic model:

$$C(t) = C_1 \exp(-kt) + C_0$$

where $C(t)$ is the effluent concentration (mg L^{-1}) at time t, $C_1 + C_0$ is the initial influent concentration (mg L^{-1}), C_0 is the final influent concentration at infinite time (mg L^{-1}), k is the first order reaction rate constant (h^{-1}), and t is the treatment time (h).

After 24 h the system reached the legal discharge levels (Directive 91/271 of the European Union) and after 48 h its maximal efficiency was obtained. In the first month of operation, the purification of the planted channels with wooly digitalis and foxglove was identical.

The concentrations of SS, BOD_5, and COD observed after 48 h of treatment show that the system was stable for 6 mo (Fig. 4) although the sewage composition varied widely: SS ranged from 37 to 400 mg L^{-1}, BOD_5 from 33 to 1100 mg L^{-1}, and COD from 142 to 1650 mg L^{-1} (Table 3). The organic matter was not accumulating in the root systems because it was degraded regularly. The result is a constant wastewater level observed in the channel throughout experiment. From the fifteenth week of system operation, all the wooly digitalis plants were dead, but no difference was observed in the wastewater purification efficacy (Fig. 4).

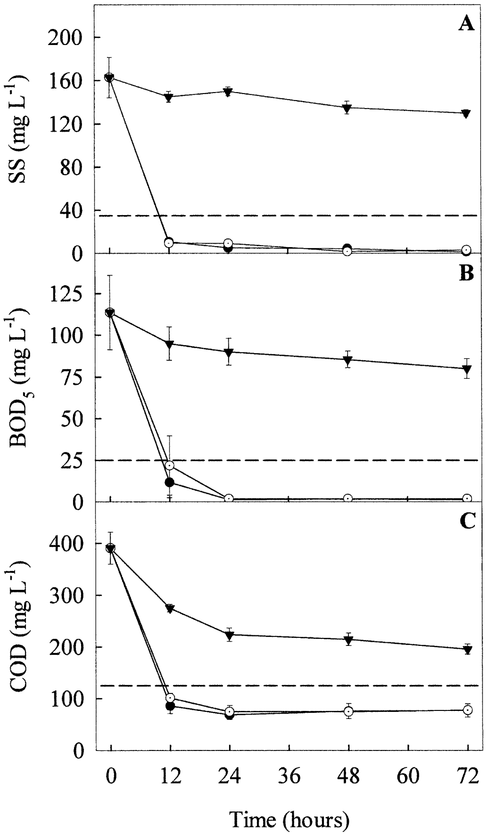

Fig. 3. Concentrations of (A) suspended solids (SS), (B) biochemical oxygen demand (BOD_5), and (C) chemical oxygen demand (COD) in the wastewater during 72 h of treatment in the planted channel with wooly digitalis (filled circles) and foxglove (open circles) and in the unplanted channel (filled triangles) in July 2000. The dashed line indicates the legal discharge level. Values are means ± standard deviations; $n = 5$.

In spite of the plant death, the dried aerial parts and the root systems remained in place in the NFT system for the duration of the experiment (<4 mo). Suspended solids and thus indirectly BOD_5 and COD were removed by filtration and adsorption; the solids trapped in the root systems were then decomposed and mineralized by bacteria. This makes it possible to have a safety period to replace the dead plants.

Total Phosphorus and Nitrogen

Figure 4D shows that when the wastewater has total P of >10 mg L^{-1}, the system removes one-third of the total P in 48 h. When wastewater is more diluted (water concentrations decreased significantly due to autumn rains) the depletion rate is less significant. The total P removal is not modified by plant mortality. An uptake of phosphorus occurs by sorption, complexation, precipitation, and assimilation into microbial and plant biomass (Tanner et al., 1999). The observed variation in depletion can be explained by the fact that phosphorus could be present in various forms that are not removed or assimilated in the same way by plants and bacteria. Total phosphorus consists of orthophosphates (PO_4^{3-}), acid-hydrolyzable phosphates, organic soluble phosphates, and particulate phosphorus. Acid-hydrolyzable

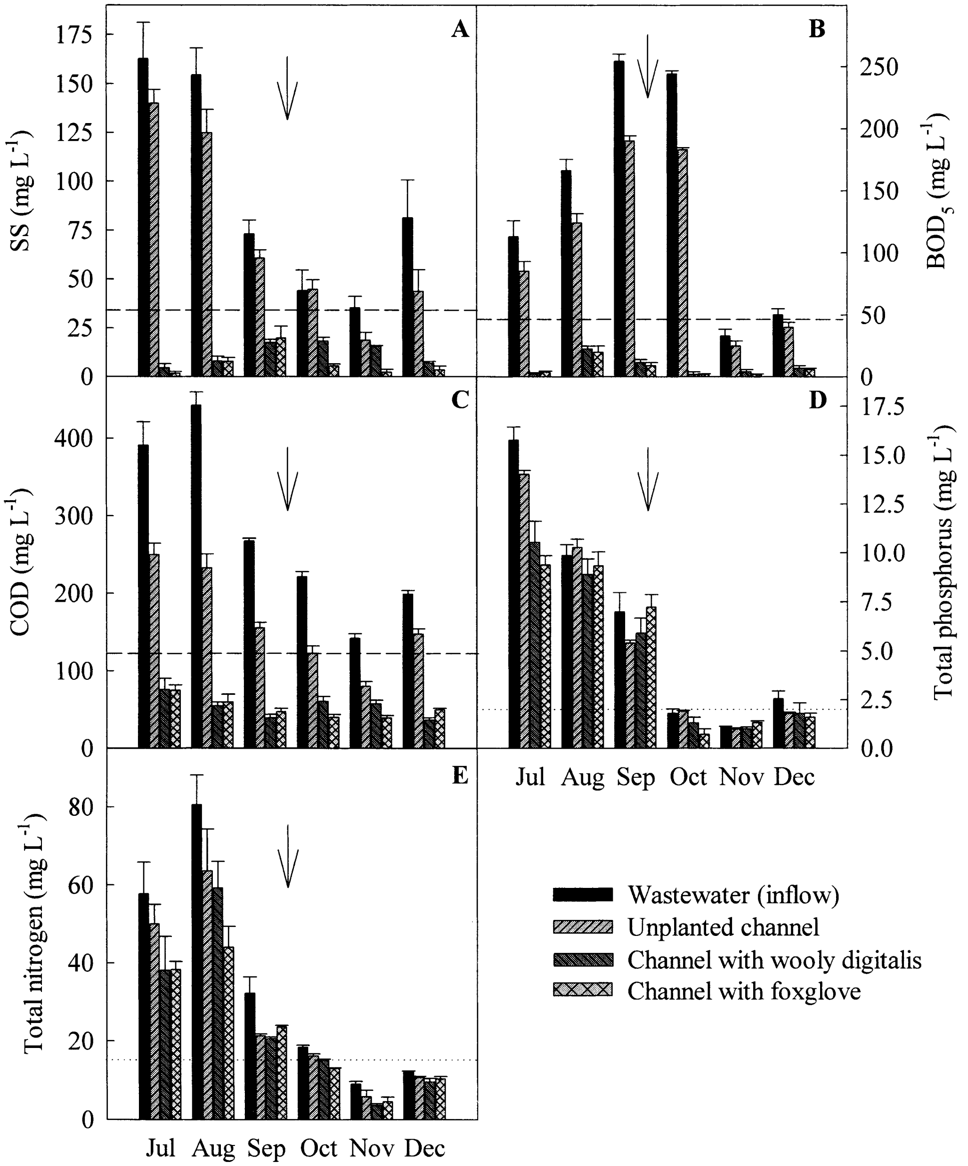

Fig. 4. Concentration of (A) suspended solids (SS), (B) biochemical oxygen demand (BOD_5), (C) chemical oxygen demand (COD), (D) total P, and (E) total nitrogen in the wastewater before the treatment and after 48 h of treatment in the planted channel with wooly digitalis and foxglove and in the unplanted channel (June–December 2000). The dashed lines indicate the legal discharge level and the dotted lines indicate the legal discharge level in eutrophically sensitive areas. Arrows represent wooly digitalis death. Values are means ± standard deviations; *n* = 5.

phosphates are negligible in sewage (Drizo et al., 2000). Organic phosphorus is converted by the bacterial activity into mineral phosphorus that can be assimilated by the plants. Particulate phosphorus is mainly removed by filtration or sorption in the root system.

Total nitrogen is composed of the nitrogen in ammonium (NH_4^+), oxidized forms ($NO_x = NO_2^- + NO_3^-$), and aggregate organic forms. The total nitrogen decreased more quickly in the presence of wooly digitalis or foxglove than in the unplanted channel (Fig. 4). Two major nitrogen removal mechanisms have been identified: microbial assimilation (Gersberg et al., 1986) and plant nitrogen uptake (Breen, 1990; Rogers et al., 1991). Initially, the wastewater had a high concentration of total N mainly composed of NH_4^+ with a very low content of NO_2^- and NO_3^-. Ammonium ranged widely from 0 to 67 mg L^{-1} in the influent (Table 2). After 48 h of treatment, the ammonium concentrations in the effluent were reduced by approximately 65% with wooly digitalis and 95% with foxglove, and were no longer measurable after 72 h processing with the two plants. The NH_4^+ removal was more significant with foxglove than wooly digitalis. The decrease was slower in the control channel: at 48 h, 60 ± 14% NH_4^+ was still present in the wastewater.

The NO_2^- concentration values remained very low with an average of 0.2 ± 0.2 mg L^{-1} and varied from 0 to 0.5 mg L^{-1}. The highest content was observed after 48 h of processing. Parallel to the NH_4^+ decrease we observed the appearance of NO_3^-. As indicated in Fig. 5, a significant proportion of the NH_4^+ removed from the wastewater was found to be converted by nitrifying bac-

Table 3. General design parameters including characteristics of the inlet (n = 20) and treatment goal discharge objectives (European Directive 91/271).

Property†	Wastewater Mean	Minimum	Maximum	Objectives
	mg L^{-1}			
SS	164	37	400	35
BOD$_5$	179	33	1100	25
COD	429	142	1650	125
Total N	41	13	100	15‡
Total P	9	3.8	15.7	2‡

† BOD$_5$, biochemical oxygen demand; COD, chemical oxygen demand; SS, suspended solids.

‡ Indicates the legal discharge level in eutrophically sensitive areas.

teria into NO_2^- and NO_3^-. With the plants, the removed NH_4^+ was mainly transformed into NO_2^- and NO_3^-. However, sometimes significant amounts of the NH_4^+ removed were not found as NO_2^- or NO_3^-. This quantity of NH_4^+, which seemed to have disappeared, was either reduced by other processes such as volatization and absorption by the plants, or by the combined nitrification–denitrification process, which eventually transforms the NO_2^- and NO_3^- into gaseous N_2 in anoxic regions (Flite et al., 2001). This processes seems also to be responsible for the removal of NH_4^+ in the control.

To study the mineralization and the oxidation of the nitrogen-containing products in the channels as affected by the presence and viability of plants, we examined the relation between BOD$_5$ and the NO_3–N and NO_2–N contents in wastewater. The nitrification process was affected by the BOD$_5$ level of the wastewater because of the competition for available oxygen between the nitrifying bacteria and the microorganisms removing BOD$_5$. Figure 6 illustrates the relationship between the NO_3–N and NO_2–N contents and the BOD$_5$ level of the effluents out of the wooly digitalis treatment, foxglove treatment, and control. Significant nitrification began to take place in the wastewater when the BOD$_5$ was reduced to less than 45 mg L^{-1} with the two plant species. In the unplanted system, NO_2^- and NO_3^- are not formed. Both are oxygen-demanding processes; nitrification proceeds much more slowly than the reaction for BOD$_5$ reduction. Therefore, under a high BOD$_5$ level most of the available oxygen transported into the root matrix is used for BOD$_5$ removal. This inhibits the establishment of a large population of nitrifying bacteria (Gray et al., 1996). Consequently, significant nitrification cannot occur until the end of the carbonaceous oxidation that removes BOD$_5$. As the BOD$_5$ drops to a low level, the available oxygen begins to be used by the nitrifying bacteria and noticeable nitrification then takes place.

After the plant death, no difference was observed in wastewater for the nitrification process; this is explained by the preservation of the root system, which still acts as a filter and support for microbial growth.

The conversion of ammonia to nitrite (ammonia oxi-

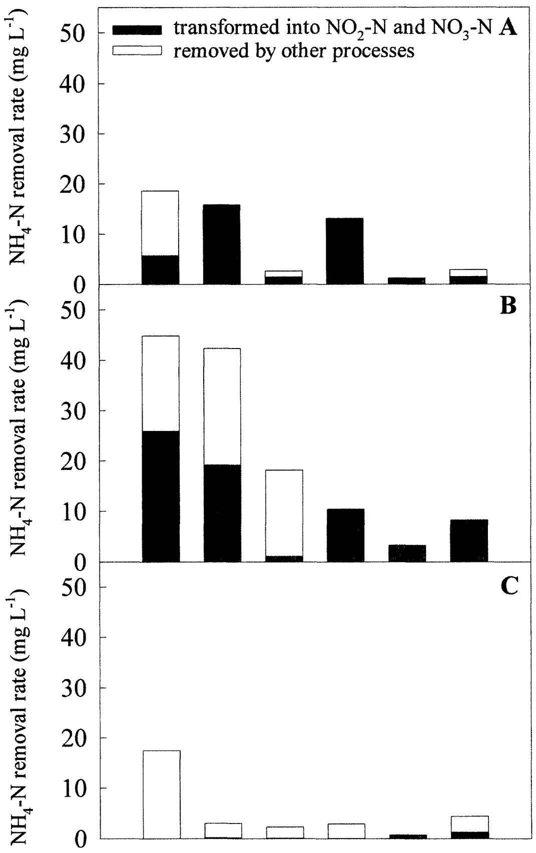

Fig. 5. Ammonium N removal rate in the wastewater after 48 h of treatment in the planted channel with (A) wooly digitalis and (B) foxglove and (C) in the unplanted channel.

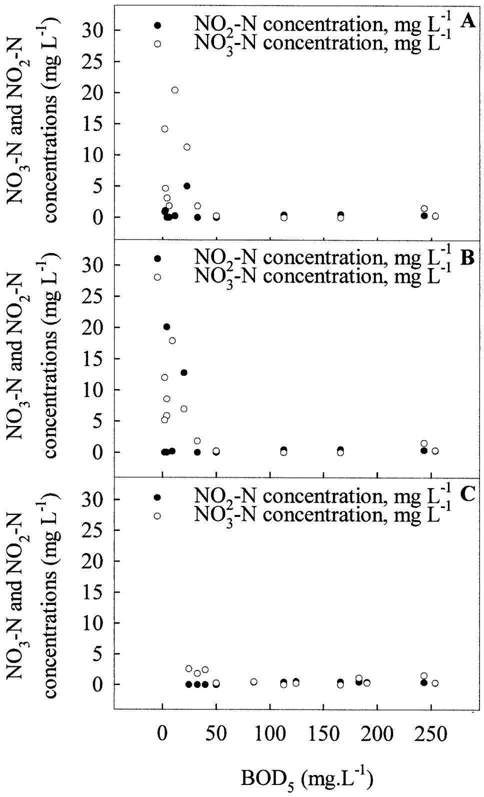

Fig. 6. Effect of biochemical oxygen demand (BOD$_5$) level on nitrification process in the planted system with (A) wooly digitalis and (B) foxglove and (C) with the unplanted system.

dation) and subsequent oxidation of nitrite to nitrate were more pronounced with the plant system. The removal of nitrogen is based on the nitrification–denitrification activity of root-associated bacteria (Farahbakhshazad and Morrison, 1997). The plant roots provide a large surface area for microbial growth (Gopal, 1999) and the system provides oxygen, which may stimulate the aerobic decomposition of organic matter and the growth of nitrifying bacteria. The dissolved oxygen determined in the inflow was generally 0.8 ± 0.2 mg L^{-1} (data not shown). The system of wastewater recirculation led to water oxygenation. Dissolved oxygen concentrations were approximately 6.5 ± 1 mg L^{-1} after 48 h with the two plants species. This value was 16% higher than in the control channel. In comparison, other studies have indicated a low efficiency of ammonium conversion to nitrite in wetland systems due to limited oxygen transfer capability (Kadlec, 1999).

In nitrogen removal, the pH is a significant parameter. Princic et al. (1998) have shown that the optimal pH range for NH_4^+ conversion to nitrite is between 5.8 and 8.5 and for the nitrification between 6.5 and 8.5. In wetlands, pH values were between 6 and 7 (Philippi et al., 1999; Martin et al., 1999). In our treatment system, the pH was constant and the values were between 7 and 8 (data not shown); hence the nitrification was active.

Removal of total phosphorus and total nitrogen is sufficient to allow the rejection of the effluent into the medium, but does not, however, reach standards permitting the discharge of water in eutrophically sensitive areas.

CONCLUSIONS

The system of wastewater purification with NFT using wooly digitalis and foxglove made it possible, as early as the first month of installation and throughout the following six months, to achieve after 48 h of processing the permitted levels for release in nature (as defined by the European Directive 21/05/1991). However, the depletion of total phosphorus and total nitrogen was not sufficient to allow release in eutrophically sensitive areas. During this period the root systems were not saturated and there was no sedimentation in the channel bottom.

The wastewater seemed to provide the necessary elements for foxglove growth and a normal photosynthetic activity. For wooly digitalis growth, wastewater is not appropriate, as it leads to the premature death of the plants. However, the root system remained in place for a significant period (<4 mo), thus continuing to filter wastewater; this makes it possible to have a safety period to replace the dead plants.

This study showed that all the plant species are not cultivable on wastewater. It will thus be necessary to carry out a selection of the vegetable species before using the purification system.

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