Biosystems Engineering (2005) **92** (4), 535–544
doi:10.1016/j.biosystemseng.2005.08.007
RD—Rural Development

Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER

Role of Macrophyte *Typha latifolia* in a Constructed Wetland for Wastewater Treatment and Assessment of Its Potential as a Biomass Fuel

M.P. Ciria[1]; M.L. Solano[2]; P. Soriano[2]

[1]Biomass Project, Renewable Energy Department CIEMAT-CEDER, Km 206 Carretera N-111 Madrid-Soria, 42290 Lubia, Soria, Spain; e-mail: pilar.ciria@ciemat.es
[2]Biomass Project, Renewable Energy Department, CIEMAT., Avda Complutense 22, 28040 Madrid, Spain; e-mail of corresponding author: ml.solano@ciemat.es

(Received 2 December 2004; accepted in revised form 17 August 2005; published online 10 October 2005)

In the last decade, constructed wetlands have been gaining in popularity as a reduced cost and low maintenance technology for treating wastewater from small urbanised areas. In these wetlands at the same time that pollutant removal from wastewater occurs, great quantities of biomass are produced. As according to some authors, plants must be harvested for the most effective removal of pollutants, large amount of biomass would be available for different uses. Although different solutions have been proposed (to transform it into compost or feed supplements for animals), the biomass potential for fuel production has been neglected. Therefore, the objectives of this work were focused to the study of the suitability of the macrophyte *Typha latifolia* produced in a wetland as a fuel. Main goals were: (1) to assess the role of the macrophyte, in the removal of biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), nitrogen, phosphorous and pathogens from raw municipal wastewater; and (2) to determine the thermochemical characterisation of the biomass produced in order to examine the suitability of the biomass as a fuel.

The constructed wetland consisted of two beds, of 40 m^2 each with gravel as the supporting medium. The hydraulic application rate was 50 mm day^{-1}. One of the beds was planted with cattail (*Typha latifolia*) and the other one was used as an unplanted control bed.

With regard to wastewater treatment efficacy, the results obtained agree with the important role of macrophytes for maintaining the wetlands treatment capability, particularly for systems with high organic matter and ammonia-N content.

Due to the high biomass yields obtained in the planted bed, and to the thermal behaviour of both cattail biomass and their ash, the utilisation of cattail biomass as fuel in thermochemical processes could be recommended.
© 2005 Silsoe Research Institute. All rights reserved
Published by Elsevier Ltd

1. Introduction

Conventional wastewater treatment plants involve large capital investments and operating costs, and for that reason these systems are not a good solution for small villages that cannot afford such expensive conventional treatment systems.

Constructed wetlands are gaining in importance as an effective alternative for the treatment of septic effluents in small villages. Compared with conventional treatment systems, wetlands: can be established in the same place where the wastewater is produced; can be maintained by relatively untrained personnel; have relatively low energy requirements; and are low cost systems.

In the wetlands, nutrient removal from wastewater occurs due to different mechanisms: (1) plant uptake; (2) microorganisms residing on the plant roots which transform nutrients (mainly N) into inorganic compounds (NH_4^+ and NO_3^-) which are directly available to plants; and (3) physical processes, such as sedimentation and filtration.

As a consequence of nutrient uptake, in planted wetlands large volumes of biomass are produced (Tanner, 1996; Billore *et al.*, 1999). Nevertheless, during

© 2005 Silsoe Research Institute. All rights reserved
Published by Elsevier Ltd

winter months, a translocation of nutrients from stems to rhizomes occurs, resulting in an increase of nutrient content in the water (Hill & Payton, 1998), moreover, according to Jing *et al.* (2001), the dead plants consume oxygen and therefore cause a negative chemical oxygen demand (COD) removal rate. For the most effective removal of pollutants, plants should be harvested at the end of each vegetative cycle, although Manios *et al.* (2002) suggested that machinery or workers in the wetland bed had a detrimental effect on the substrate hydraulic characteristics. Proper methods of biomass disposal and/or utilisation are required. Biomass can be transformed into raw material for the paper industry, fertilizers, compost or as a feed supplement for animals (Badcock *et al.*, 1983; Billore *et al.*, 1999; Stottmeister *et al.*, 2003); however, the potential for fuel production is neglected, in spite of the fact that aquatic plants provide a promising source of clean energy due to their high biomass yield and neutral CO_2 balance.

It is well known that the use of biomass as a fuel for energy production is restricted by the fact that, as a consequence of fertilisation, biomass contains a large amount of elements such as Ca, K, Mg, Na and Si with very reactive and problematic behaviour. Depending on temperature and redox conditions during the thermo-chemical processes, those elements can vaporise if they are in form of simple salts. Particularly, alkalis and alkali earth metals tend to react with silicon in the form of silica (SiO_2) and create low melting point silicates. These silicates deposit on the heat exchanger surfaces which reduces the efficiency of combustion (Davidsson *et al.*, 2002; Arvelakis *et al.*, 2005).

In the case of aquatic plants grown in wetlands, no information about their composition on alkaline elements is currently available. For this reason, studies on biomass composition and thermal behaviour are necessary in order to assess the suitability of the biomass as a fuel.

The objectives of this work were focused to the study of the suitability of the macrophyte *Typha latifolia* produced in a wetland as a fuel. Main goals were: (1) to assess the role of a macrophyte, cattail (*Typha latifolia*), in the removal of biochemical oxygen demand (BOD), COD total suspended solids (TSS), ammonia-N, nitrate-N, phosphorous and pathogens from raw municipal wastewater; and (2) to determine the chemical characterisation and thermal behaviour of the macrophyte biomass.

2. Materials and methods

2.1. *Description of the experimental site*

The artificial wetland was built near the Soria sewage treatment plant (latitude 41°47′N, longitude 2°30′W, mean sea level 1010 m), situated in the north-central part of Spain. The climate of the area is semi-arid Mediterranean with an average rainfall of 480 mm.The mean maximum and minimum temperatures during the experiment were 22 and 5 °C.

This constructed wetland consisted of two beds of 40 m^2 each and a length to width ratio of 10:1(see Table 1). The depth of each bed was 1 m and a 40 cm layer of 0·5–1 cm diameter gravel was utilised as the supporting medium. The hydraulic application rate (HAR) was 50 mm day^{-1}. The beds had regular shape and flat bottoms (Solano *et al.*, 2004). An impermeable plastic liner was placed at the bottom of each bed to prevent groundwater contamination. Each bed had a polyvinyl chloride (PVC) inlet pipe at its top, ending with a horizontal drainage pipe 1·5 m long and 50 mm in diameter. The influent into each bed was controlled manually every day by measuring the flow rate and adjusting the inlet valve to maintain a continuous daily flow rate. Two lengths of 50 mm slotted PVC tubes were inserted in each bed to allow sampling at two different positions. One of the beds was planted with cattail (*Typha latifolia*) and the other one was used as an unplanted control bed. The main characteristics and operation parameters of the wetland are shown in Table 1.

Municipal raw wastewater from the treatment plant was used as influent in each of the two beds. This wastewater was composed of domestic wastewater, urban runoff, and a small percentage (1·5–3%) is industrial wastewater, mainly from the food processing industry. The characteristics of raw wastewater utilised are shown in Table 2. Duplicated samples were collected monthly for a period of 2 yr. The influent was considered to be more polluted during the second year due a decrease in the rainfall (*Fig. 1*). The lowest COD, BOD or TSS values were found at the highest rainfall values, indicating a clear dilution effect.

2.2. *Sowing and biomass growing*

The most commonly used macrophyte in subsurface flow (SSF) wetlands is *Phragmites australis*. However, *Typha latifolia* was chosen because of the higher

Table 1
Main characteristics and operation parameters of wetland

Bed dimensions	20 m by 2 m
Bed depth	1 m
Gravel depth	0·40 m
Gross capacity	16 m^3
Net capacity	9·4 m^3
Hydraulic application rate (HAR)	50 mm day^{-1}
Loading rate	150 kg ha^{-1} day^{-1}
Retention time	4·7 day

biomass yields obtained in a previous study (Solano *et al.*, 2004).

Young cattail plants (*Typha latifolia*) were collected in the surrounding natural marshes at the end of April, and were transplanted on the same day in the planted bed. Each plant, composed of a piece of about 20 cm length rhizome and stem, was established in the bed at a density of three plants per square metre. After planting, both planted and unplanted beds were flooded with fresh water to about 10 cm above the gravel level, and the plants were allowed to establish themselves in fresh water. Two months later, raw wastewater replaced the fresh water as the influent to the beds.

Table 2
Composition of the raw wastewater utilised as wetland influent

Parameter mg l^{-1}	*1st year*	*2nd year*
BOD	340	485
COD	536	744
TSS	272	359
NH_4^+ -N	36	43
NO_3^- -N	16	22
NO_2^- -N	0·077	0·099
Phosphorous	23	29

Values in this table correspond to mean values of 12 samples BOD, biochemical oxygen demand; COD, chemical oxygen demand; TSS, total suspended solids.

These cattails exhibited a good survival rate, demonstrating a vigorous spread a few weeks after planting. No changes were noted after changing the influent. At the end of autumn the biomass was harvested and a new vegetative cycle began in the following spring. In the first week of March, plants began to sprout.

2.3. *Methodology*

Sampling and analysis began in June of the first year, 2 months after the establishment, and continued until the end of November in the second year, so influent and effluent samples were collected from each bed once a month over an 18 month period. Samples were analysed to determine the reduction in concentrations of BOD, COD, TSS, ammonia-N (N-NH_4^+), nitrate-N (N-NO_3^-) and phosphorous. In addition, total and faecal coliforms and faecal streptococci were determined by multiple tube fermentation. All water samples were analysed in accordance with the Standard Methods for Examination of Water and Wastewater (APHA, 1989). In the case of BOD determination, the incubation period was 5 days. Ammonia-N and nitrate-N were determined using Bremner's steam distillation extraction method (Bremner, 1982). All the analyses were completed within 24 h of sample collection.

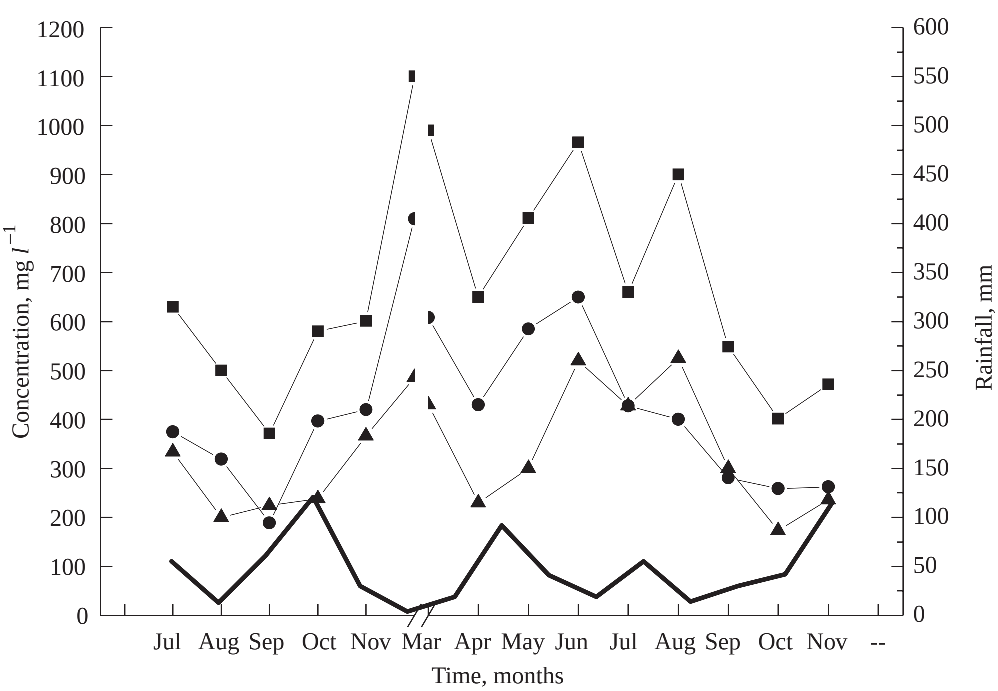

Fig. 1. Fluctations of chemical oxygen demand (COD), biochemical oxygen demand (BOD), and total suspended solids (TSS) concentrations in the influent during the 18 months of wetland operation in comparison to the monthly mean rainfall. COD; BOD; TSS; Rainfall

Treatment efficiency was calculated as the per cent removal R for each parameter and was calculated by

$$R = (1 - C_e/C_i)100 \tag{1}$$

where C_i and C_e are the influent and effluent concentrations in mg l^{-1}.

The harvesting of biomass in the planted bed was performed by hand at the end of autumn. Eight 0·25 m^2 samples were randomly harvested at the ground level. The wet biomass was weighed and dried at 105 °C for 24 h following standards, E 871-82. (ASTM, 1998). The ratio of wet/dry weight was then determined and it was used to determine total dry matter production.

At the completion of all two-time periods, a statistical analysis consisting of a multi-factor analysis of variance (MANOVA) was performed on the entire data set to determine if significant differences exist between the bed planted with cattail and the unplanted bed. The statistical analysis was performed using STATGRAPHICS *Plus* Version 4.0.

Biomass characterisation was carried out in accordance with the following standards.

Ash content

The sample (30–40 g) was burnt at 550 °C following the norm ASTM D-1102-84 'Test method of ash in wood' (ASTM, 1995).

Heating value

The sample (about 1 g) was burnt in a calorimeter Leco AC-300, to determine the gross calorific value (HHV) (norm ASTM E 711-87 'Gross calorific value of refuse derived fuel by calorimeter') (ASTM, 1996). Low heating value (LHV) was calculated from HHV and hydrogen content.

Chlorine

Chlorine was determined in the biomass sample following the norm ASTM D-2361-02 'Test for chlorine in coal' (ASTM, 2002) by means of dry ashing at 775 °C of the biomass sample and Eschka mixing.

Minor and trace elements

The elements Si, Ca, Mg, K, Na, Al, Fe, P and S, were determined by an inductively coupled plasma emission spectrometry after the microwave digestion of the biomass sample.

2.4. *Thermal analysis*

Thermal analysis was attained using a Seiko 6300 Instrument. This balance has two platinum sample pan supports to which thermocouples are attached in contrast to most of the thermogravimetric balances where thermocouples are slightly away from the sample. This kind of sample and thermocouple assembly provides simultaneous thermogravimetric (TG) and differential thermal analysis (DTA) data and minimises the error caused due to any difference in the actual sample surface temperature and the one that is being measured.

To obtain the burning profiles, the content of combustible part–volatile matter and fixed carbon-was taken into account. For volatile release profiles, the volatile matter alone was considered. Consequently the derivative thermogravimetric (DTG) curves are normalised and peak heights are directly comparable.

Samples were placed in a platinum sample pan and heated from room temperature (about 25 °C) to 1200 °C at 10 °C min^{-1} using a 50 ml min^{-1} flow of air or N_2. The performance of the system was regularly checked by measuring the three decomposition steps for calcium oxalate monohydrate.

Continuous on-line records of weight loss and temperature were obtained to plot the TG curve, the derivative thermogravimetric analysis (DTG) curve, and the DTA curve.

3. Results and discussion

3.1. *Wastewater treatment efficacy*

Results from the 2 yr of constructed wetland operation showed high levels of BOD, COD and TSS removal both in planted and unplanted beds (Table 3). For these parameters, no significant differences between the 2 yr of wetland operation were found, in spite of the differences between the influents (Table 2).

Biological oxygen demand (BOD) removal in wetlands is due to physical and biological processes that involve sedimentation and microbial degradation, principally by aerobic bacteria attached to plant roots. With respect to this parameter, the performance of the planted bed was higher than that of the unplanted control. This is in agreement with different authors (Ansolla *et al.*, 1995; Tanner *et al.*, 1995; Brix, 1997; Naylor *et al.*, 2003). These authors have presented data from gravel-based subsurface-flow systems in which planted beds performed better than similar unplanted beds, at least as far as organic pollutant removal was concerned. Macrophytes, by providing a suitable habitat for many decomposing microorganisms in the rhizosphere, play an indirect but important role in reducing organic matter from various types of wastewater.

However, with respect to COD, the analysis of variance (ANOVA) showed that the removal percentages for this parameter were not significantly different in the planted and unplanted beds. Therefore, and according to Manios *et al.* (2003), it can be said that the presence of a macrophyte like cattails did not lead

Table 3
Biochemical oxygen demand (BOD), chemical oxygen demand (COD) and total suspended solids (TSS) removals during the two years of wetland operation

	Removal, %					
	1st year			*2nd year*		
	BOD	*COD*	*TSS*	*BOD*	*COD*	*TSS*
Cattail bed	97 ± 1·2	79 ± 0·3	92 ± 4·2	97 ± 3·0	81 ± 1·0	92 ± 1·3
Unplanted bed	86 ± 0·5	75 ± 1·3	93 ± 3·0	83 ± 2·7	79 ± 2·1	91 ± 2·8

Mean values ± standard deviation.

Table 4
Percentages of removal of ammonium nitrogen (NH4-N), nitrate nitrogen (NO3-N) and P-phosphate during the 2 years of wetland operation

Year	*Season*	*NH_4-N removal, %*		*NO_3-N removal, %*		*Phosphorous removal, %*	
		Cattail bed	*Unplanted bed*	*Cattail bed*	*Unplanted bed*	*Cattail bed*	*Unplanted bed*
1st year	Summer	19 ± 1·1	10 ± 3·1	63 ± 2·1	76 ± 1·1	39 ± 5·1	31 ± 0·5
	Autumn	22 ± 0·8	6 ± 2·8	64 ± 0·9	78 ± 2·0	33 ± 0·9	34 ± 1·1
	Winter	20 ± 1·0	7 ± 0·9	60 ± 1·7	74 ± 0·8	36 ± 2·0	30 ± 0·8
2nd year	Spring	30 ± 6·0	13 ± 1·0	70 ± 0·9	84 ± 1·6	−34 ± 2·8	−28 ± 2·1
	Summer	40 ± 3·5	11 ± 3·4	73 ± 1·1	80 ± 0·9	11 ± 0·2	8 ± 3·3
	Autumn	35 ± 3·0	17 ± 3·0	69 ± 1·0	82 ± 1·1	12 ± 1·0	−4 ± 2·8
	Winter	38 ± 4·1	13 ± 0·9	75 ± 2·1	82 ± 0·8	−40 ± 3·7	−30 ± 7·0

to an increase in wetland performance in terms of COD reduction. This means that the removal in this parameter was mainly due to physical processes (sedimentation and filtration) rather than biological processes.

In the case of total suspended solids (TSS), the percentage of removal for the cattail bed was not significantly different from the unplanted bed. This indicates that, as in the case of COD, the removal of TSS is almost entirely due to physical processes rather than biological processes associated with the microbial community or with the plants. This is in accordance with Lee *et al*. (2004).

In contrast with the results obtained by Stober *et al.* (1997), Mandi *et al*. (1998) and Jing *et al*. (2001), but in agreement with Hill and Payton (1998) and Manios *et al*. (2000), the wetland performance did not seem to be affected by weather changes throughout the different seasons of the year. According to Armstrong and Beckett (1992), this could be due to the fact that oxygen transport takes place during winter when the p lants are dead by a ‘venturi’ mechanism through the open-ended (cut or broken) culms. This finding suggest that the microorganisms which are in the plant roots are playing an important part in the process.

With respect to nitrogen, its removal in a wetland system is dependent on a combination of the settlement of particulate matter, its uptake into plants and bacterial biomass, and bacterial nitrification and denitrification.

Several studies (Brix, 1987) have indicated that the rate of nitrification is the limiting factor controlling nitrogen removal *via* the nitrification and denitrification processes. Nitrifying bacteria, which are slow growing and have a high oxygen requirement, develop in the aerobic zones and convert ammonium to nitrate. As water flows into the anaerobic zone, the denitrifying bacteria convert nitrate to nitrogen gas.

As can be seen in Table 4, removals of both ammonia-N and nitrate-N were often low. According to Hammer and Knight (1994) and Gray *et al*. (2000), a poor removal of nitrogen is attributed to nitrification being limited by low oxygen and high carbon concentrations derived from the influent sewage (Table 2). This could be due to the fact that, available oxygen, in wastewater with a high BOD and nitrogen content, is quickly utilized by heterotrophic bacteria for the metabolism of organic carbon. On the other hand, Green *et al*. (1996) and Ibekwe *et al*. (2003) think that low removal efficiencies may be attributable to the high nitrogen levels presented in the influents (Table 2).

With respect to ammonia-N, the apparent low percentage removal obtained actually represents a much higher percentage removal when incoming NH_4 from breakdown of organic N (BOD) is considered. According to Drizo *et al.* (2000) but in contrast with results recorded by Manios *et al.* (2002), significantly higher ammonia-N removals were observed in the cattail bed (Table 4). This could be due to the important role of aquatic plants in translocating oxygen from the upper parts of the plants to the ends of the roots, which facilitates the nitrification of ammonia into nitrate. However, some authors (Jin *et al.*, 2002) have pointed out plant uptake as the main responsible factor for ammonia-N removal.

On the other hand, the low removal rates obtained in the unplanted bed could suggest that the nitrification/denitrification processes may have been limited by inadequate microbial activity in an unplanted mineral medium.

In relation to nitrate-N, as can be seen in Table 4, significantly lower removal rates were obtained in planted beds. This behaviour could be due to the fact that, in the cattail bed, plants are supplying oxygen to the gravel medium thereby decreasing the anaerobic conditions which are necessary for dentrification processes.

Concerning phosphorous, according to several authors (Billore *et al.*, 1999), there are different processes by which phosphorous compounds may be removed from wastewater: adsorption, ionic exchange, plant uptake and absorption. Some authors (Mann & Bavor, 1993) have reported that substrate is the main sink for phosphorous in the long term. Moreover, they have demonstrated that the use of gravel materials as substrates in wetland systems increased the removal of phosphorous. However, in our case, lower removal efficiencies were obtained (Table 4). These low efficiencies, according to Ibekwe *et al.* (2003) may be attributable to the high phosphorus levels in the influents to the wetland (Table 2).

The results obtained during the first year of wetland operation showed that there were not significant differences between the cattail bed and the unplanted bed (Table 4). According to Green *et al.* (1996), it could be in accordance with the fact that phosphorous removal in wetlands is governed mainly by adsorption or by precipitation and complexation reactions in the gravel.

However, during the second year of operation, the results obtained showed lower phosphorous removal rates. An increase of phosphorous in the wastewater was observed during the winter and early spring months in both of the beds. According to Green *et al.* (1996) and Schonerklee *et al.* (1996), this could be a result of a saturation of the sorption capacity of the gravel.

Phosphorous reductions display complex seasonal variations that imply that the least efficient phosphorous removal occurs in winter and the most efficient reduction occurs in summer. The removal variations observed might be explained by the fact that phosphorous could be presented in various forms (ortophosphates, acid-hydrolysable phosphates, organic soluble phosphates and particulate phosphorous), that are not removed or assimilated in the same way by plants and bacteria (Vaillant *et al.*, 2003).

With respect to bacteriological analysis, the removal efficiency of total coliforms (TC), faecal coliforms (FC) and faecal streptococci (FS) varied within a very wide range, from 97 to 73%. Mean percentages of removal for each of the measured parameters (TC, FC and FS) are shown in Table 5. As can be seen in this table, in the case of total and faecal coliforms, and in agreement with Soto *et al.* (1999), the best removal efficiencies were found in the cattail bed. However, no significant differences between the planted and the unplanted beds were observed in the removal of faecal streptococci.

With regard to wastewater treatment efficacy, the results obtained agree with the important role of aquatic plants for maintaining the wetland's treatment capability, particularly for systems high in organic matter and ammonia-N.

Nevertheless, as has been mentioned above, for a constructed wetland to be effective in the removal of pollutants, biomass harvesting should be performed (Hill & Payton, 1998). According to this and taking into account the high biomass yields obtained in the cattail

Table 5
Percentages of removal of total and faecal coliforms, and faecal streptococci, during the 2 years of wetland operation

Year	*Total coliforms removal, %*		*Faecal coliforms removal, %*		*Faecal streptococci removal, %*	
	Cattail bed	*Unplanted bed*	*Cattail bed*	*Unplanted bed*	*Cattail bed*	*Unplanted bed*
1st year	92±9·5	79±9·3	97±7·8	88±8·0	80±6·0	73±7·1
2nd year	95±8·2	83±8·1	93±3·2	77±4·7	81±2·9	78±3·8

Mean values±standard deviation.

bed ($2{\cdot}8\,kg\,m^{-2}$ of dry matter, which is equivalent to $28\,t\,ha^{-1}$ of dry matter), cattail biomass utilisation was proposed. Due to the fact that the cattail biomass presented a relatively high heating value ($19{\cdot}6\,MJ\,kg^{-1}$), its use in thermochemical conversion processes for the production of heat and/or electricity has been suggested.

3.2. *Thermal behaviour and chemical composition of cattail biomass*

Biomass usually contains large amounts of alkaline elements that may cause considerable maintenance problems during thermochemical conversion processes. As has already been mentioned, alkaline elements released during combustion are involved in low melting point salt deposition on the heat exchanger surfaces; this reduces the efficiency of combustion processes. For that reason, studies carried out on biomass thermal behaviour and chemical composition were necessary in order to investigate the possible utilisation of this aquatic biomass as a fuel.

With respect to its thermal behaviour, burning profile TG/DTA curves were obtained (*Fig. 2*). As can be seen in this figure, the TG curve showed that there were three combustion steps: the first, around 100 °C, due to water evaporation, the second (100–312 °C) and the third (312–430 °C) due to the combustion processes. Similarly, the DTA curve showed two exothermic processes with peaks clearly defined at 296 and 422 °C; these correspond to the maximum levels of separation for volatile substances and char, which occurs during the combustion steps. According to that burning profile and taking into account a method described by Ghetti *et al.* (1996), reactivities of $8{\cdot}8\,mg$ and $5\,mg\,min^{-1}\,K^{-1}$ for the second and third combustion steps were obtained. These reactivities which were higher than those reported for other kind of biomass (Ghetti *et al.*, 1996) and along with the high heating value mentioned above, support the use of this cattail biomass as a fuel.

Tables 6 and 7 present the main chemical and energy characteristics of both the cattail biomass and its ashes. A statistical analysis (ANOVA) which was performed on the entire data set showed that there were no significant differences between the two vegetative cycles. For this reason, only mean values for the two cycles are shown in Tables 6 and 7. As can be seen in Table 6, the cattail biomass presented a high ash content perhaps due to the fact that this emergent aquatic plant has taken up a great quantity of nutrients from the wastewater.

Table 7 shows the analysed elements recalculated from their corresponding oxides. As can be observed in this table, ashes from cattails presented high calcium, potassium and sodium concentrations in comparison with coal ashes (Zevenhoven-Onderwater *et al.*, 2000). Besides, cattail also presented a higher chlorine content (Table 6) than fossil fuels. The high ash content, in addition to the high chlorine, sodium and potassium contents of this ash (Table 7) could cause sintering

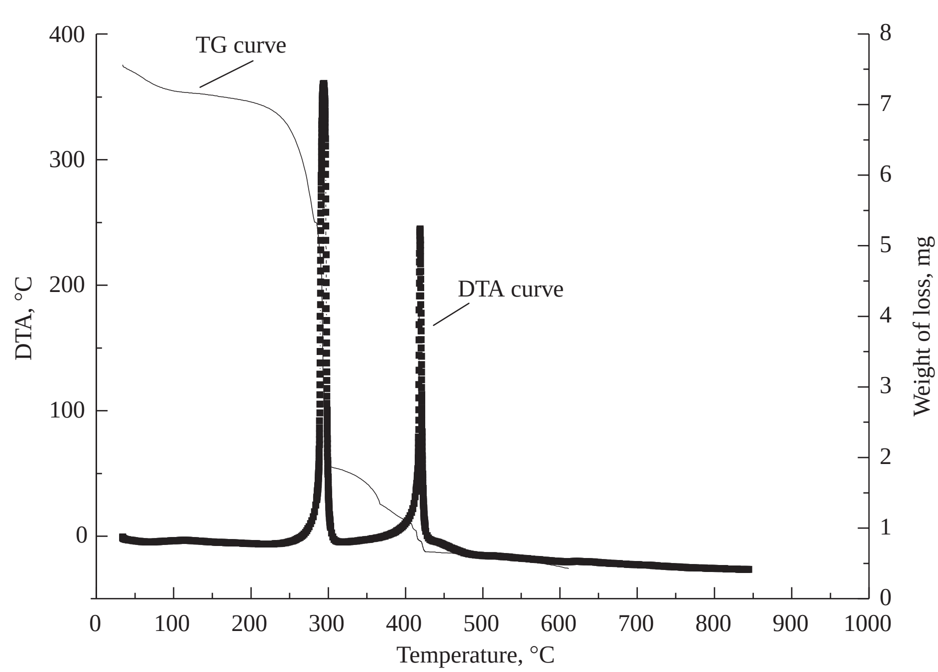

Fig. 2. Thermogravimetric/differential thermal analysis (TG/DTA) curves for cattail biomass in air atmosphere

problems in combustors. Compounds such as KCl and NaCl, can condense on heat exchanger surfaces, and oxides such as K_2O or Na_2O, at high temperatures, can result in the formation of eutectics which melt at low temperatures.

Table 6
Main characteristics of the cattail biomass

Characteristics	*Cattail biomass*
Moisture content, %	85·7±9·7
Lower heating value, MJ/kg	19·63±0·32
Proximate analysis, %	
Volatile matter	71·9±0·9
Fixed carbon	18·0±0·5
Ash	10·2±1·3
Ultimate analysis, %	
C	43·45±0
H	5·98±0·09
O	30·89±3·70
N	2·49±0·38
S	0·52±0·19
Cl	3·31±0·55

Table 7
Ash analysis of cattail biomass expressed as % by weight- of their oxides

	Cattail ash	*Coal ash**
CaO, %	24·5±0·5	4·7
Fe_2O_3, %	0·39±0	8·5
K_2O, %	19·4±0·4	0·7
MgO, %	2·54±0	2·0
Na_2O, %	8·8±0·1	0.7
P_2O_5, %	8·73±0·05	2·38

*Fuel 2000, 79:1353–1361.

In order to verify if the high chlorine, potassium and sodium contents of cattail ash could produce sintering, slagging and fouling in the thermoconversion processes, a DTA analysis of the ash was carried out.

As shown in the DTA curve in *Fig. 3*, no low melting temperature eutectic was produced at elevated temperatures (950–1200 °C). The first endothermic peak at 654 °C was attributed to the decomposition of $Ca(OH)_2$. The DTA endothermic peak at 950 °C proved the presence of $CaCO_3$, and the release of CO_2. These endothermic peaks were in accordance with the two steps observed in the corresponding TG curve. As can be seen in *Fig. 3*, the DTA curve did not show any more peaks above 950 °C, so there was no formation of low melting temperature eutectics, at least in the tested temperature range. Therefore, in spite of the high potassium, sodium and chlorine contents, deposit formation was not observed. So, according to that, the utilisation of cattail biomass as fuel in thermochemical processes could be recommended.

4. Conclusions

The main conclusions that can be drawn from this study are regarding the wastewater treatment efficacy

(1) The presence of macrophytes lead to an increase in wetland performance in terms of biological oxygen demand (BOD), ammonia-N and pathogen bacteria reduction.
(2) The removal of total suspended solids (TSS) in the planted bed was not significantly different from the removal in the unplanted bed. This indicates that

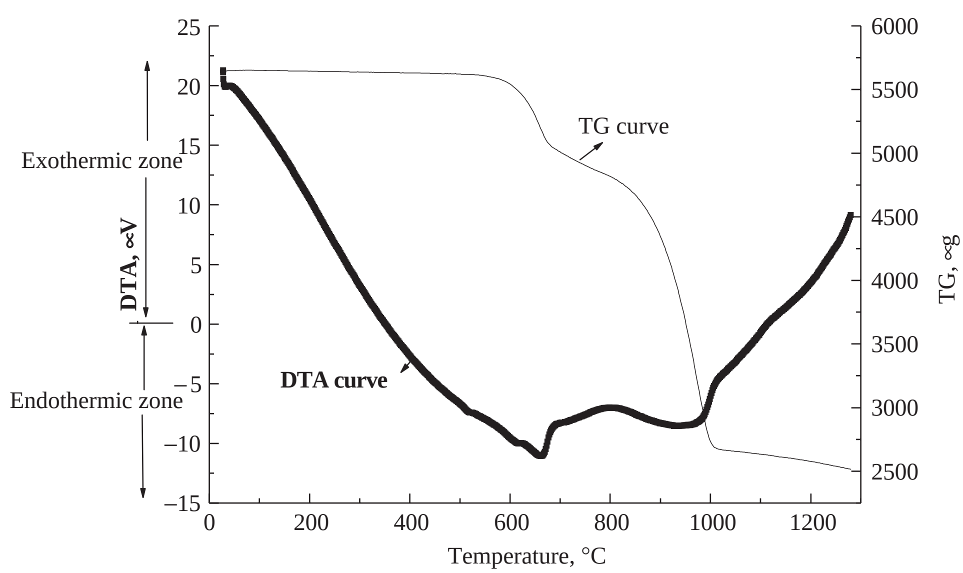

Fig. 3. Thermogravimetric/differential thermal analysis (TG/DTA) curves for cattail ash in air atmosphere

TSS removal is almost entirely due to physical processes rather than biological processes associated with the microbial community or with the plants

(3) The nitrate was similarly removed in both planted and unplanted bed suggesting that denitrification is the dominant mechanism of nitrate loss and that it can occur without the presence of macrophytes.

(4) No seasonal differences were observed in pollutants removal except in the case of phosphorous, which was more efficiently removed in summer.

With respect to the macrophyte biomass use as a fuel results demonstrate that cattail (*Typha latifolia*) is an adequate raw material to be used as fuel in thermochemical processes.

To sum up, results of this study point out that constructed wetlands with macrophytes can be a solution for small villages that cannot afford a conventional wastewater treatment. Wetlands would carry out the wastewater treatment and at the same time, the harvested biomass could be utilised as a fuel in domestic boilers for heating some of the village buildings in substitution for conventional fossil fuels.

Acknowledgements

This study is partially supported by the EU (Project reference IC 18-CT97-0163). We also express our thanks to ONDAGUA S.A. (Group IBERDROLA) for its valuable collaboration.

References

Ansolla G; Fernández C; de Luis E (1995). Removal of organic matter and nutrients from urban wastewater by using an experimental emergent aquatic macrophyte system. Ecological Engineering, **5,** 13–19

APHA (1989). In: Standard Methods for the Examination of Water and Wastewater (Clesceri L S; Greenberg A F; Trussell R R, eds). American Public Health Association, Washington DC

Armstrong W; Beckett P M (1992). *Phragmites australis*: Venturi- and humidity-induced pressure flows enhance rhizome aeration and rhizosphere oxidation. New Phytologist, **120,** 197–207

Arvelakis S; Gehrmann H; Beckmann M; Koukios E G (2005). Preliminary results on the ash behavior of peach stones during fluidised bed gasification: evaluation of fractionation and leaching as pre-treatments. Biomass & Bioenergy, **28,** 331–338

ASTM D1102-84 (1995). Standard Method for Ash in Wood. Vol. 04.10. American Society of Testing Materials, Philadelphia

ASTM E711-87 (1996). Standard Test Method for Gross Calorific Value of Refuse-Derived Fuel by Bomb Calorimeter. Vol. 11.04. American Society of Testing Materials, Philadelphia

ASTM E871-82 (1998). Standard Method of Moisture Analysis of Particulate Wood Fuels. Vol. 11.05. American Society of Testing Materials, Philadelphia

ASTM D2361-02 (2002). Standard Test Method for Chlorine in Coal. Vol. 05.06. American Society of Testing Materials, Philadelphia

Badcock M F; Evans D W; Alberts J J (1983). Comparative uptake and translocation of trace elements from coal ash by *Typha latifolia*. The Science of the Total Environment, **28,** 203–214

Billore S K; Singh N; Sharma J K; Nelson R M (1999). Horizontal subsurface flow gravel bed constructed wetland with *Phragmites karka* in central India. Water Science and Technology, **40**(3), 163–171

Bremner J M (1982). Inorganic forms of soil nitrogen. In: Methods of Soil Analysis. Part 2. Chemical and Microbiology Properties. American Society of Agronomy (Black C A; Evans D E; White J L; Ensminger L E; Clark F E, eds), pp 1179–1237. Madison, Wisconsin

Brix H (1987). Treatment of wastewater in the rhizosphere of wetland plants: the root-zone method. Water Science and Technology, **19,** 107–118

Brix H (1997). Do macrophytes play a role in constructed treatment wetlands. Water Science and Technology, **35**(5), 11–17

Davidsson K O; Pettersson J B C; Nilsson R (2002). Fertiliser influence on alkali release during straw pyrolysis. Fuel, **81,** 259–262

Drizo A; Frost C A; Grace J; Smith K A (2000). Phosphate and ammonium distribution in a pilot-scale constructed wetland with horizontal subsurface flow using shale as substrate. Water Research, **34**(9), 2483–2490

Ghetti P; Ricca L; Angelini L (1996). Thermal analysis of biomass and corresponding pyrolysis products. Fuel, **75**(5), 565–573

Gray S; Kinross J; Read P; Marland A (2000). The nutrient assimilative capacity of maerl as a substrate in constructed wetland systems for waste treatment. Water Research, **34**(8), 2183–2190

Green M; Safry I; Agami M (1996). Constructed wetlands for river reclamation: experimental design, start-up and preliminary results. Bioresource Technology, **55,** 157–162

Hammer D A; Knight R L (1994). Designing constructed wetlands for nitrogen removal. Water Science and Technology, **29**(4), 15–27

Hill D T; Payton J D (1998). Influence of temperature on treatment efficiency of constructed wetlands. Transactions of the ASAE, **41**(2), 393–396

Ibekwe A M; Grieve C M; Lyon S R (2003). Characterization of microbial communities and composition in constructed dairy wetland wastewater effluent. Applied and Environmental Microbiology, **69**(9), 5060–5069

Jin G; Kelley T; Freeman M; Callahan M (2002). Removal of N, P, BOD_5, and coliform in pilot-scale constructed wetland systems. International Journal of Phytoremediation, **4**(2), 127–141

Jing S-R; Lin Y-F; Lee D-Y; Wang T-W (2001). Nutrient removal from polluted river water by using constructed wetlands. Bioresource Technology, **76,** 131–135

Lee C-Y; Lee C-C; Lee F-Y; Tseng S-K; Liao C-J (2004). Performance of subsurface flow constructed wetland taking pretreated swine effluent under heavy loads. Bioresource Technology, **92,** 173–179

Mandi L; Bouhoum K; Ouazzani N (1998). Application of constructed wetlands for domestic wastewater treatment in an arid climate. Water Science and Technology, **38**(1), 379–387

Manios T; Millner P; Stentiford E I (2000). Effect of rain and temperature on the performance of constructed reed beds. Water Environment Research, **72,** 305–312

Manios T; Stentiford E I; Millner P (2002). The removal of NH3-N from primary treated wastewater in surface reed beds using different substrates. Journal of Environmental Sciences Health A, **37**(3), 297–308

Manios T; Stentiford E I; Millner P (2003). The removal of chemical oxygen demand from primary-treated domestic wastewater in surface-flow reed beds using different substrates. Water Environment Research, **75**(4), 336–341

Mann R A; Bavor H J (1993). Phosphorous removal in constructed wetlands using gravel and industrial waste substance. Water Science and Technology, **27,** 107–113

Naylor S; Brisson I; Labelle M A; Drizo A; Comeau Y (2003). Treatment of freshwater fish farm effluent using constructed wetlands: the role of plants and substrate. Water Science and Technology, **48**(5), 215–222

Schonerklee M; Koch F; Perfler R; Haberl R; Laber J (1996). Tertiary treatment in a vertical flow reed bed system-a full-scale pilot plant for 200–600 p.e. In: The 5th International Conference on Wetland Systems for Water Pollution Control, Vol 1 Vienna, September 1996, pp 15–19

Solano M L; Soriano P; Ciria M P (2004). Constructed wetlands as a sustainable solution for wastewater treatment in small villages. Biosystems Engineering, **87**(1), 109–118

Soto F; Garcia M; de Luis E; Bécares E (1999). Role of the *Scirpus lacustris* in bacterial and nutrient removal from wastewater. Water Science and Technology, **40**(3), 241–247

Stober J; O'Connor J T; Brazos B J (1997). Winter and spring evaluations of a wetland for tertiary wastewater treatment. Water Environmental Research, **69**(5), 961–968

Stottmeister U; Wießner A; Kuschk P; Kappelmeyer U; Kästner M; Bederski O; Müller R A; Moormann H (2003). Effects of plants and microorganisms in constructed wetlands for wastewater treatment. Biotechnology Advances, **22,** 93–117

Tanner C C; Clayton J S; Upsdell M P (1995). Effect of loading rate and planting on treatment of dairy farm wastewater in constructed wetlands—I. Removal of oxygen demand, suspended solids and faecal coliforms. Water Research, **29,** 17

Tanner C C (1996). Plant for constructed wetland treatment systems – A comparison of the growth and nutrient uptake of eight emergent species. Ecological Engineering, **7,** 59–83

Vaillant N; Monnet F; Sallanon H; Coudret A; Hitmi A (2003). Treatment of domestic wastewater by an hydroponic NFT system. Chemosphere, **50**(1), 121–129

Zevenhoven-Onderwater M; Blomquist J-P; Skrifvars B-J; Backman R; Hupa M (2000). The prediction of behaviour of ashes from five different solid fuels in fluidised bed combustion. Fuel, **79,** 1353–1361